inFOCUS

Special Edition

SEPTEMBER
2025

A PUBLICATION OF:
HAEE
HELLENIC ASSOCIATION *for* ENERGY ECONOMICS

TOPICS

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SPECIAL EDITION

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for ENERGY ECONOMICS

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Prof. Dr. Emilios Galariotis
BoD Member HAEE; BoD Member IAPR; HAEE Chair of the Scientific Committee of the 10th HAEE Energy Transition Symposium; Full Professor of Finance at KFUPM Business School

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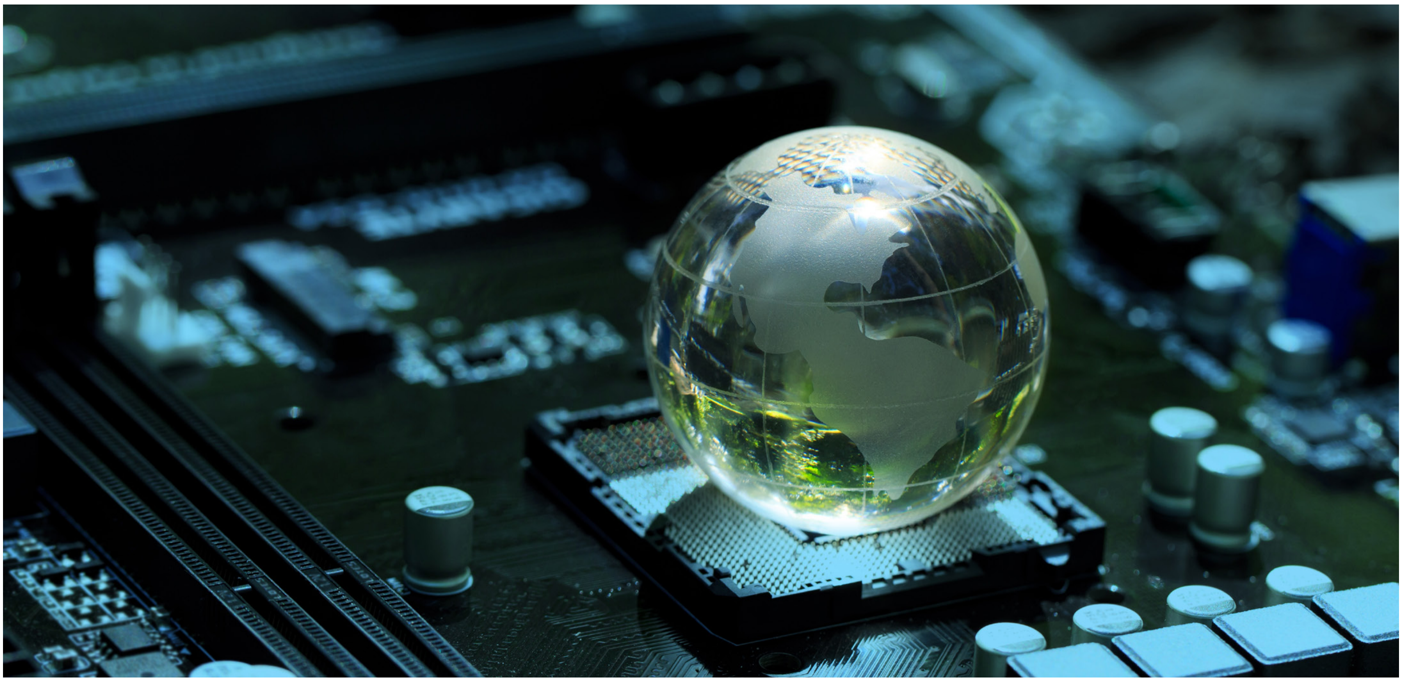

Prof. Dr. Emilios Galariotis
BoD Member HAEE; BoD Member IAPR; HAEE Chair of the Scientific Committee of the 10th HAEE Energy Transition Symposium;
Full Professor of Finance at KFUPM Business School

As the Hellenic Association for Energy Economics (HAEE) celebrates its 10 years, we find ourselves at a pivotal moment in the global energy landscape. Over the past decade, the energy sector has been reshaped by profound geopolitical, economic, and technological forces, challenging nations, industries, and communities to rethink their approaches to security, sustainability, and equity.

I proudly present this special edition of In Focus that reflects the very mission that has guided HAEE since its inception: fostering informed debate, advancing interdisciplinary research, and creating a platform where innovative ideas meet practical solutions. The contributions in this issue demonstrate the breadth and depth of scholarship needed to navigate the energy transition. From the role of financial markets in enhancing energy security and the promise of decentralised district heating to the challenges of integrating Carbon Capture Utilization and Storage (CCUS) into existing gas infrastructure, these works provide a multi dimensional view of the opportunities and obstacles before us.

In particular, this issue's dual structure — Emerging Research Insights and In Depth Research Articles — allows the reader to engage with both the cutting edge of academic inquiry and the comprehensive analyses required for policy and investment decision making. The abstracts offer a concise view of evolving debates and innovative methodologies, while the full papers provide robust examinations of critical topics such as electricity market reform, lifecycle cost analysis of building interventions, and pathways for green hydrogen expansion.

The work presented here would not have been possible without the commitment of our contributors, who have shared their expertise and insight to enrich this edition, nor without the collaborative efforts of our editorial and scientific teams. As Chair of the Scientific Committee, I extend my gratitude to all those who participated in the development of this issue.

As HAEE embarks on its second decade, we remain committed to providing a forum for dialogue and knowledge exchange that bridges academia, industry, and policy. It is our hope that this edition of INFOCUS will not only inform but also inspire readers to engage in the urgent and transformative work of shaping a sustainable, secure, and equitable energy future.

Introduction

This special edition of In Focus marks a milestone for the Hellenic Association for Energy Economics (HAEE) as we celebrate a decade of advancing dialogue, research, and innovation in the field of energy. Over the past ten years, HAEE has been at the forefront of Greece's and Europe's energy transition, fostering collaboration between academia, industry, and policymakers. As the energy landscape continues to evolve amid geopolitical uncertainties, ambitious climate commitments, and rapid technological advancements, this anniversary edition reflects on the progress achieved and the work that still lies ahead.

This issue collects the academic papers and abstracts that were presented in the 10th HAEE Energy Transition Symposium held in June, and specifically in the Academic sessions of the Symposium. The contributors to this issue had the opportunity to present their work to their peers, sparking interesting dialogue and advancing the knowledge sharing around the topic of energy.

The structure of the issue comprises two complementary sections designed to give readers both breadth and depth of insight. The first section, Focused Research, presents a collection of extended abstracts highlighting new ideas and evolving debates in the energy domain. These contributions offer concise yet rich explorations of some of the most pressing questions in the field, ranging from the role of financial markets in enhancing energy security to the paradoxes and potential of decentralised district heating in the EU. The abstracts also address critical issues such as integrating Carbon Capture Utilization and Storage (CCUS) into natural gas infrastructure, rethinking policy strategies for energy efficiency gains through technology integration, and improving forecasting at the secondary substation level to enable distribution system operators' participation in local flexibility markets. Together, these studies provide a snapshot of emerging approaches that bridge the gap between research, policy, and practice.

The second section, In-depth Research, offers full-length papers that provide comprehensive analyses of key aspects of the energy transition. These articles delve deeper into technical, economic, and policy dimensions, covering topics such as the risks posed by fire and flood hazards to photovoltaic parks, life-cycle cost analyses of energy interventions in the Hellenic building stock, and Kalamata's pioneering climate contract under the NETZEROCITIES initiative. Readers will also find detailed examinations of Greece's electricity market design and reform priorities, a water-energy-emissions assessment of the Greek industrial sector, strategies for improving energy security through electricity storage in open and semi-open markets, and a forward-looking exploration of pathways for expanding green hydrogen use. Together, these papers provide both granular detail and systemic perspectives, offering practical recommendations for stakeholders across the energy ecosystem.

By combining these two sections this edition aims to serve as both a thought-starter and a reference point for those working at the intersection of energy policy, economics, and technology.

Focused Research

Enhancing energy security through financial markets' trading: A bridge for energy transition

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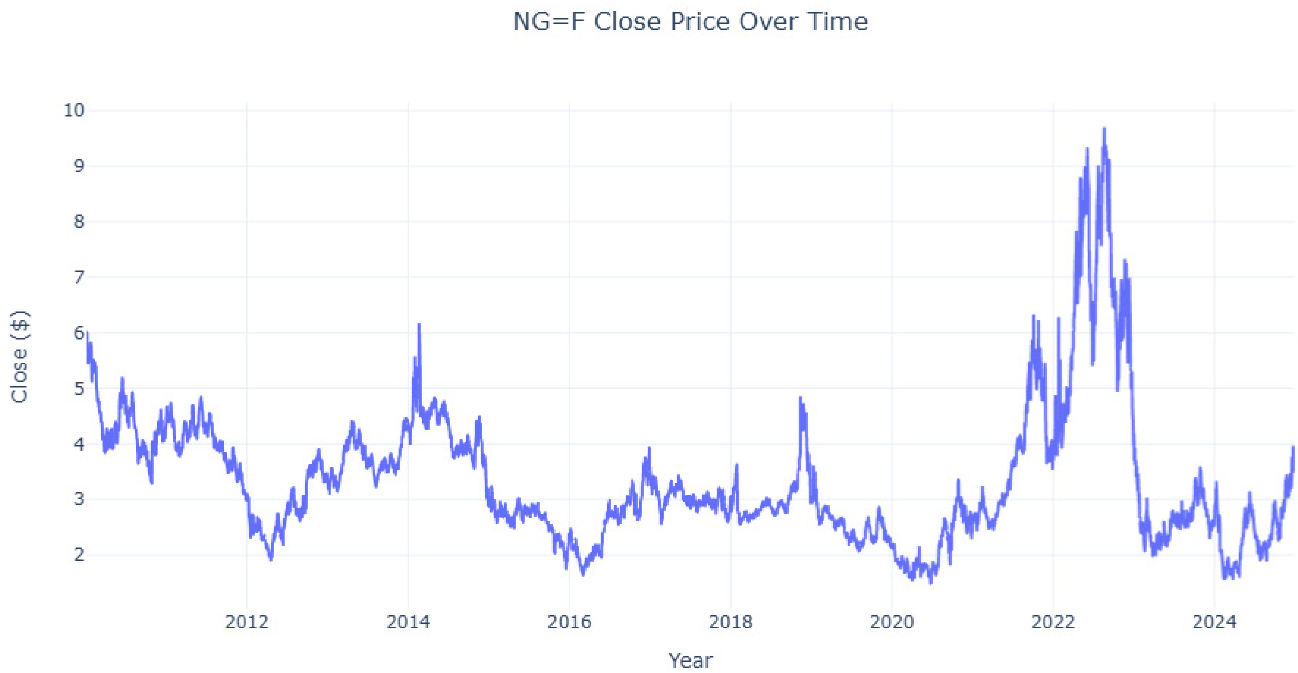
Overview

The need for accessible and affordable energy is invasive in today's volatile, uncertain, complex, and ambiguous world stage. Europe in particular, as a major consumer of imported energy, has frequently borne the financial, social, and geopolitical consequences of energy dependency. Although major steps have been taken in recent years and relevant technologies such as renewable energy sources, energy storage systems, hybrid-electric vehicles, and even novel nuclear technology are in various stages of maturity, the question of energy security remains as relevant as in the winter of 1973, aptly demonstrated during the 2022 resumption of hostilities in Ukraine and the resulting energy crisis (Bouazizi et al., 2024). However, energy security may be elusive to a universally acceptable definition (Azzuni and Breyer, 2017). Existing energy technologies, green or otherwise, cannot hitherto replace imported energy in the framework of internationally connected financial markets, nor can they effectively do so during periods that crises – energy, financial, or geopolitical – erupt and escalate. The present paper proposes an alternative approach to the pursue of energy security, through direct active participation in global energy financial markets, not with the intention of merely hedging risk exposure, as often practiced at the organisational and (supra)national level, but to actively trade relevant underlying commodities and financial products with the aim of securing net profit. Such financial gains can serve to cushion escalating energy costs during crises and effectively dampen energy price shocks, thus materially contributing to the protection of respective national economies, socioeconomic cohesion and social peace, and even, assist in hedging geopolitical risk to (supra)national sovereignty by mitigating the spectre of energy insecurity utilised as a direct or potential threat to enforce conformity (Sovacool, 2012).



Methods

The present work employs a quantitative approach to develop and evaluate a systematic trading strategy and analyse the potential for deriving financial profit from direct participation in international energy financial markets. The strategy focuses on natural gas futures contracts, in particular the NG=F continuous front-month futures contract traded in the New York Mercantile Exchange (NYMEX). NG=F price movement closely follows the actual price of natural gas by reflecting the price of the NYMEX natural gas futures contract closest to expiration. It is a highly liquid financial instrument, and due to its integral automatic roll-over, a few days prior to the actual expiration of the closest-to-expiration-date natural gas futures contract, the risk of actual expiration and consequent physical delivery of the underlying asset is negated. The proposed strategy consists of opening a Buy position in the NG=F continuous front-month futures contract at the Close price just prior to the end of a trading session, if the Close price is lower than the Close price of the previous session. The position is closed at the end of the next trading session, at the next Close price. Effectively, the proposed strategy is a systematic implementation of the "Buy Low" principle of trading, counting on the nature of the underlying commodity to achieve a profit when closing-selling the position opened earlier when the Close price decreased. As natural gas is a preferred fuel due to its properties, versatility, ease of use and transportation, price pull-backs are frequently "bought-into" as they present opportunities for buyers/consumers to achieve a lower price. Although this strategy approach may appear controversial due to its contrarian nature, it can prove to be quite effective, as will be shown. The strategy was implemented in a custom-written algorithm (Python 3.11.9) utilizing NG=F market price data, which are freely available online through open-access databases such as Yahoo! Finance.

Results

Backtesting the proposed strategy on NG=F from January 4th, 2010, with an allocated initial capital equal to 10,000 USD ($), the proposed strategy accumulated a total capital of 95,844.51 USD ($) by the end of 2024 for a total returns' percentage equal to 858.45% after a period of extensive growth, as shown in Figure 1. Over a period of 15 years, 1944 trades were taken, of which 987 were closed for a profit, and 957 were closed at a loss, representing a win rate equal to 50.77%. During the aforementioned period, there were 3773 trading days, during which the markets were open and active, thus we conclude that there was approximately 1 trade every 2 trading days. A "Buy-and-Hold" strategy over the same time period would result to a net loss, as 10,000 USD ($) invested in NG=F and held until 31/12/2024 would result to a total of 6,174.37 USD ($), thus incurring a loss of 3,825.63 USD ($), amounting to a negative total returns performance equal to -38.26 %. Thus, considering the large number of trades and extensive backtesting period, it can be deducted that the proposed strategy clearly outperforms the benchmark "Buy and Hold" strategy, despite the considerable volatility exhibited by the price of the underlying commodity (natural gas) and the financial instrument utilised (NG=F). Furthermore, the proposed strategy on NG=F considerably outperforms the returns of the Standard & Poor's 500 (S&P500) index, routinely utilized as an enduring investment performance benchmark, over the aforementioned time period.

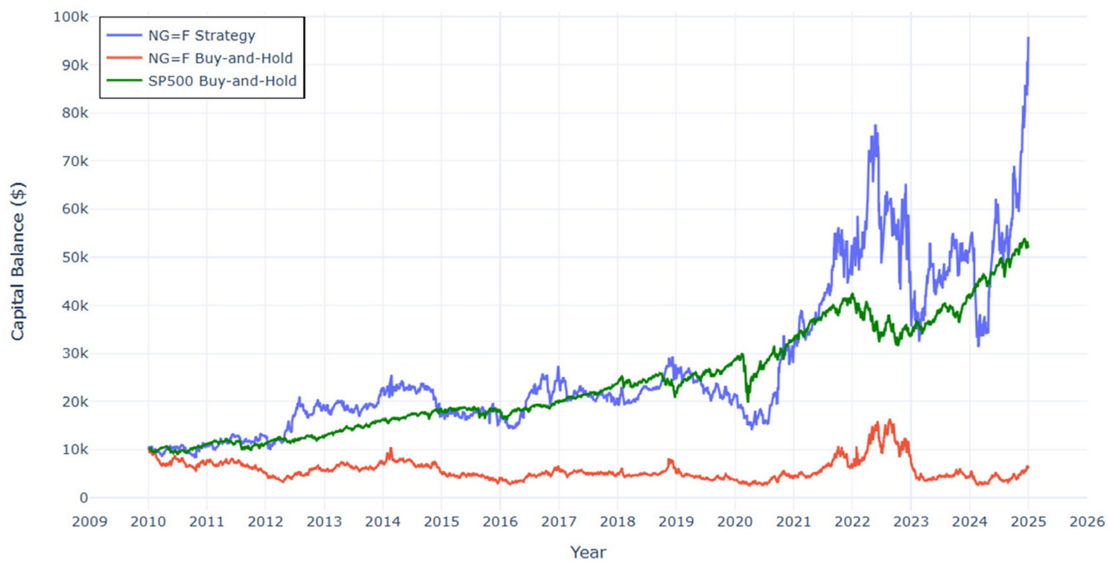


Figure 1. Accumulated capital of the proposed strategy implemented on NG=F compared to the accumulated capital for Buy-and-Hold strategies on NG=F and S&P 500 financial instruments.

Conclusions

Energy security remains an ever-present challenge, despite the great efforts and investment afforded to its mitigation. As global energy demand is projected to continue increasing for the foreseeable future, mirroring the increase in living standards and human population worldwide, it is exceedingly probable that the upward trend of energy prices will persist. Heightened geopolitical tensions, such as the ones already witnessed in Eastern Europe, Middle East, Africa and beyond, can exacerbate energy insecurity on a global scale, feeding into the aforementioned price effect and in turn, being amplified by them, in a vicious cycle of escalation. Although the proposed trading strategy cannot negate such effects single-handedly, arguably no solution can. Far from being a silver bullet, the proposed strategy can serve as a useful arrow in the quiver of any aware institution or (supra)national entity seeking realistic, if imperfect, solutions to the pressing problem of escalating energy costs and consequent energy insecurity. The proposed approach offers a major advantage, in that it requires little in the way of innovation and is highly flexible. Financial infrastructure required for financial trading is simple, mature, stable, and present worldwide. Any profits resulting from the implementation of such financial strategies would already be in cash or cash-equivalent form, and thus can easily be directed to any priority need at will, whether it is support of energy infrastructure, research on new technologies aimed at green energy production and storage, or supporting the energy burden of society's less fortunate. Finally, the proposed approach aims to further democratize financial and energy markets in the interests of the many, that ultimately form the backbone of developed societies.

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Focused Research

Charting the energy transition: rethinking green policy strategy and sustainable technology integration for energy efficiency gains – sectoral evidence from europe

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Overview

The European Union's goal of achieving carbon-neutrality is tied to the successful implementation of energy transition strategies. Traditionally, energy transition has focused on improving energy efficiency, but this view overlooks crucial factors such as the energy efficiency gains and energy efficiency savings rate, which better reflect the decoupling of fossil fuel dependence. The paper investigates the impact of integrating sustainable technologies and climate action on energy efficiency gains as well on energy efficiency savings rate within the European economy, industry, and services sectors. It examines the effectiveness of different green policy strategies and how sustainable technology integration responds to various policy frameworks, which is often underexplored in existing literature.

Methods

The analysis employs panel quantile regression within an instrumental variables (IV) framework. This methodology allows for a more robust analysis of energy efficiency gains and energy efficiency savings rate across different performance tiers, addressing potential endogeneity issues that could arise from policy variables. The study uses a dataset spanning the EU-28 from 2010 to 2019, integrating multiple sources to create a comprehensive dataset. Besides the whole economy level, the industry, and services sectors are considered in this framework for the first time. The energy efficiency gains and the energy efficiency savings rate, both derived from the Energy Efficiency Index (EEI) is central to the analysis. EEI accounts for changes in energy consumption at the sector level. The study also uses policy data from EU directives and green fiscal policies to assess the impact of sustainable technologies and climate action.

Results

At the economy level, the analysis shows that the energy efficiency gains, is a superior indicator for tracking energy transition compared to traditional energy intensities. It is particularly useful as it eliminates structural changes and factors unrelated to energy efficiency, providing a more accurate representation of energy transition progress. Econometric results indicate that energy taxes negatively affect energy efficiency gains across the low performance tiers, while in medium performance tiers there is a non significant effect. This impact suggests that such taxes may discourage investment in energy efficiency improvements, particularly in industries and sectors with lower energy performance. It seems that lower performers struggle to translate tax pressure into improvements. On the contrary, environmental public R&D has a positive effect on energy efficiency gains, suggesting that public investments in green R&D can foster significant energy efficiency improvements and guide energy transition progress. In addition, green technology development, proves to be an energy-intensive path, hindering energy efficiency gains, suggesting lock-in effects and reduced access to superior foreign technologies. Results also show that environmental policy effectiveness has varying effects across tiers as it promotes energy efficiency at Q50 but not at Q75. The evidence suggests that flexible policy frameworks are more effective in promoting energy efficiency gains (EEG). Sectoral evidence is in line with economy-wide findings whith some important differentiations. Robustness checks using lagged policy and technology variables confirm results, accounting for potential diffusion and endogeneity within the EU-28.

Results

The study concludes that environmental public R&D and environmental policy effectiveness play a significant role in driving energy efficiency gains and energy efficiency savings rate progress. Sustainable technologies, emerge as a key driver in charting energy transition within the EU. The findings emphasize the importance of more targeted policy approaches and green technology integration to achieve the EU's climate-neutrality objectives.

Keywords

Energy efficiency gains, energy efficiency savings, green policy and technology, panel quantile regression, Sectors, Europe

Focused Research

Energy Forecasting at the Secondary Substation Level for DSO Participation in Residential Local Flexibility Markets

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Overview

The transition toward decarbonization, along with the increasing integration of Distributed Energy Resources (DERs), and the growing penetration of Renewable Energy Sources (RES) has led to the active incorporation of explicit flexibility within Local Flexibility Markets (LFMs). This flexibility is crucial for ensuring grid stability, minimizing thermal losses, and preventing critical network contingencies [1]. Explicit flexibility, defined as the proactive commitment of participants to modify their energy consumption or generation in response to signals from a Flexibility Service Provider (FSP), following a request from the Distribution System Operator (DSO), is a key mechanism in LFMs [2]. In recent years, the participation of low-voltage (LV) consumers through an aggregator has been proposed as a viable solution to enhance the volume of available flexibility in the distribution network. However, the effectiveness of this approach depends on accurate power demand forecasting [3], which is essential for performing power flow analyses, calculating the required flexibility, and submitting the respective flexibility request to the FSP. Furthermore, once a flexibility request is accepted, a baseline must be established to validate the dispatched flexibility.

To assess the challenges of forming flexibility requests from the side of a DSO in an intra-day LFM with LV residential users, we examined the process of identifying and forming flexibility requests to address voltage violation issues and define a baseline for validating the flexibility dispatch. Given the stochastic nature of consumer behavior, accurately forecasting individual household loads is highly challenging. Therefore, we adopted an aggregated approach by performing energy forecasting using machine learning techniques on secondary substation energy consumption data. The resulting forecasted energy time series were utilized for grid analysis to assess potential voltage violations within an LFM experimental setup in Mesogeia, Greece. To mitigate the identified constraints and restore voltage levels, the minimum load reduction required was determined through grid optimization, forming the basis for a flexibility request.

Methods

In this study, real-world energy consumption and production data were obtained from telemetered secondary substations of the Hellenic Distribution Network Operator (HEDNO), the Greek DSO, focusing specifically on residential consumers. The metering devices used (DinRail 3-Phase Advanced by Meazon, Greece) provide both energy consumption and power quality data. To enable a direct comparison with the consumption data of individual residential users, the baseline was forecasted in energy units with 15-minute intervals (Market Time Units, MTUs). For this purpose, a Long Short-Term Memory Neural Network (LSTM NN) was employed to perform the forecasting [4]. To enhance predictive accuracy, the raw data undergoes several preprocessing steps. Initially, we enrich the dataset with external weather variables (temperature and cloud-coverage), retrieved from Open Meteo (https://open-meteo.com/). The enriched data are normalized and separated to multiple fixed-length train and test sequences based on the specific experimental settings, such as input sequence length and prediction sequence length. The Mean Absolute Percentage Error (MAPE) was used as metric to evaluate the results.

The forecasted energy time series for the telemetered substations were converted to active power and used for grid flow analysis with the commercially available simulation software PowerFactory (version SP5, DIgSILENT GmbH, Germany). The power factor for the analysis was set to 0.95, obtained as the average of the historical metering data. For the remaining substations in the grid (Fig. 2), a load factor of 80% and a power factor of 0.95 were applied. A Newton-Raphson power flow analysis was then conducted to assess the grid's operating conditions.

Results

Eight weeks of energy and weather data were used to train an LSTM model with two hidden layers, designed to predict the 6th Market Time Unit (MTU). Figure 1 presents a comparison between the metered and forecasted data over a 48-hour period. The MAPE was calculated as 0.085. Since the forecasting process runs iteratively for the next six MTUs, the forecasted values for the 6th MTU were used for the power flow analysis to allow for one hour to realize the market bidding processes. To review the process of forming flexibility requests we simulated an undervoltage issue at the specific telemetered substation located in an urban area, which propagated to adjacent nodes, further exacerbating voltage instability in the surrounding network (Fig. 2). To address this issue, a flexibility optimization algorithm was applied to the node where the LFM participants are connected, determining a required flexibility demand of 84 kW. This power adjustment would be requested from the residential consumers to alleviate the undervoltage problem and maintain grid stability. The dispatch will be validated based on the forecasted value at the substation.

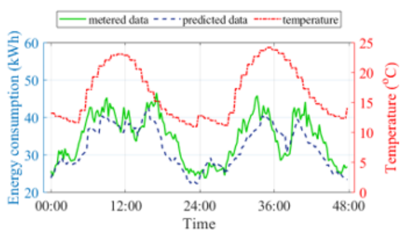

Fig.1 Energy forcasting results (dotted line), the actual metered data (solid line) and the respective temperature data (dash-dot line) over a 48-hour period with 15-minute intervals.

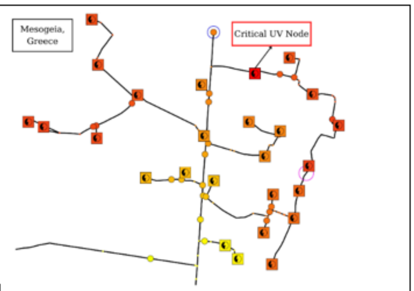

Fig. 2 Grid analysis results for the Medium Voltage Network, with a color-coded representation highlighting undervoltage levels.

Conclusions

This study explores how AI-driven load forecasting, combined with power system analysis and flexibility optimization, can enhance grid reliability and operational efficiency. By applying LSTM-based energy forecasting at the secondary substation level, the proposed approach enables DSOs to proactively identify and address grid stress conditions, such as undervoltage propagation in urban areas. Integrating forecasted flexibility requests into grid simulations allows DSOs to dynamically procure the necessary flexibility, effectively mitigating voltage violations. This work is part of an ongoing effort by our research group. The next steps include incorporating additional features into the LSTM models to enhance their robustness. Furthermore, we aim to develop a mechanism to replace metered data with forecasted baselines during demand-response events, ensuring that the normal energy consumption patterns of consumers remain unaffected.

Funding

This project has received funding from the European Union's Horizon Europe research and innovation program under the Grant Agreement number 101136216. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

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Decentralised district heating in the eu: evaluating the paradox and Proposing a framework for energy community expansion

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Overview

To meet its obligations under the Paris Agreement (2015) the European Union developed the Green Deal in 2019, followed by Fit-for-55 which envisages reducing GHG emissions in the EU by 2030. The phase out of natural gas is one key policy priority for the EU – including decarbonising the Heating and Cooling (H&C) sectors, currently relying on fossil fuels and accounting for a staggering 62% of EU energy consumption. District Heating (DH) has been described as a "Swiss army knife for decarbonisation" due to its potential for combining the use of local renewable electricity and the use of excess heat from industrial and urban sources. On the other hand, to meet the new Commission's policy mandate for a consumer-centric energy transition that leaves no one behind, EU Directives have aimed to enable active energy citizenship through collective and individual means – including mainstreaming energy communities (ECs) in heating and cooling solutions. The decarbonisation of the H&C sectors by DHC cannot be treated in isolation from the justice-centric approach underlying EU energy policy and law. To this end, the decentralisation of DH through the expansion of ECs in the EU is a key opportunity for the decarbonisation of the H&C sectors while empowering active energy citizens in the EU. This paper conducts a Rapid Evidence Assessment to study the state of EC-owned and fuelled DH, providing an overview of the current state of ECs in the EU, and assessing their limitations. This presents a case-study analysis of the Danish heating transition to distil lessons learnt for the EU. The study highlights the need for a robust, interdisciplinary enabling Framework for ECs in the EU and concludes by proposing policy suggestions for the expansion of community district heating.

Methods

This article aims to answer the following research question: to further the EU Climate Law what role can regulated Energy Communities play in expanding decentralised and decarbonised District Heating in the EU? To analyse the role that ECs play in expanding decentralised and decarbonised DH in the EU Climate Law context, this article offers a structured search and assessment of the evidence related to the state of EC-owned and powered DH using the Rapid Evidence Assessment (REA) methodology. This is a type of structured and transparent search, collection, and assessment of evidence to inform law and enhance accountability within evidence gathering pertaining to regulatory and other analyses (Stone, 2013). The research also uses a case-study investigation of the Danish heating transition – specifically investigating the role of energy decentralization in district heating systems. Evaluating the heating transition in Denmark and the impact of decentralization through energy community development and the non-profit principle enables this research to understand the sphere of energy law and its application in a different context and to draw lessons from that (Yin, 2014). Denmark was chosen as the case study for several reasons. Firstly, Denmark has been successful in decarbonising heat due to path dependencies (Gross & Hanna, 2019). The comprehensive infrastructure planning in Denmark has resulted in cost-effective District Heat Networks (DHN) (Eikeland & Inderberg, 2016). Secondly, Denmark ranked first in the Energy Trilemma Index (2023), indicating a balanced and robust energy system. Given the potential for delivering decarbonised heat using DHN (Stabler & Foulds, 2020) in the EU, and the successful implementation of DHN in Denmark presents an appropriate country case study for potential policy and implementation lessons. In 2023, DH supplied heat (space and hot water) to two-thirds of the heat demand for Danish households (Johannsen et al., 2023; State of Green, 2023). Cooperative culture and bottom-up innovation have played a key role in the socio-technical deployment of RES (Johansen, 2022). Further, DHN play a crucial role in achieving Danish net-zero goals (Lund et al., 2017, 2018; Ma et al., 2020; Sorknæs et al., 2020; Johannsen et al., 2023). Data was collected from a variety of sources to ensure a comprehensive understanding of the heating transition in Denmark. These sources include government reports, energy policy documents academic literature, grey literature. By using Denmark as a case study, this research hopes to contribute to the broader understanding of how energy decentralization can play a role in achieving a sustainable and consumer-centric natural gas phase-out and heating transition.

Results

The evidence review reveals a gap in the literature and practice as to the implementation of EC-powered DHNs in the EU. While the Danish case study shows the benefits of localised DH ownership and decentralised fuels, this is not applied in the EU. Further, there is no enabling mechanism for the realisation of ECs' broad benefits, let alone their application in the H&C sector. Energy communities face some key challenges that can be categorised under: infrastructural, financial, capacity-building and governance barriers in EU Member States. Some good practices are identified across the Bloc, but these are limited to 'professionalised' contexts, where ECs have been historically operational. The Danish case study further reveals good practices – that may be transferrable in the European context. DH is technologically complex, which further amplifies the abovementioned challenges faced by ECs. DHNs are characterised as natural monopolies, leading to issues in relation to price regulation and ownership structures. The inclusion of ECs in heating, and the extent to which these can be vessels for community engagement in the heating transition, is limited by the need for local stakeholder collaboration – particularly the engagement of municipalities. The following 'lessons learnt' can be distilled: a) the reimagining of ownership models for heating – particularly in relation to municipal and cooperative ownership; b) the implementation of the no-profit principle to enable affordable heating prices – particularly for vulnerable households – and the reinvestment of revenues in community initiatives; and c) strengthening municipal capacity to participate in DHNs. This informs policy proposals that account for some conceptual and practical stumbling blocks. First, the need for a balance between prescription and flexibility to allow ECs to engage in social innovation. Second, the need for a balance between a top-down approach enabling a bottomup governance vs the creation of a bottom-up decentralisation and decarbonisation.

Conclusions

In summary, this paper uses a REA and case-study to assess the role ECs can play in the decarbonisation of heating in the EU using DHN. This concludes by proposing policies for expanding the role of ECs in establishing decentralized and decarbonized DH to meet the European policy objectives for energy. Enabling EC involvement in DH, whether through community ownership or the distribution of renewable energy by ECs for DH systems, can yield significant socio-technical and political benefits, as demonstrated by the case study of Denmark.

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Focused Research

Natural gas: Overcoming the challenges to gas turbines "gts" In adopting "ccus" carbon capture utilization & storage

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Abstract
For the immediate and medium range terms the energy transition strategy is factoring Natural Gas "Gas Turbines" (Simple cycle and Combined Cycle), though Natural Gas has the lowest CO2 emissions compared to oil or Coal, large plants produce significant amounts of CO2. Hence, CCUS is needed. Because of the large Air to Fuel ratio in typical Gas Turbines, the CO2 concentration is the exhaust gases is quite low. This leads to expensive CO2 separation. The current technologies for CC is complex and amount to a large chemical facility that uses coming sophisticated systems from the Oil and Gas industry. The addition of such facility to the typical power plant is a major challenge. Further to collocating the CO2 separation plant with the power plant, the low CO2 concentration leads to excessive additional costs. Yet, the need for dispatchable generation assets points to finding an optimum solution. It is recommended that a Feasibility study be undertaken with the participation of the stake holders, Owner of a Power plant, TSO System Operator, Gas Supplier, and Regulatory Body.

Keywords
Natural Gas /LNG, Gas Turbine, Combined Cycle, CCUS

Energy Transition

Figure 1 shows two paths for Energy Transition, Path I at the upper part of the figure is the target when we eliminate fossil fuel and use Renewable Energy and Hydrogen in combination with battery storage. That path while is a target, may be difficult to attain in the short / medium term because of the difficulties of attaining Green Hydrogen from large scale Green Hydrogen plants at acceptable commercial levels. Path II is where we are in 2025, as Natural Gas which has lowest CO2 emissions compared to oil and coal and in particular e for electric generation the simple cycle and combined cycle plants have proved to be quite dependable and continue to serve the electric grids quit well offering the electric grid the best solution for dispatchable electricity generation assets, It is e that path II, needs a complementary Carbon Capture scheme in general CCUS , for carbon capture utilization & storage. Path II requires adoption of the right CCUS commensurate with use of Natural Gas. The main thrust of this paper primarily for gas turbine (simple cycle gas and combined cycle).

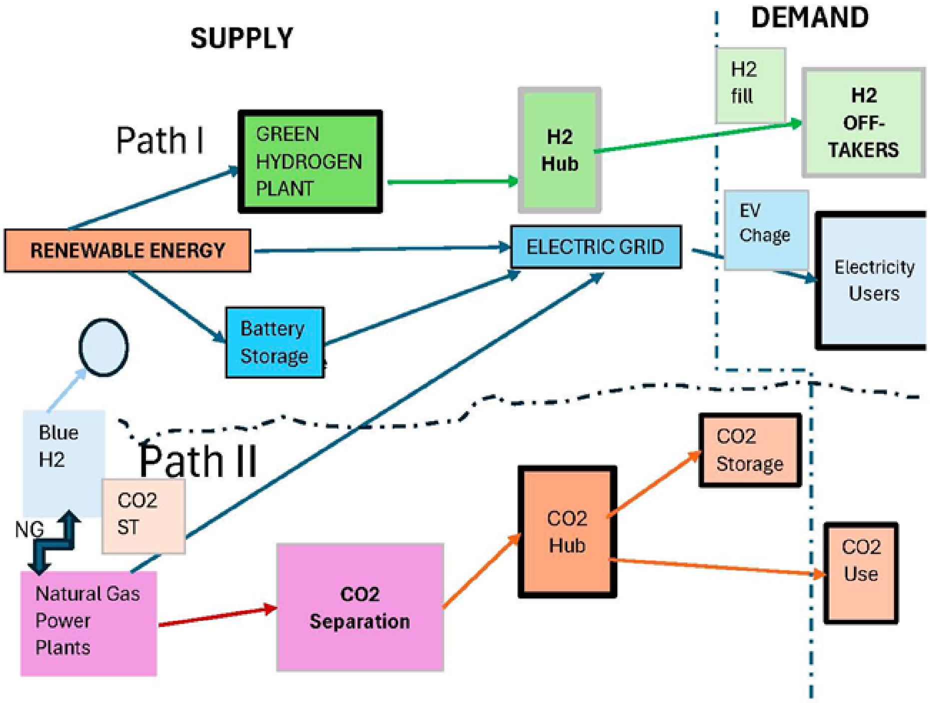

Figure 1 Two Paths for the Energy Transition

Main Challenge for Gas Turbines (Path II)

Because Gas Turbines use a high Air Fuel Ratio, the exhaust gases from Simple Cycle and Combined Cycle plants, approximately 40- 60 compared to the stoichiometric air-fuel ratio for natural gas 17.2. Thus, the exhaust gases have low concentration of CO2 that requires an extensive concentration process to separate CO2 from the rest of gases (Nitrogen and Oxygen) forming large % of the exhaust gases. Please refer to step 2 in Figure 2 – which is also referred to as CC Enrichment.

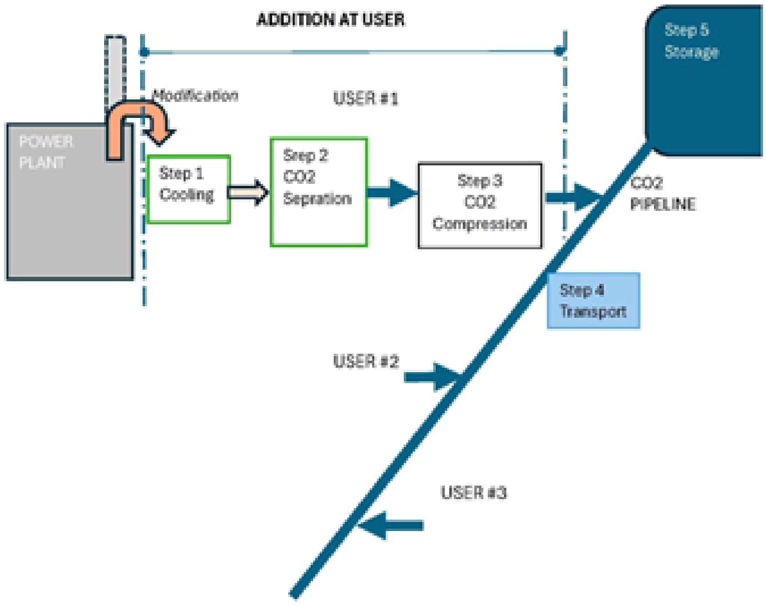

Figure 1 Two Paths for the Energy Transition

Referring to Figure 2 one notes that steps 1-3 are added to the power plant and hence they would be an expanded scope for the power plant ending with step 3 delivering CO2 at high pressure to an external pipeline operated by a different entity that is responsible of the CO2 transport pipeline. The contemplated scheme ends with large storage in an onshore or offshore cavern for long term storage of the received CO2. The transport-storage is to serve a hub that serves multiple users, industrial facilities and power plants. Each of the users completes steps 1-3 before the CO2 is injected in the transport hub.

Step 2 CC Enrichment (Separation of CO2 from the exhaust gases)

The main hurdle is in the complexity of the Carbon Separation – Table 1shows the estimates of CO2 and the associated gases in the exhaust gases of select gas turbines. Typical for gas turbines available from the four Major OEMs

GT		HL	F		E	SGT-800					SGT-700	
Output	MW	593	329	385	198	62.5	57	55.6	49.9	45.3	35.2	32.8
CO2	Ton/day	9,914	5,766	6,667	3,787	1,093	1,021	1,013	911	848	665	633
N2 & Other in Exh.	Ton/day	80,806	56,787	69,365	44,424	10,614	10,782	10,885	9,863	9,096	7,863	7,575

Available technologies that can be applied are

- PSA Pressure Swing Adsorption - Linde
- Amine Wash - BASF / Shell / MHI

The merits of choosing among these technologies can investigated after the initial consideration covered hereafter. The initial look at the CC Enrichment plant reveals that it entails complex facility and comes at CAPEX that could surpass the Combined Cycle plant's CAPEX, On the top of that the OPEX and the energy costs, together they render the Solution to be unattractive. The CAPEX for the large GT / Combine Cycle plants is very large making the investment decision hard to attain. Smaller GTs / Combined Cycle plants will have lower CAPEX but they higher USD/ MW installed. In an era where the Natural Gas plants are to be cycling not run as a base load, the economics gets worse with the large costs for the CC Enrichment addition.

Focus on Greece

Greece is going to depend on electricity to remedy the large CO2 contributions of fuel oil from transport. Please refer to Table 2 showing the largest power plants in Greece in early 2025. Note, that Greece is retiring the Oil fuel plants in the islands as projects for electric links to the islands from the mainland are well underway. The large additions of new Natural Gas power plants (Table 3) is an obvious pointer to Greece electricity preference.

#	Large Plants in Mainland Location	Type	Capacity MW	Owner	Notes
1	Agios Dimitrios, Kozani	Lignite-	1,595	PPC	Will be retired in 2025
2	Agios Nikolaos, Boeotia	NG CTTG	1,604	Mytilineos Group	High efficiency
3	Arcadia, Peloponnese	Lignite	850	PPC	Older signficnt for South Greece
4	Lavrio, Attica	NG	914	PPC	Important fo Attica
5	Ptolemaida, Western Macedonia	Lignite-	660	PPC	Modern plant 2023
6	Drama, E. Macedonia	Hydro	384	PPC	includes pumped-storage capabilities.
7	Aitoloakarnania, W. Greece	Hydro	437	PPC	Largest Hydro in Greece
8	Komotini, E Macedonia & Thrace	NG	485	PPC	Important for the region
9	Aliveri, Euboea	NG	417	PPC	Modernized to run on NG
10	Thisvi, Boeotia	NGNG	410	Elpedison	One of two plants owned & operated by Elpedison
#	Large Plants ib Islands	Type	Capacity MW	Owner	Notes
1	Souda Power Plant Crete	Oil	250		One of the main plants on Crete, run by PPC
2	Atherinolakkos Power Plant Crete	Oil	310		Largest on Crete; base-load thermal plant
3	Rhodes Power Plant (Soroni)	Oil	220		Serves the Dodecanese islands
4	Kos Power Plant	Oil/Diesel	100		Key for Kos and surrounding islands

Table 2 – Large Power Plants in Greece 2025

	New / Under construction	Type	Capacity MW	Owner	Notes
1	GEK Terna â€“ Motor Oil Komotini CCGT	CCGT	877	GEK Terna & Motor Oil Hellas	Commercial early 2025.
2	Alexandroupolis Combined Cycle Power Plant	CCTG	840	PPC (51%), DEPA Commercial (29%), Damco Energy (20%)	Commercial operation end of 2025
3	Agios Nikolaos (Viotia) CCGT	CCGT	826	Mytilineos Group	Commercial operation 2025
4	Thessaloniki II CCGT (Elpedison)	CCTG	826	Elpedison (Hellenicq Energy & Edison)	Expected commisxioning 2027
5	Ptolemaida V (Lignite)	Lignite	660	Public Power Corporation (PPC)	Ligne Unit operation on 2025, potential conversion to NG
6	Larissa CCTG	CCGT	792	Clavenia Ltd, DEPA Commercial S.A., EUSIF Larissa S.A., and Volton S.A	Agrrement signed May 2025

Table 3 New Large Plants Planned and under Construction

Recognizing that power plants have a long life of order 20 to 25 years and they entail large investments, hence they should have large utilization, measured by a high capacity. If the capacity factor is low, then the economics deteriorate, and that comes on the expense of the owner, the utility and the customers. This will be compounded with significant investments for CCUS.

Concluding Remarks

To Support the Energy Transition path II, it si recommended to sponsor a feasibility study to investigate the optimum solution for a CO2 Separation from the Combined Cycle plant. It is recommended that the Owner of the Plant, be joined together with the Electric System Operator, the Gas Supplier and the Regulator. The author is ready to take part in such and effort.

In-depth Research

Netzerocities 2030: a race to zero: cutting-edge international accounting standards and kalamata's climate contract for a carbon-free future.

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0. SUMMARY

This paper provides a detailed examination of the NetZeroCities European program, specifically focusing on the commitment of 100 European cities to achieving climate neutrality by 2030.
The study additionally provides an overview of the ISSA 5000 standard, focusing on its implications for public sector sustainability practices. It further examines the board decisions aligned with the Global Reporting Initiative (GRI) and the Task Force on Climate-related Financial Disclosures (TCFD) standards. These standards are evaluated for their suitability and potential implementation within public sector accounting and reporting, with a specific focus on enhancing sustainability and transparency in climate-related reporting for municipal and governmental entities involved in the NetZeroCities initiative. This analysis aims to establish a comprehensive framework for public sector entities to adopt standardized, reliable accounting practices that support climate neutrality goals.
A significant portion of the research focuses on the Kalamata implementation program. As part of this, a pilot questionnaire was distributed to students of departments at the University of Peloponnese, which are located in Kalamata, in order to gather insights on their perspectives. Statistical analysis, including descriptive and regression methods, was applied to evaluate the responses, yielding key findings on climate-related attitudes and awareness.
At the time of the paper's preparation, decisions had been documented for three participating Greek cities—Athens, Kalamata, and Trikala. Looking forward, the study aims to build upon the foundational analysis of Kalamata's climate contract, with an expanded focus. The goal is to examine in detail every decision related to the six Greek cities involved in the NetZeroCities initiative, contributing further research for the 2026 paper selection process.

*Has received scholarship from the Foundation for Education and European Culture (Ίδρυμα Παιδείας και Ευρωπαικού Πολιτισμού) for the academic year 2024-2025.

1. BOARDS ON SUSTAINABILITY AND PUBLIC ACCOUNTING/REPORTING

1.1. IASB and Public Accounting : News on ISSA 5000 designed by IASB (IFAC,2024)
The International Auditing and Assurance Standards Board (IAASB) has recently approved the International Standard on Sustainability Assurance (ISSA) 5000, marking a significant advancement in sustainability assurance practices. This standard is designed to enhance the credibility and consistency of sustainability reporting globally.

Key Features of ISSA 5000:

- **Comprehensive Scope**: ISSA 5000 applies to all forms of sustainability reporting, accommodating various frameworks such as those from the International Sustainability Standards Board (ISSB) and the Global Reporting Initiative (GRI).
- **Risk-Based Approach**: The standard emphasizes assessing risks of material misstatements in sustainability information, allowing practitioners to tailor their procedures accordingly.
- **Enhanced Professional Skepticism**: ISSA 5000 underscores the importance of professional skepticism, especially given the evolving nature of sustainability reporting and the challenges in verifying non-financial data.

The IAASB finally approved ISSA 5000 on September 20, 2024. The standard is currently undergoing finalization for certification by the Public Interest Oversight Board, with formal publication expected by the end of 2024. Guidance and application materials are anticipated to be available in January 2025.

It is reminded that the key features of the draft (named ED 5000) were the below:

- **Broad Applicability**: ED-5000 encompasses all sustainability topics (e.g., environmental, social, and economic aspects) and applies to various reporting methods, whether integrated with financial reports or stand-alone.
- **Framework-Neutral and Inclusive**: The standard can be applied to sustainability reports prepared under any recognized criteria and is suitable for both limited and reasonable assurance engagements. It allows assurance on diverse sustainability topics, regardless of user needs.
- **Standards for Assurance Levels**: The standard accommodates both limited and reasonable assurance engagements, providing clear indicators ("L" and "R") to differentiate requirements. It also includes procedures for the scope of engagement, ensuring clarity in sustainability information assurance.
- **Scope and Definitions**: ED-5000 defines "sustainability information" broadly, covering aspects like governance, policies, and goals. It aligns closely with other IAASB standards, such as ISAE 3410 for greenhouse gas reporting, and coordinates with the IESBA to maintain ethical and independence standards.
- **Assurance Practitioner Flexibility**: ED-5000 allows use by both accountants and other assurance providers, emphasizing ethics and quality management. It acknowledges the value of including specialists when necessary.
- **Significant Considerations**: -5000 also incorporates materiality concepts, requiring assurance providers to consider materiality both qualitatively and quantitatively based on user needs. Additionally, the standard outlines requirements for understanding the internal controls of an entity and distinguishes between limited and reasonable assurance needs. The standard addresses performance materiality for quantitative disclosures, helping to mitigate risks of aggregation.
- **Governance, Communication, and Reporting**: ED-5000 sets expectations for communication with those in governance and includes guidance for handling additional information in reports. It aligns assurance reporting with ISA standards, such as ISA 700 and ISA 720, for consistency. Illustrative reports are also provided for both limited and reasonable assurance scenarios.

1.2. GRI and Public Accounting:
The Global Reporting Initiative (GRI) guidelines have become a cornerstone for sustainability reporting, with a significant influence on how public and private organizations disclose their environmental, social, and economic impacts. Initially developed to standardize corporate sustainability disclosures, the GRI framework has gradually been adapted to meet the needs of public sector entities. Given their critical role in sustainable development, public agencies are adopting GRI standards to improve transparency, accountability, and overall governance practices. Public organizations, such as state-owned enterprises (SOEs) and local governments, are responsible for delivering essential services and managing resources that directly affect societal welfare, making their adherence to sustainability standards crucial for a balanced and sustainable future.(Dumay et al. 2010)
Sustainability reporting (SR) within public organizations serves multiple purposes. It enables agencies to document their social, environmental, and economic impacts, providing stakeholders with an insight into how these entities contribute to national and local sustainability goals. The GRI framework emphasizes a structured approach to reporting, aiming to standardize disclosures across various sectors, thus ensuring comparability and consistency in sustainability data. This structured approach is particularly useful for public agencies, as they hold significant responsibility for long-term societal and environmental welfare. By adopting GRI standards, public entities can support transparent decision-making processes that align with global sustainable development objectives.(Farneti &Guthrie,2008)

Despite the clear advantages, public agencies encounter several challenges in adopting the GRI framework fully. Studies reveal that the implementation of GRI standards in the public sector is often inconsistent, with agencies selectively choosing indicators that best align with their immediate priorities, a practice often referred to as "cherry-picking." This selective adoption can result in fragmented disclosures that may not provide a complete view of an organization's impact on sustainability. Additionally, many public sector entities lack external assurance for their sustainability reports, which can affect the reliability and credibility of the information provided. Without rigorous third-party verification, stakeholders may question the accuracy of reported data, undermining the goals of transparency and accountability that GRI guidelines are meant to promote.
Another significant challenge is the tendency of GRI-aligned reports in the public sector to focus heavily on internal metrics and managerial performance rather than addressing broader societal and environmental issues. This managerial focus can detract from the ecological and social objectives that sustainability reporting aims to support. Some critics argue that public agencies use these reports primarily to enhance their public image, rather than to drive substantial improvements in their sustainability practices. In this way, GR reporting sometimes falls into a "greenwashing" trap, where reports highlight positive achievements but obscure areas requiring improvement. The risk here is that public organizations may emphasize "cosmetic compliance" over genuine commitment to sustainability(Guthrie& Farneti 2008).

A critical viewpoint within the literature suggests that for public sector sustainability reporting to truly reflect societal and ecological values, agencies must go beyond a "managerialist" approach and adopt an "eco-justice" perspective. This approach emphasizes the need for sustainability reports to account for ecological boundaries and social equity, ensuring that public organizations are not only managing resources sustainably but also prioritizing the needs of vulnerable populations and future generations. The ecological and eco-justice approach advocates for a broader definition of sustainability that integrates social justice principles, such as equitable resource distribution and inter-generational equity. Public agencies, therefore, have an opportunity to lead by example, setting standards that align not only with the immediate economic goals but with the long-term social and environmental needs of their communities Integrated Reporting (IR) is another framework that has gained traction alongside GRI, offering a more holistic view of an organization's performance by combining financial and non-financial metrics into a single report. The IR framework emphasizes "value creation over time," aligning with GRI's sustainability goals while focusing on long-term outcomes. For public sector organizations, IR can complement GRI standards by incorporating aspects of financial accountability alongside sustainability performance, thus appealing to both policymakers and the general public. However, the IR framework has faced criticism for subordinating sustainability to financial concerns, potentially diluting its effectiveness as a tool for promoting environmental and social sustainability. Nonetheless, studies show that adopting IR in the public sector has led to improvements in report comprehensiveness and stakeholder engagement, as seen in state-owned enterprises that have pioneered the use of IR to enhance their sustainability disclosures
Despite the challenges, GRI reporting provides several benefits for public agencies aiming to increase their accountability and transparency. The GRI framework requires organizations to disclose information about a wide range of topics, from environmental impact and resource use to social equity and governance practices. This comprehensive disclosure allows stakeholders, including citizens, government bodies, and NGOs, to assess an agency's impact on sustainability and hold it accountable. By reporting on these issues, public organizations can identify areas where they may need to improve, aligning their operations with societal expectations for responsible governance. Furthermore, GRI-aligned reporting can help public entities track their progress over time, providing a basis for continuous improvement in sustainability practices.(Montecalvo et al., 2018)

Examples of GRI Reporting in the Public Sector
Several studies highlight the varied experiences of public agencies in implementing GRI guidelines. For instance, Australian public sector organizations have been recognized for pioneering sustainability reporting practices, despite challenges related to report consistency and the comprehensive adoption of GRI standards. In one study of Australian agencies, researchers found that while most organizations referenced GRI guidelines, the level of adherence varied significantly, with some entities reporting selectively on GRI indicators. This variation underscores the need for more consistent guidelines and possibly more stringent requirements to ensure that public sector sustainability reporting meets the same standards as corporate reports.(Juthrie&Farneti,2008)

Another example is New Zealand Post, a state-owned enterprise that adopted the IR framework to enhance its sustainability disclosures. By integrating financial and non- financial performance data, New Zealand Post was able to present a more balanced view of its organizational impact, demonstrating progress in areas like energy efficiency and community involvement. This case exemplifies how public agencies can leverage both GRI and IR frameworks to meet the evolving expectations of stakeholders while enhancing their sustainability practices. (Dumay et al,2010)
The adoption of GRI guidelines in the public sector marks a significant step towards more transparent and accountable governance. However, for GRI reporting to achieve its full potential, public organizations must address existing challenges, such as inconsistent adherence, limited external assurance, and an overemphasis on internal managerial goals. Future research and policy development should focus on enhancing the applicability of GRI standards to public sector needs, possibly by incorporating more robust requirements for ecological and social justice considerations.

Additionally, the integration of GRI with frameworks like IR could further strengthen sustainability reporting by providing a more holistic view of public organizations' contributions to sustainable development. Ultimately, public sector entities are uniquely positioned to model sustainable practices for other sectors, and by fully embracing comprehensive sustainability reporting, they can lead the way toward a more resilient and equitable future.(Bellini et al. , 2019)

1.3. TCFD and Public Accounting (O'Dwyer &Unerman,2015 /Carney, 2020/Demers et al., 2024/ Soyombo et al., 2024)
The TCFD, established by the Financial Stability Board (FSB) in 2015 and chaired by Michael Bloomberg, seeks to enhance transparency regarding climate-related financial risks. This framework responds to the increasing need for investors, insurers, and regulators to access consistent, comparable, and reliable information on how climate change impacts businesses and public accounting.
Here is a detailed, accounting-focused examination of TCFD's influence:

- **Accounting for Climate-related Risks and Liabilities**
  CFD requires companies to disclose financial risks from climate change, impacting traditional accounting treatments of assets and liabilities:
  Asset Impairment: Physical and transition risks from climate change, such as extreme weather or regulatory changes, can decrease the value of physical assets. Accounting standards (e.g., IAS 36 on impairment) mandate impairment reviews for assets. TCFD disclosures can prompt companies to re-evaluate asset valuations by considering climate scenarios that predict physical risks (e.g., flooding, droughts). This may result in asset write-downs or accelerated depreciation schedules.
  Liabilities for Transition Costs: Transition risks, such as compliance with stricter environmental regulations or the costs of shifting to renewable energy sources, may create or increase liabilities. Under IFRS or GAAP, companies may need to account for these as contingent liabilities if regulations impose future costs. TCFD's focus on transition risks aids accountants in identifying, estimating, and disclosing potential liabilities linked to regulatory or technological shifts

- **Scenario Analysis in Financial Planning and Forecasting**
  Scenario analysis, a core component of TCFD, has implications for financial planning and projections, which are vital to accounting:
  Financial Impact Forecasting: Scenario analysis under TCFD includes projecting how climate scenarios (e.g., a 2°C or 4°C global temperature increase) impact revenue, costs, and asset values. Accountants use these projections to adjust financial forecasts and recognize the potential future impact on cash flows, debt covenants, and solvency.
  Incorporation into Financial Models: For example, if a company operates in a carbon- intensive sector, TCFD-compliant scenario analysis would require projecting how carbon taxes or market demand shifts impact its long-term profitability. Accountants incorporate these findings into discounted cash flow (DCF) models and fair value calculations for assets.

- **Risk Management and Internal Controls in Accounting**
  TCFD encourages companies to establish climate-focused risk management frameworks that can also enhance internal accounting controls:
  Internal Audits of Climate Risks: Accountants may conduct internal audits focusing on climate risk identification, assessment, and response, as TCFD requires transparent reporting on climate risks integrated into the overall risk management framework.
  Integration with Financial Controls: TCFD promotes embedding climate considerations into financial controls. For instance, a company might implement controls to monitor compliance with climate-related financial disclosures and adjust operational budgets in response to climate risk changes

- **Financial Statement Disclosures and Materiality Considerations**
  TCFD affects the scope and approach of disclosures in financial statements, particularly under IFRS and GAAP standards that require materiality assessments:
  Materiality of Climate Risks: TCFD requires companies to disclose climate risks if they are material. In accounting, materiality determines whether an item must be disclosed in financial statements. The TCFD framework helps accountants decide which climate-related financial risks and opportunities should be included as material disclosures, ensuring investors are informed of risks impacting long-term performance

  Detailed Disclosure of Assumptions: TCFD emphasizes transparent disclosures regarding assumptions used in climate-related financial forecasts (e.g., carbon pricing or energy costs). Accountants play a key role in documenting these assumptions, making disclosures reliable and understandable for investors.

- **Revenue Recognition and Cost Management Adjustments**
  Climate-related risks can alter revenue streams and operating costs, areas directly managed through accounting processes:
  Revenue Projections and Segment Reporting: TCFD disclosures may reveal that certain revenue streams are at risk due to climate impacts (e.g., reduced demand for high-emission products). This leads to adjustments in revenue recognition for affected segments. Accountants might use TCFD scenario analysis results to adjust revenue projections and align segment reporting with climate-related business risks
  Cost Allocation for Climate-related Investments: As companies invest in low-carbon technologies or infrastructure to mitigate climate risks, these expenses require careful accounting treatment. Capitalization versus expense decisions will reflect the expected long- term benefits of these investments, informed by TCFD's guidance on the financial impacts of transitioning to a sustainable business model

- **Alignment with International Accounting Standards and Emerging Regulatory Requirements**
  The TCFD framework aligns well with evolving accounting standards and regulations aimed at improving climate-risk transparency:
  IFRS and GAAP Compatibility: The TCFD's emphasis on disclosure and materiality aligns with IFRS and GAAP principles, which require reporting of material risks impacting financial performance. Emerging standards like the IFRS S2 Climate-related Disclosures standard (based on TCFD) provide additional structure for aligning financial disclosures with climate risk assessments.
  Preparation for Mandatory Disclosure Compliance: As regulatory bodies increasingly adopt TCFD-based requirements (e.g., the SEC's proposed climate disclosure rules), accountants are essential in preparing disclosures that meet these new requirements. They ensure that TCFD-aligned disclosures are audit-ready and compliant with international accounting standards, reinforcing the robustness of financial reporting in the context of climate risks. The TCFD framework brings climate-related risks into the domain of corporate accounting by reshaping how companies account for asset impairment, recognize revenue, allocate costs, and disclose material risks. Accounting professionals play a critical role in adapting traditional practices to integrate climate considerations, using scenario analysis, managing climate-related liabilities, and enhancing transparency. TCFD's alignment with IFRS and GAAP and the emerging regulatory mandates solidify its role as a critical tool in modern accounting practices, aimed at making corporate financial statements a more comprehensive reflection of climate-related risks and opportunities.

2. KALAMATA CLIMATE'S ACTIONS and SUSTAINABLE URBAN TRANSFORMATION PLAN

Kalamata has embarked on an ambitious journey to achieve climate neutrality by 2030, aligning with the EU's Mission for 100 Climate-Neutral and Smart Cities. This effort builds on the strategic framework outlined in three key documents: the Climate Contract («Κλιματικό Συμβόλαιο Καλαμάτας»,Kalamata Municipality,2023), the Sustainable Energy and Climate Action Plan («Σχέδιο δράσης για την Αειφόρο Ενέργεια και το Κλίμα του δήμου Καλαμάτας»,Covenant of mayors for Climate and Energy Municipality of Kalamata, 2021), and the Sustainable Urban Mobility Plan («Σχέδιο βιώσιμης αστικής κινητικότητας Δήμου Καλαμάτας», 2021). Together, these documents lay out Kalamata's pathway to reducing carbon emissions, promoting sustainable energy, enhancing urban mobility, and fostering community engagement.

2.1. Vision: Climate Neutrality by 2030

At the core of Kalamata's Climate Contract lies a commitment to environmental resilience, an ambition sparked by a history of natural disasters and the need to reduce energy costs. The city aims to cut its emissions by 94% across buildings, transportation, waste, and industrial processes. Significant progress is targeted, particularly in the building sector, with a goal of reducing emissions by 97%, and in transportation, where a 99% reduction is envisioned. The Climate Contract integrates multiple strategies focusing on behavioral change, eliminating fossil fuels, and driving digital transformation to make Kalamata a model of urban sustainability.

2.2. Energy and Infrastructure Upgrades (ΣΔΑΕΚ)

The Sustainable Energy and Climate Action Plan (ΣΔΑΕΚ) identifies Kalamata's primary sectors for emissions reduction and energy efficiency. Among these is an emphasis on energy-efficient buildings, with plans to upgrade residential, commercial, and municipal buildings to improve insulation, lower energy consumption, and integrate renewable energy. Renewable energy generation projects play a key role in the city's plan, harnessing Kalamata's abundant solar and geothermal resources, and include solar farms and bio-waste recycling initiatives. Bio-waste from local agricultural practices, like olive oil production, will contribute to biogas and hydrogen production, further supporting Kalamata's transition to cleaner energy sources. In addition, there is a concerted effort to encourage residents to embrace energy-saving practices and participate in initiatives within the Municipal Energy Community. Together, these actions not only aim to reduce emissions and household energy costs but also create local green jobs and foster a citywide culture of sustainability.

2.3. Sustainable Mobility and Urban Accessibility (ΣΒΑΚ)
Kalamata's Sustainable Urban Mobility Plan (ΣΒΑΚ) provides a 20-year vision for creating a pedestrian-friendly, accessible city. This vision includes enhancing walkability and expanding cycling infrastructure, particularly within the city center and along major roads. Public transportation improvements are integral to the plan, with initiatives such as upgrading the bus fleet to electric or low-emission vehicles, expanding coverage, and implementing real-time routing systems to increase reliability and reduce car dependency. Traffic management and parking policies, including controlled parking zones and reduced speed limits in select areas, further contribute to Kalamata's goal of a greener urban landscape. The promotion of electric vehicles (EVs) forms another pillar, with plans to install EV charging stations citywide and introduce incentives to encourage adoption. Collectively, these initiatives aim to reduce air pollution, promote low-carbon travel, and make Kalamata more accessible and attractive for residents and visitors, supporting local business and tourism.

2.4. Circular Economy and Waste Management
Kalamata's circular economy initiatives span waste reduction, recycling, and sustainable resource management. Organic waste management is a high priority, with the establishment of local composting facilities and programs for home and neighborhood composting. Expanded recycling efforts include neighborhood recycling stations and community awareness campaigns. Waste from agricultural production, particularly olive pulp, will be repurposed to produce bioenergy, contributing to Kalamata's renewable energy goals. These initiatives reflect Kalamata's commitment to reducing landfill dependency, promoting sustainable agricultural practices, and fostering a sense of community responsibility in waste management.

2.5. Strategic Objectives and Pathways for Transformation
The transformation envisioned in Kalamata is structured into four primary scenarios, each focused on creating a livable, sustainable, and economically vibrant city.
- Kalamata, a City for Living: This scenario envisions revitalizing urban spaces, improving public facilities, and supporting cultural assets to make the city an attractive place for residents and visitors.
-Kalamata, a City of Low-Emission Mobility: Building eco-friendly transport infrastructure, promoting cycling and pedestrian mobility, and advancing public transit systems to minimize vehicular emissions.
- Kalamata, a City for Production and Innovation: This pathway promotes local industries, particularly in agriculture and tourism, with a focus on energy-efficient practices and low- carbon product standards.
- Kalamata, a Learning City: Emphasizing education and community engagement, this scenario promotes awareness and participation in sustainability initiatives.

2.6. Stakeholder Engagement and Community Involvement
Public involvement is central to Kalamata's climate strategy. Through extensive consultations, residents, businesses, local institutions, and universities have co-created a roadmap that fosters local support while integrating community values and needs. This collaborative approach allows stakeholders to contribute to shaping initiatives that address the unique challenges of Kalamata's urban and rural landscapes.

2.7. Partnerships and Funding
Kalamata actively collaborates with national and international networks, including ClimaNet, Net Zero Cities, and CIVITAS, to share best practices and secure essential funding. Through these partnerships, the city can access technical expertise and financial resources, ensuring successful implementation of its projects. The total estimated budget for Kalamata's sustainability initiatives is over €2 billion, funded through a combination of public funds, private investments, and EU grants. Investments cover infrastructure, technological advancements, renewable energy projects, and community-based programs.

2.8. Anticipated Outcomes and Long-Term Impact
Kalamata's comprehensive sustainability plan promises to transform the city's economic, social, and environmental landscape by 2030. The city expects significant reductions in CO2 emissions, with any remaining emissions mitigated through reforestation and the expansion of green spaces. Enhanced air quality, reduced noise pollution, and increased green areas will improve public health and residents' quality of life. The green transformation is also anticipated to stimulate Kalamata's economy, generating new jobs and growth opportunities in renewable energy, sustainable tourism, and green infrastructure. Furthermore, the city's emphasis on education and community engagement will help cultivate environmental responsibility across generations, ensuring lasting change.

3. PILOT QUESTIONNAIRE
A questionnaire was drafted based on the Kalamata Climate Contract, initially distributed to students of the University of the Peloponnese. Specifically, the following link (https://forms.gle/yGAEqAdnCPus8isC7) was opened for the following departments of the University located in the municipality of Kalamata:
- Department of Accounting and Finance
- Department of Business and Organization Management

- Department of Philology
- Department of History and Archaeology
- Department of Agronomy
- Department of Dietetics and Nutrition
- Department of Speech Therapy

The questionnaire was composed in three successive versions, with the final version distributed to students to assess the average completion time, receive suggestions from students, and primarily to gather initial statistical insights regarding students' attitudes towards the proposals that the municipality of Kalamata has designed and budgeted. A total of 71 students responded. The main purpose of the pilot questionnaire was to make necessary adjustments so that the final questionnaire could be distributed to as many residents of the Municipality of Kalamata as possible.

3.1 Questionnaire, Main Content.
As stated before the Kalamata Climate Contract is ultimately based on four pillars.

- **Kalamata, a City to Live In**
  1. L.1 Revitalization of Urban Areas
  2. L.2 Aesthetic and Functional Enhancement of Public Spaces
  3. L.3 Kalamata, a Clean City
  4. L.4 Climate-Neutral Housing
  5. L.5 Sports and Education

- **Kalamata, a City for Low-Emission Mobility**
  1. M.1 Sustainable Urban Mobility Infrastructure
  2. M.2 Promotion of Eco-Friendly Transport
  3. M.3 Freight Transportation
  4. M.4 Promotion of Low-Emission Vehicles

- **Kalamata, a City for Production and Creativity**
  1. P.1 Emission Reduction Actions in the Agricultural Sector
  2. P.2 Transformation of Manufacturing and Craft Units
  3. P.3 Energy Upgrades of Buildings and Facilities in the Tertiary Sector
  4. P.4 Energy Production and Distribution

- **Kalamata, a Learning City**
  1. R.1 Pilot and Research Actions
  2. R.2 Research and Innovation Structures
  3. R.3 Public Awareness and Sensitization

Questions **1-9** are demographic in nature, designed to gather essential background information about the respondent. They inquire about the respondent's age, gender, and highest level of education, as well as household size and location of permanent residence, offering insight into the respondent's basic personal and geographical context. Additional questions cover family status and annual household income, which help to understand the respondent's socioeconomic background. The survey also asks if the respondent is a student, and if so, requests details about their department and year of study. Together, these questions provide a well-rounded demographic profile, facilitating more nuanced analysis of responses based on personal, educational, and socioeconomic factors.

Questions 10-40 regard each of the above pillars.

For pillar 1, Kalamata a city to live in, we created statements that inquire about the significance of unifying existing renovations in squares, pedestrian areas, and green spaces to create a cohesive urban space for recreation and greenery. Additionally, they explore the importance of reducing energy costs by upgrading municipal lighting, creating pedestrian

zones on major roads, and using digital tools—such as smart networks and pollutant monitoring systems—to manage the city's climate response. The questions also gauge the respondent's views on incorporating geothermal energy in public buildings to enhance energy independence, promoting cleanliness and waste removal in the urban center, and continuously improving the urban space to support sustainability. Other areas of interest include the creation of a municipal energy community to encourage local renewable energy production, developing new green spaces and parks, and adopting bioclimatic materials in public buildings to improve energy efficiency and thermal comfort. Collectively, these questions aim to understand public opinion on measures that support environmental responsibility, energy efficiency, and the enhancement of urban livability in Kalamata.

For pillar 2, Kalamata, a City for Low-emission Mobility, the questions focused on gauging the respondent's views on sustainable urban mobility initiatives aimed at reducing carbon emissions and improving the quality of life in the city. They ask about the importance of implementing a Sustainable Urban Development strategy that emphasizes car-free mobility, suggesting a shift towards environmentally friendly transportation options. Additionally, they explore the perceived value of developing cycling and pedestrian paths as a means to lower the city's carbon footprint, highlighting the role of active transportation in reducing CO_2 emissions. The questions also assess the significance of a strategic mobility plan designed to enhance traffic flow and accessibility within the city. This plan includes measures such as establishing pedestrian zones, creating bike paths, improving public transportation, and promoting sustainable modes of urban mobility. Together, these questions aim to understand public opinion on various aspects of sustainable transport planning and their potential impact on urban environmental quality and accessibility.

Regarding pillar 3, (production and creativity) the questions created seek to understand the respondent's views on sustainable practices that could benefit the local economy and environment. They inquire about the importance of using local olive oil waste to produce fertilizer, supporting a circular economy approach. Additionally, they assess the perceived value of initiatives aimed at enhancing the city's tourism potential through sustainable practices, such as ecotourism, renewable energy in accommodations, and eco-friendly waste management. Finally, they ask about the importance of incorporating climate considerations into local economic development through green entrepreneurship, renewable energy adoption, and improved energy efficiency for businesses.

As far as pillar 4 is concerned, questions aim to assess the respondent's views on various social and educational factors that support climate action and environmental sustainability. They explore the perceived importance of educational programs to increase climate awareness among residents, legislative changes to promote sustainable urban development, and citizen group involvement in climate initiatives. Additionally, they address the significance of climate action's impact on public health and the role of cultural and community centers in fostering environmentally protective habits among citizens. Together, these questions highlight the importance of community engagement, education, and policy in achieving sustainable goals.

FULL QUESTIONNAIRE IS STATED IN APPENDIX (CHAPTER 7)

4. FIRST CATEGORIZATION, PCA ANALYSIS AND REGRESSION

The specific pillars led to forty questions that except the first 9 that are referred to demographic data were categorized and matched to each of the abovementioned pillars:
- PORTFOLIO 1.QUESTIONS 11,12,13,14,15,16,17,18,25,26,27,28
- PORTFOLIO 2. QUESTIONS 19, 20, 24
- PORTFOLIO 3. QUESTIONS 22, 29
- PORTFOLIO 4.QUESTIONS 21,23,30,31,32,33,34,35,36,37,38,39,40
- Question 10 will be excluded

We set f(x)= external funding(question 38) as the dependent variable .The independent variables were 6:
1) Question 10 itself and
2) The 6 sub-groups extracted from the PCA factor analysis to the 4 categories of questions.

In essence, we want to examine whether the attitude of the respondents towards the changes that will occur in the urban area of Kalamata, will affect the attitude of external investors for further financing in green infrastructure.

Then, a **Factor Analysis** was conducted, resulting in the following groups in SPSS.

4.1. Kalamata, a city to live in

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	6,145	51,211	51,211	6,145	51,211	51,211	4,110	34,254	34,254
2	1,141	9,507	60,718	1,141	9,507	60,718	3,176	26,464	60,718
3	,829	6,905	67,623						
4	,725	6,041	73,664						
5	,619	5,161	78,824						
6	,560	4,663	83,487						
7	,477	3,975	87,462						
8	,399	3,329	90,790						
9	,382	3,179	93,969						
10	,292	2,434	96,403						
11	,233	1,942	98,345						
12	,199	1,655	100,000						

Extraction Method: Principal Component Analysis.

Picture 1: Eigenvalues table,PCA analysis

Questions that have been included in each group, have been selected after comparison of the values in the rotated component matrix. The highest value between the two component groups leads to the assignment of the specific question to the specific group.

Rotated Component Matrix[a]

	Component 1	Component 2
28. Βαθμολογήστε τη σημασία της υιοθέτησης βιοκλιματικών υλικών (υλικά που βελτιώνουν την ενεργειακή απόδοση και τη θερμική άνεση των κτιρίων, όπως φυσικά μονωτικά και υλικά που προάγουν το φυσικό δροσισμό) στις δημόσιες κτιριακές κατασκευές	,763	,226
26. Πόσο σημαντικός είναι ο εκσυγχρονισμός των εγκαταστάσεων επεξεργασίας λυμάτων για την προστασία του περιβάλλοντος;	,760	,058
15. Πόσο σημαντική θεωρείτε την ενσωμάτωση της χρήσης γεωθερμικής ενέργειας(δηλαδή τη φυσική θερμική ενέργεια της Γης που διαρρέει από το θερμό εσωτερικό του πλανήτη προς την επιφάνεια) στα δημόσια κτίρια για την ενεργειακή ανεξαρτησία της πόλης;	,736	,242
18. Πόσο σημαντική θεωρείτε τη δημιουργία μιας δημοτικής ενεργειακής κοινότητας στην Καλαμάτα για την ενίσχυση της τοπικής παραγωγής και διαχείρισης ενέργειας από ανανεώσιμες πηγές;	,695	,521
27. Πόσο σημαντική είναι η ανάπτυξη νέων χώρων πρασίνου και πάρκων εντός της πόλης;	,691	,341
25. Θεωρείτε σημαντική τη χρήση των τοπικών αποβλήτων ελαιόλαδου για την παραγωγή λιπασμάτων;	,678	,253
17. Πόσο σημαντική θεωρείτε τη συνεχιζόμενη αναβάθμιση του αστικού χώρου για τη βιωσιμότητα της πόλης;	,637	,493
11. Πόσο σημαντική θεωρείτε την ενοποίηση των υφιστάμενων αναπλάσεων των πλατειών, πεζοδρομήσεων και πράσινων χώρων στο ιστορικό κέντρο της Καλαμάτας για τη δημιουργία μιας ενιαίας αστικής οντότητας αναψυχής και πρασίνου;	,195	,804
13. Πόσο σημαντική θεωρείτε τη δημιουργία ζωνών πεζών σε κύριες οδικές αρτηρίες;	,109	,770
14. Πόσο σημαντικό θεωρείτε το ρόλο των ψηφιακών εργαλείων (όπως έξυπνα δίκτυα, συστήματα παρακολούθησης εκπομπών ρύπων) στη διαχείριση της κλιματικής αντιμετώπισης της πόλης;	,451	,680
12. Πόσο σημαντικό θεωρείτε ότι είναι να μειωθεί το ενεργειακό κόστος μέσω της αναβάθμισης του δημοτικού φωτισμού;	,535	,596
16. Πόσο σημαντική είναι για εσάς η προώθηση δράσεων καθαριότητας και απομάκρυνσης απορριμμάτων στο αστικό κέντρο;	,204	,557

Picture 2: Rotated component matrix

Component 1 (which consists of questions 15,17,18.25.26.27.28) can be named GREEN AND ENERGY EFFICIENT SQUARE. Component 2 (which consists of questions 11,12,13,14,16) can be named GREEN AND SMART INFRASTRUCTURE.

4.2. Kalamata, a City for Low-Emission Mobility

Total Variance Explained

Component	Initial Eigenvalues: Total	% of Variance	Cumulative %	Extraction Sums of Squared Loadings: Total	% of Variance	Cumulative %
1	2,267	75,551	75,551	2,267	75,551	75,551
2	,438	14,598	90,150			
3	,296	9,850	100,000			

Extraction Method: Principal Component Analysis.

Picture 3: Eigenvalues table, PCA analysis

One group emerges.

Component Matrix[a]

	Component
	1
19. Πόσο σημαντική θεωρείτε τη στρατηγική για τη Βιώσιμη Αστική Ανάπτυξη με έμφαση στην κινητικότητα χωρίς αυτοκίνητο;	,888
20. Αξιολογήστε τη σημασία της στρατηγικής ανάπτυξης ποδηλατικών και πεζοπορικών διαδρομών για τη μείωση του ανθρακικού αποτυπώματος (ποσότητα CO2 που εκπέμπεται στην ατμόσφαιρα) της πόλης.	,884
24. Βαθμολογήστε τη σημασία του στρατηγικού σχεδίου κινητικότητας για τη βελτίωση της συνολικής κυκλοφορίας και προσβασιμότητας της πόλης. Το στρατηγικό σχέδιο κινητικότητας προβλέπει τη δημιουργία ζωνών πεζών, ποδηλατοδρόμων, βελτιώσεις στη δημόσια συγκοινωνία και ενίσχυση της αστικής κινητικότητας μέσω βιώσιμων μεταφορικών μέσων.	,835

Extraction Method: Principal Component Analysis.

a. 1 components extracted.

Rotated Component Matrix[a]

a. Only one component was extracted. The solution cannot be rotated.

Picture 4: Rotated component matrix

4.3. Kalamata, a City for Production and Creativity

Total Variance Explained

	Initial Eigenvalues			Extraction Sums of Squared Loadings		
Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	1,441	72,067	72,067	1,441	72,067	72,067
2	,559	27,933	100,000			

Picture 5: Eigenvalues table,PCA analysis

One group emerges.

Component Matrix[a]

	Component
	1
29. Πόσο κρίσιμες θεωρείτε τις πρωτοβουλίες για την ενίσχυση του τουριστικού δυναμικού της πόλης μέσω βιώσιμων πρακτικών (όπως η προώθηση του οικοτουρισμού, η χρήση ανανεώσιμων πηγών ενέργειας στα τουριστικά καταλύματα, και η εφαρμογή περιβαλλοντικά φιλικών μεθόδων διαχείρισης αποβλήτων);	,849
22. Πόσο σημαντική θεωρείτε τη συμβολή του ιδιωτικού τομέα στη χρηματοδότηση ενεργειακών και περιβαλλοντικών έργων;	,849

Extraction Method: Principal Component Analysis.

a. 1 components extracted.

Rotated Component Matrix[a]

a. Only one component was extracted. The solution cannot be rotated.

Picture 6: Rotated component matrix

4.4. Kalamata, a Learning City

Two groups submerge after taking the Eigenvalues into consideration.

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	6,942	53,403	53,403	6,942	53,403	53,403	4,138	31,831	31,831
2	1,072	8,243	61,646	1,072	8,243	61,646	3,876	29,815	61,646
3	,957	7,361	69,007						
4	,746	5,737	74,744						
5	,700	5,384	80,128						
6	,515	3,965	84,093						
7	,461	3,547	87,640						
8	,422	3,247	90,887						
9	,362	2,788	93,675						
10	,315	2,427	96,102						
11	,193	1,488	97,590						
12	,174	1,338	98,929						
13	,139	1,071	100,000						

Extraction Method: Principal Component Analysis.

Picture 7: Eigenvalues table,PCA analysis

Questions that have been included in each group, have been selected after comparison of the values in the rotated component matrix. The highest value between the two component groups leads to the assignment of the specific question to the specific group.

Rotated Component Matrix[a]

	Component 1	Component 2
33. Πόσο σημαντικές θεωρείτε τις ενημερώσεις και αλλαγές στις νομοθετικές ρυθμίσεις για την υποστήριξη της βιώσιμης αστικής ανάπτυξης;	,838	,221
39. Πόσο σημαντική είναι η ενίσχυση των χώρων πρασίνου για τη βελτίωση της ποιότητας του αστικού αέρα;	,836	,263
34. Πόσο σημαντική είναι η συμμετοχή ομάδων πολιτών στη διαδικασία δράσης για το κλίμα;	,726	,325
38. Αξιολογήστε τη σημασία της εξασφάλισης εξωτερικής χρηματοδότησης για πρωτοβουλίες μεγάλης κλίμακας για το κλίμα.	,695	,334
37. Πόσο κρίσιμη θεωρείτε την ανάγκη για ενισχυμένες εγκαταστάσεις ανακύκλωσης και συστήματα διαχείρισης αποβλήτων;	,605	,263
35. Πόσο σημαντικός είναι ο αντίκτυπος των πρωτοβουλιών δράσης για το κλίμα στη δημόσια υγεία των κατοίκων;	,571	,461
36. Βαθμολογήστε τη σημαντικότητα των δράσεων που αναλήφθηκαν για την ενσωμάτωση των κλιματικών θεμάτων στην τοπική οικονομική ανάπτυξη (όπως η προώθηση πράσινης επιχειρηματικότητας, η ενίσχυση της χρήσης ανανεώσιμων πηγών ενέργειας, και η βελτίωση της ενεργειακής απόδοσης [illegible]	,137	,840
23. Πόσο σημαντικός είναι ο ρόλος των εκπαιδευτικών προγραμμάτων στην ευαισθητοποίηση των κατοίκων σχετικά με την κλιματική αλλαγή;	,261	,811
32. Πόσο σημαντική είναι η επένδυση σε λύσεις έξυπνης πόλης (όπως έξυπνα δίκτυα ηλεκτρικής ενέργειας, συστήματα διαχείρισης κυκλοφορίας και έξυπνος φωτισμός) για την αποτελεσματικότερη διαχείριση της ενέργειας και των υποδομών;	,407	,687
40. Πόσο σημαντικός είναι ο ρόλος των πολιτιστικών και κοινοτικών κέντρων στην προώθηση συνηθειών πολιτών για την προστασίας του περιβάλλοντος;	,365	,680
30. Πόσο σημαντικός είναι ο ρόλος της διεθνούς συνεργασίας και της μάθησης από άλλες πόλεις για την ενίσχυση των τοπικών δράσεων για το κλίμα;	,464	,645
31. Βαθμολογήστε τη σημασία της εφαρμογής τεχνολογιών εξοικονόμησης νερού σε ολόκληρη την πόλη.	,424	,533
21. Πόσο σημαντική είναι η συμμετοχή των τοπικών και περιφερειακών δυνάμεων (περιφέρεια Πελοποννήσου και συνεργασία με όμορους δήμους) στη στρατηγική της πόλης για το κλίμα;	,505	,511

Picture 8: Rotated component matrix

Component 1 (which consists of questions 33,34,35,37,38,39) can be named LEGISLATIVE AND CITIZEN INITIATIVES FOR A GREEN KALAMATA. Component 2 (which
consists of questions 21,23,30,31,32,36,40) can be named EDUCATION AND KNOWLEDGE DISSEMINATION LOCALLY/ INTERNATIONALLY.

4.5. Regression

We define f(x)) as external funding (Question 38) and consider as independent variables Question 10 and the five sub-groups derived from the PCA factor analysis. Essentially, we aim to examine the extent to which respondents' attitudes toward changes in the urban fabric of Kalamata influence external investors' stance on further funding for green infrastructure.

Since the explanatory power is close to 60% (R square and Adjusted R square), we have made the correct choice in both the selection of groups and the model.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	,778[a]	,605	,568	,672

a. Predictors: (Constant), REGR factor score 6 for analysis 1, REGR factor score 5 for analysis 1, REGR factor score 4 for analysis 1, REGR factor score 3 for analysis 1, REGR factor score 2 for analysis 1, REGR factor score 1 for analysis 1

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	44,356	6	7,393	16,349	<,001[b]
	Residual	28,940	64	,452		
	Total	73,296	70			

a. Dependent Variable: 38. Assess the importance of securing external financing for large-scale climate initiatives.

b. Predictors: (Constant), REGR factor score 6 for analysis 1, REGR factor score 5 for analysis 1, REGR factor score 4 for analysis 1, REGR factor score 3 for analysis 1, REGR factor score 2 for analysis 1, REGR factor score 1 for analysis 1

Picture 9: Linear Regression, General Results

More analytically:

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	3,845	,080		48,181	<,001
	REGR factor score 1 for analysis 1	,352	,080	,344	4,373	<,001
	REGR factor score 2 for analysis 1	,620	,080	,606	7,710	<,001
	REGR factor score 3 for analysis 1	,169	,080	,166	2,108	,039
	REGR factor score 4 for analysis 1	,212	,080	,208	2,643	,010
	REGR factor score 5 for analysis 1	,187	,080	,183	2,329	,023
	REGR factor score 6 for analysis 1	,131	,080	,128	1,636	,107

a. Dependent Variable: 38. Assess the importance of securing external financing for large-scale climate initiatives.

Picture 10: Linear Regression, Coefficient Results

The regression model estimate is:
External funding=3.845 + (0.352*Green & efficient Square) + (0.62*Green& smart infrastructure) + (0.169*Low emissions)+(0.212*City to produce) +(0.187 *Legislative & Citizen Initiatives)+ (0.131*Education & Knowledge dissemination)

Green and energy efficient square: B = 0.352, p < 0.001, indicating that it is statistically significant. Each one-unit increase in this factor's score raises the estimated importance of external financing by 0.352 units.

Green and smart infrastructure: B = 0.620, p < 0.001, also statistically significant, with the highest coefficient value among all factors. This indicates that this factor has the strongest impact on the importance of external financing.

Kalamata, a City for Low-Emission Mobility: B = 0.169, p = 0.039, is statistically significant but with a lower impact.

Kalamata, a City for Production and Creativity: B = 0.212, p = 0.010, also statistically significant with a moderate impact.

Legislative and citizen initiatives for a green Kalamata: B = 0.187, p = 0.003, statistically significant and shows a positive association.

Education and Knowledge Dissemination locally and internationally: B = 0.131, p = 0.107, not statistically significant, meaning that its impact on the importance of external financing is not strong enough to be considered sign.

5. SECOND CATEGORIZATION AND SECOND PROPOSED ANALYSIS.

Wanting to categorize the questions so that the number of questions in each group does not vary significantly compared to the previous analysis, we reclassified the questions. Additionally, to increase relevance within each group, we removed certain questions.

The new categorization excludes questions 30 (regarding international cooperation in expertise), as well as question 38 and 22, which concern external funding.
Question 10 was also excluded as it was considered quite general. (general attitude of the students towards Kalamata's climate contract).
Question 22 is our new dependent variable:The involvement of local and regional entities (such as the Peloponnese Region and cooperation with neighboring municipalities) in the city's climate strategy

The re-categorization follows:
-GENERAL PORTFOLIO 1: Kalamata, a City to Live In | Questions: 11, 12, 13, 15, 16, 17, 18, 26, 27, 28
-GENERAL PORTFOLIO 2: Kalamata, Low-Emission Mobility | Questions: 14, 19, 20, 24, 32
-GENERAL PORTFOLIO 3: Kalamata, a City for Production and Creation | Questions: 25, 29, 31, 36, 37
-GENERAL PORTFOLIO 4: Kalamata, a Learning City | Questions: 23, 33, 34, 35, 40, 39

Before presenting the statistical analysis, we need to clarify certain terms.(University of Athens, 2021)

- Factor analysis (FA) allows us to simplify a set of complex variables or items, using statistical procedures, in order to explore the underlying dimension that explain the relationships between the multiple variables.
- Principal Component Analysis(PCA), is a statistical procedure that allows us to summarize the information content in large data tables by means of smaller set of "summary indices" than can be, more easily, visualized and analyzed.
- Croanbach's alpha is a way of assessing reliability, by comparing the amount of shared variance or covariance, among the items, making up an instrument to the amount of overall variance.

Regarding alpha values range, the following table follows:

Cronbach's alpha	Internal consistency
α>=0,9	Excellent
0,9>α>=0,8	Good
0,8>α>=0,7	Acceptable
0,7>α>=0,6	Questionable
0,6>α>=0,5	Poor
0,5>α	Unacceptable

- Rotated component matrix, is the key output of principal components analysis. It contains estimates of the correlations between each of the variables and the estimated components.
- Eigenvalues, show the number of groups to be created (values under 1 mean that in the specific spot we should stop creating more groups).
- After concluding on how many groups to work, our decision on which question of the group, will be used in each subgroup depends on the values of rotated component matrix.
- The questions that receive the highest value(in comperative terms) in each subgroup, belong to the specific subgroup.
- Kaiser Meyer Olkin test values (KMO values) between 0,8 and 1,indicate that the sampling is adequate.

5.1. Kalamata, a City to Live In

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	5,145	51,452	51,452	5,145	51,452	51,452	3,613	36,134	36,134
2	1,080	10,803	62,256	1,080	10,803	62,256	2,612	26,122	62,256
3	,820	8,202	70,457						
4	,626	6,263	76,720						
5	,565	5,650	82,370						
6	,529	5,292	87,662						
7	,402	4,023	91,685						
8	,374	3,744	95,429						
9	,236	2,357	97,786						
10	,221	2,214	100,000						

Extraction Method: Principal Component Analysis.

2 components

Picture 11: Eigenvalues table.

Rotated Component Matrix[a]

	Component 1	Component 2
28. Rate the importance of adopting bioclimatic materials (materials that improve the energy efficiency and thermal comfort of buildings, such as natural insulation and materials that promote natural cooling) in public building constructions	,801	
15. How important do you consider the integration of the use of geothermal energy (i.e. the natural thermal energy of the Earth that leaks from the warm interior of the planet to the surface) in public buildings for the energy independence of the city?	,773	
26. How important is the modernisation of wastewater treatment plants for environmental protection?	,729	
27. How important is the development of new green spaces and parks within the city?	,724	,319
18. How important do you consider the creation of a municipal energy community in Kalamata to enhance local production and management of energy from renewable sources?	,702	,499
17. How important do you consider the continuous upgrading of urban space for the sustainability of the city?	,661	,492

Rotated Component Matrix[a]

	Component 1	Component 2
11. How important do you consider the unification of the existing renovations of squares, pedestrian streets and green spaces in the historic center of Kalamata for the creation of a single urban entity of recreation and greenery?		,800
13. How important do you consider the creation of pedestrian zones on main roads?		,775
16. How important is it for you to promote cleaning and waste removal actions in the urban center?		,606
12. How important do you think it is to reduce energy costs by upgrading municipal lighting?	,536	,574

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.[a]

a. Rotation converged in 3 iterations.

Picture 11: Eigenvalues table.

2 groups are created, and each of the questions fall under in the above groups

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
,891	,891	10

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		,880
Bartlett's Test of Sphericity	Approx. Chi-Square	329,437
	df	45
	Sig.	<,001

Picture 13: Cronbach's alpha & KMO pictures

Cronbach's alpha and KMO receive excellent values.

Component 1 (which consists of questions 15.,17,18,26,27,28) can be named USE OF NEW MATERIAL TECHNOLOGY. Component 2 (which consists of questions 11,12,13,16 can be named REDEVELOPMENT OF HISTORIC CENTER AND SIDEWALKS.

5.2. Kalamata, low-emission travel

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
,846	,850	5

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		,808
Bartlett's Test of Sphericity	Approx. Chi-Square	147,211
	df	10
	Sig.	<,001

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3,125	62,497	62,497	3,125	62,497	62,497
2	,791	15,821	78,317			
3	,421	8,414	86,731			
4	,370	7,392	94,123			
5	,294	5,877	100,000			

Extraction Method: Principal Component Analysis.

1 component

Component Matrix[a]

	Component 1
20. Assess the importance of the strategic development of cycling and hiking routes to reduce the carbon footprint (amount of CO2 emitted into the atmosphere) of the city.	,818
24. Rate the importance of the strategic mobility plan to improve the overall traffic and accessibility of the city. The Strategic Mobility Plan foresees the creation of pedestrian zones, cycle paths, improvements to public transport and enhancement of urban mobility through sustainable modes of transport.	,813
19. How important do you consider the strategy for Sustainable Urban Development with emphasis on car-free mobility?	,809
32. How important is investing in smart city solutions (such as smart electricity grids, traffic management systems and smart lighting) for more efficient energy and infrastructure management?	,768
14. How important do you consider the role of digital tools (such as smart grids, emission monitoring systems) in managing the city's climate response?	,742

Extraction Method: Principal Component Analysis.
a. 1 components extracted.

Picture 14: Low emission travel PCA

1 group is created.Cronbach's alpha and KMO receive excellent values.

5.3. Kalamata, city to produce and create

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
,868	,871	6

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		,809
Bartlett's Test of Sphericity	Approx. Chi-Square	196,695
	df	15
	Sig.	<,001

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3,653	60,891	60,891	3,653	60,891	60,891
2	,761	12,688	73,579			
3	,562	9,371	82,950			
4	,481	8,013	90,962			
5	,320	5,332	96,294			
6	,222	3,706	100,000			

Extraction Method: Principal Component Analysis.

1 component

Communalities

	Initial	Extraction
23. How important is the role of educational programs in raising awareness of climate change among residents?	1,000	,494
33. How important do you consider updates and changes in legislation to support sustainable urban development?	1,000	,605
34. How important is the involvement of citizens' groups in the climate action process?	1,000	,674
35. How significant is the impact of climate action initiatives on residents' public health?	1,000	,616
39. How important is the enhancement of green spaces to improve urban air quality?	1,000	,708
40. How important is the role of cultural and community centres in promoting citizens' habits for environmental protection?	1,000	,557

Extraction Method: Principal Component Analysis.

Picture 16: Kalamata, city to learn PCA

1 group is created.
Cronbach's alpha and KMO receive acceptable values.

5.5. Linear regression
In our regression we set as independent variables:
Portfolio 1 group (2 SUBGROUPS according to PCA ANALYSIS)
Portfolio 2 group (verified by PCA ANALYSIS)
Portfolio 3 group (verified by PCA ANALYSIS) Portfolio 4 group (verified by PCA ANALYSIS)

We set F(x)=cooperation of local and regional municipalities, a question that has also been asked and has been isolated for research purposes.

This model evaluates how the respondents' attitudes towards innovation influence the cooperation of local and regional entities in advancing the city's climate transformation strategy. By analyzing these attitudes, the model aims to understand the degree to which support for innovative practices can foster collaboration among local and regional forces, such as municipalities and regional authorities, thus impacting the effectiveness and cohesion of the city's climate strategy.

R^2 Value: The explanatory power of this model, represented by the R^2 value, is 63.8%. This indicates that approximately 63.8% of the variation in the cooperation of local and regional entities within the city's climate strategy can be explained by respondents' attitudes towards innovation. This relatively high R^2 value suggests that attitudes towards innovation play a significant role in shaping collaborative efforts for the city's climate goals.

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					Durbin-Watson
					R Square Change	F Change	df1	df2	Sig. F Change	
1	,815[a]	,664	,638	,621	,664	25,678	5	65	<,001	2,514

a. Predictors: (Constant), City_to_learn, City_to_live_2, City_to_live_1, City_to_produce_create, Low_emissions

b. Dependent Variable: 21. How important is the participation of local and regional forces (Peloponnese region and cooperation with neighboring municipalities) in the city's climate strategy?

Picture 17: R squared of the new linear regression

More specifically, the resulting regression is depicted below.

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	49,558	5	9,912	25,678	<,001[b]
	Residual	25,089	65	,386		
	Total	74,648	70			

a. Dependent Variable: 21. How important is the participation of local and regional forces (Peloponnese region and cooperation with neighboring municipalities) in the city's climate strategy?

b. Predictors: (Constant), City_to_learn, City_to_live_2, City_to_live_1, City_to_produce_create, Low_emissions

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95,0% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	3,930	,074		53,295	<,001	3,782	4,077
	City_to_live_1	,551	,149	,533	3,688	<,001	,252	,849
	City_to_live_2	,312	,127	,302	2,457	,017	,058	,566
	Low_emissions	,452	,163	,438	2,770	,007	,126	,778
	City_to_produce_create	-,220	,146	-,213	-1,500	,139	-,512	,073
	City_to_learn	-,033	,146	-,032	-,227	,821	-,325	,258

a. Dependent Variable: 21. How important is the participation of local and regional forces (Peloponnese region and cooperation with neighboring municipalities) in the city's climate strategy?

Picture 18: Linear Regression, Coefficient Results

The estimated regression is:

Co-operation of local and regional forces = 3.93+ 0.551* Use of new material technology+0.312* Redevelopment of historic center and sidewalks+ 0.452*Low emissions
-0.220*City_to_produce +0.033* City_to_learn.

More specifically:

- **Use of new material technology**: B = 0.551, $p < 0.001$. This variable is statistically significant, with a standardized coefficient (Beta) of 0.533, the highest among all predictors. Each unit increase in City_to_live_1 is associated with an increase of 0.551 in the dependent variable, making it a strong predictor of the importance of local and regional forces in the city's climate strategy.
- **Redevelopment of historic center and sidewalks**: B = 0.312, p = 0.017, also statistically significant with a moderate standardized coefficient (Beta = 0.302). This predictor has a positive relationship with the dependent variable, though its effect is weaker than City_to_live_1.
- **Low_emissions**: B = 0.452, p = 0.007, statistically significant with a standardized Beta of 0.438. This suggests that low emissions positively impact the perceived importance of local and regional participation, with a moderately strong effect.
- **City_to_produce_create**: B = -0.220, p = 0.135, not statistically significant ($p > 0.05$). The negative coefficient suggests a potential negative relationship, but this effect is not strong enough to be considered significant.
- **City_to_learn**: B = -0.033, p = 0.821, also not statistically significant, indicating no meaningful impact on the dependent variable.

6. CONCLUSION

In conclusion, this paper has provided a comprehensive examination of the NetZeroCities European program, emphasizing the commitment of 100 European cities to reach climate neutrality by 2030. Additionally, it has highlighted the ISSA 5000 standard and its implications for advancing sustainability practices within the public sector. The study also reviewed board decisions aligned with the Global Reporting Initiative (GRI) and the Task Force on Climate-related Financial Disclosures (TCFD), assessing these standards' suitability for integration within public sector accounting and reporting to enhance sustainability and transparency for municipal and government entities engaged in the NetZeroCities initiative.

A particular focus of the research centered on Kalamata's implementation program. As part of this, a pilot questionnaire was administered to students at the University of Peloponnese in Kalamata to gain insights into their perspectives on climate-related issues. Statistical analysis, including descriptive and regression methods, was employed, revealing critical findings on climate attitudes and awareness.

At the time of this study, documented decisions had been made for three Greek cities— Athens, Kalamata, and Trikala. Future research will expand upon this foundational analysis of Kalamata's climate contract to comprehensively examine every decision associated with the six Greek cities involved in the NetZeroCities initiative. This ongoing research will contribute valuable insights for the 2026 paper selection process, further supporting the ambitious climate neutrality goals set forth by this initiative.

7. APPENDIX

Questionnaire for Evaluating the Actions of the Municipality of Kalamata

University of the Peloponnese - Department of Accounting and Finance

This questionnaire is one of the research tools for my dissertation titled: "Accounting Changes Resulting from the Study of 100 Sustainable Cities: European Initiative - NetZeroCities."

The purpose of this research is to derive conclusions regarding respondents' views on actions that have been decided upon by the Municipality of Kalamata, as part of implementing its climate contract. This climate contract has been developed by the Municipality of Kalamata as a result of the European NetZeroCities initiative, under which 100 cities in Europe are committed to achieving net-zero carbon dioxide emissions by 2030.

Participation Information: Your participation in this survey will require approximately 6-8 minutes of your time. The researcher guarantees your complete confidentiality and anonymity, and assures that the results derived from the statistical analysis of your responses will remain confidential and will be used solely for drawing research conclusions.

Sincerely,
Dimitrios Koutsouroupas
Email: d.koutsouroupas@go.uop.gr

Asterisk (*) Indicates a Required Question

Demographic Information:

1. What is your age? *
2. What is your gender? *
3. What is your level of education? *
4. How many people are in your family (including yourself)? (Or, how many total members are in your household, including yourself?) *
5. In which regional unit of the country does your family permanently reside? *
6. What is your family status? *
7. What is your annual family income? *
8. Are you a student? *
9. If yes (question 8), please indicate your department and year of study.

Evaluation of Climate and Sustainability Initiatives:

10. How important do you consider the Municipality of Kalamata's participation in the EU mission for 100 climate-neutral cities by 2030? *
11. How important do you consider the unification of existing renovations in squares, pedestrian areas, and green spaces in the historic center of Kalamata for creating a unified urban space for recreation and greenery? *
12. How important do you consider reducing energy costs through the upgrade of municipal lighting? *
13. How important do you consider the creation of pedestrian zones on major roads? *
14. How important do you consider the role of digital tools (such as smart networks, pollutant emissions monitoring systems) in managing the city's climate response? *
15. How important do you consider the integration of geothermal energy use (i.e., the natural thermal energy of the Earth that flows from its warm interior to the surface) in public buildings for the city's energy independence? *
16. How important is the promotion of cleanliness and waste removal actions in the urban center to you? *
17. How important do you consider the ongoing enhancement of the urban space for the city's sustainability? *
18. How important do you consider the creation of a municipal energy community in Kalamata to support local energy production and management from renewable sources? *
19. How important do you consider the strategy for Sustainable Urban Development with a focus on car-free mobility? *
20. Please rate the importance of developing cycling and pedestrian paths to reduce the city's carbon footprint (the amount of CO2 emitted into the atmosphere). *
21. How important is the involvement of local and regional forces (Peloponnese region and collaboration with neighboring municipalities) in the city's climate strategy? *
22. How important do you consider the contribution of the private sector in financing energy and environmental projects? *
23. How important is the role of educational programs in raising residents' awareness of climate change? *
24. Rate the importance of the strategic mobility plan to improve the overall traffic and accessibility of the city. This mobility plan includes the creation of pedestrian zones, bike paths, improvements in public transportation, and the enhancement of urban mobility through sustainable transport modes. *
25. Do you consider it important to use local olive oil waste for fertilizer production? *
26. How important is the modernization of wastewater treatment facilities for environmental protection? *
27. How important is the development of new green spaces and parks within the city? *
28. Rate the importance of adopting bioclimatic materials (materials that improve the energy efficiency and thermal comfort of buildings, such as natural insulators and materials that promote natural cooling) in public building constructions. *
29. How critical do you consider initiatives to strengthen the city's tourism potential through sustainable practices (such as promoting ecotourism, using renewable energy sources in tourist accommodations, and implementing environmentally friendly waste management methods)? *
30. How important is the role of international cooperation and learning from other cities in enhancing local climate actions? *
31. Rate the importance of implementing water-saving technologies across the entire city. *
32. How important do you consider investment in smart city solutions (such as smart electricity grids, traffic management systems, and smart lighting) for more efficient management of energy and infrastructure? *
33. How important do you consider legislative updates and changes to support sustainable urban development? *
34. How important is the participation of citizen groups in the climate action process? *
35. How significant is the impact of climate action initiatives on public health for residents? *
36. Rate the importance of actions taken to integrate climate issues into local economic development (such as promoting green entrepreneurship, increasing the use of renewable energy sources, and improving the energy fficiency of local businesses)*.
37. How critical do you consider the need for enhanced recycling facilities and waste management systems? *
38. Rate the importance of securing external funding for large-scale climate initiatives. *
39. How important is enhancing green spaces to improve urban air quality? *
40. How important is the role of cultural and community centers in promoting citizen habits for environmental protection? *

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In-depth Research

Navigating Electricity Market Design of Greece: Challenges and Reform Initiatives

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Abstract

The huge penetration of renewable energy sources poses several challenges for the function of electricity markets, such as increased price volatility and massive curtailments. This paper investigates the current structure of the wholesale electricity market in Greece under the Target Model guidelines. Our analysis put under scrutiny the formation and function of both spot and balancing markets by highlighting key challenges and reforms. Empirical evidence reveals that the domestic market is currently in accordance with the European Target Model; however, the anticipated benefits in terms of more competitive prices are not evident yet. The oversupply of electricity accompanied by low demand that is apparent in the Greek market points to the rapid participation of storage units in the system. The paper provides a detailed description of the recent support mechanism to facilitate the integration of BESS into the system. Eventually, this is anticipated to reduce price volatility and smoothen the price curves.

Keywords

wholesale electricity market; target model; spot market; balancing market; storage

1. Introduction

The integration of energy markets in the European Union (EU) has gradually evolved since 1990 to achieve price convergence and enhance competition of European products [1]. Different directives and guidelines facilitated the drive towards a pan-European energy market, which was thoroughly structured with the introduction of the Third Energy Package in 2009. The Target Model was formulated with a vision of achieving an integrated European energy market, offering a more efficient, robust and competitive energy system, while enhancing security and cross-border trading. In that framework, surplus energy produced in one country would easily be transferred to a neighboring country facing scarcity, bringing both countries in balance concerning price coupling and environmental aspects [2]. Following more than two decades in this direction towards energy transition and sustainability, the primary challenge at the EU level is the increased electrification rates of today's system. This development poses a significant need for enhanced interconnections between countries and proper modelling of energy flows [3].

The structure of the wholesale electricity market to date was designed to accommodate mainly conventional electricity production sources [4,5]. Yet, the ongoing energy transition accompanied by the immense penetration of Renewable Energy Sources (RES) drives the need for significant modifications in the design of the wholesale electricity market, as well as requiring massive investments towards upgrading infrastructures in interconnections and storage solutions [6,7]. Thus, various storage technologies and grid connections are essential to secure the smooth operation of the system and manage the heavy loads of generated energy during peak production hours [8]. The absence of these interventions could lead to curtailments and congestion problems in the grid accompanied by zero and even negative prices, as seen in many member states [9]. Another critical issue arising due to the increased penetration of RES is price volatility throughout the day, and especially in the Intraday Markets [10].

This paper investigates the current structure of the wholesale electricity market in Greece, accounting for Spot and Balancing Markets. By exploiting the abundance of RES, Greece aims to become an energy hub supported by cross-border interconnections that would allow for the export of surplus electricity to neighboring counties. Indicatively, the share of RES in the electricity mix of Greece skyrocketed to 44.4% from 17.1% in 2014, marking Greece among the first European countries to lead the installation and exploitation of renewables. In that context, the focal role of Greece in the southeast region is reflected in the projections of the "National Energy Climate Plan" (NECP), with installed capacity of RES reaching more than 27 GW by 2030. In this setting, the lack of energy storage units in the system makes Greece an appropriate case study to review the recent developments in terms of market design by highlighting all the recent initiatives to support their implementation in the electricity mix.

Considering this, the inverted supply–demand relationship that is apparent in the Greek wholesale electricity market is seeking means of storage to exploit the remaining and curtailed renewable energy. Eventually, this would instantly lower the price volatility and smoothen the price curve during the day. As Greece has yet to implement storage technologies, combined with the saturation of non-dispatchable RES in the electricity system, utilizing them in a price optimization manner would facilitate the system's flexibility, thus lowering price volatility [11,12]. Our analysis put under scrutiny the formation and function of both spot and balancing markets by highlighting the key challenges and reforms to be addressed in the following period. Empirical evidence reveals that the domestic market is currently in accordance with the European Target Model; however, the anticipated benefits in terms of more competitive prices are not evident yet.

The remainder of this paper is structured as follows. In Section 2, we review the literature related to the function of the wholesale electricity market in Greece. In Section 3, the current structure of the spot market in Greece is analyzed. The next section reviews the function of the Balancing Market and highlights the existence of non-compliance charges along with a discussion on the Balancing Capacity Market (Section 4). Finally, in Section 5, we conclude and provide directions for future research.

2. Literature Review

The liberalization of the energy market in Greece began in the late 1990s, implemented by the EU to create a pan-European Energy Market, resulting in a robust and resilient energy system. The liberalization began through the smooth introduction of various energy packages, consisting of EU directives and regulations. The First Energy Package consisted of Directive 96/92/EC and Directive 98/30/EC, established in 1996 and 1998, respectively. These directives introduced common rules for the internal market regarding electricity and natural gas (NG) and were active from 1998 to 2003, while establishing the right of Third-Party Access and operational unbundling. Under those directives, national regulatory authorities took the role of market supervision, monitoring compliance and regulation of the electricity supply.

The Second Energy Package extended prior directives by introducing Directive 2003/55/EC, which granted access to cross-border NG transmission networks. Regulation (EC) No 1228/2003 established conditions to the network for cross-border exchanges in electricity. Specifically, these changes were issued to set technical rules for access to the transmission network, capacity allocation and congestion management. In that context, Ref. [13] investigated the cross-border electricity trading in Southeast Europe with respect to the Internal European Market. Next, the Third Energy Package, which took place from 2009 to 2019, consisted of Directive 2009/72/EC, Regulation (EC) No 714/2009 and Regulation (EC) No 713/2009, which established the Agency for the Cooperation of Energy Regulators.

The Fourth Energy Package added Regulation (EU) 2019/943 and Directive (EU) 2019/944. The new framework established common rules for the internal wholesale electricity market, aiming at a competitive and robust market, while integrating renewable energy and removing barriers to cross-border trading. In 2021, the Fifth Energy Package was established, also named "Fit for 55", setting targets for 2030 towards decreasing greenhouse gas (GHG) emissions by at least 55% compared to 1990 levels and achieving climate neutrality by 2050. An early investigation on the electricity sector in Greece accompanied by the initial reforms to liberalize the wholesale market is provided by [14]. The author identified a couple of key pending reforms to boost the liberalization process, for instance, transparency in pricing formation, promotion of competition, unbundling of transmission networks and introduction of a regulatory framework aligned with European guidelines. Next, Ref. [15] outlined an overview of Greece's wholesale electricity market with emphasis on ancillary services. Since then, the developments recorded in the wholesale electricity market of Greece have been fundamental.

To begin with, one important milestone considering the liberalization of the domestic market during the past decade was the transformation of the state-controlled electricity firm, Public Power Company (PPC), under a period of severe financial and economic crisis in Greece [16]. For about 50 years, the electricity sector in Greece has been structured under a monopolistic model, where the state-owned and vertically integrated PPC was granted exclusive rights as regards all electricity activities [14]. The gradual transition from this dominant model towards a more liberalized one along with the penetration of RES initiated in 2010.

At that time, the EU's commitment to achieving a reduction in greenhouse gas emissions, increasing the share of RES in the final energy consumption and improving energy efficiency led also to the acceleration of domestic policies towards the support of RES. In parallel, empirical findings identified increased levels of acceptability of renewable energy applications by the Greek population [17,18]. In this framework, Ref. [19] investigated the effect of solar and wind power generation with respect to volatility of wholesale electricity prices in the Greek electricity market from 2012 to 2018. The authors argue that renewables in general lead to decreased price volatility, while wind power tends to increase it, and solar power tends to decrease it. Furthermore, according to their findings, during peak hours, wind and solar power generation tend to decrease price volatility.

Next, aiming to achieve a smooth energy transition, along with increasing the share of RES in the energy mix, the EU proposed the Target Model mainly focusing on the electricity mix. Prior to the launch of the Target Model, a Day-Ahead Mandatory pool was established including the following processes: Day-ahead scheduling, Dispatch scheduling, Real time dispatch operation and Imbalances settlement. By 1 November 2020, the Target Model was introduced in the Greek market, setting a key milestone for the market reform in Greece. The transition replaced the Mandatory Pool model, aligning Greece with the EU framework, working toward a single EU Pan-European Hybrid Electricity Market Integration Algorithm (EUPHEMIA) [20]. In that context, Refs. [21,22] provide optimization approaches to balance short-term and long-term decision making on energy planning. Consequently, regarding the Greek power generation system, a plethora of papers have analyzed the optimal long-term energy planning and the incorporation of the EUPHEMIA algorithm [23–27]. In that context, a recent paper by [28] presents an investigation into a novel multi-energy trading market model, which is based on the concept of matching prices.

Under the newly established framework, the Target Model consists of four distinct markets, the Forward Market (FM), the Day-Ahead Market (DAM), the Intraday Market (IDM) and the Balancing Market (BM) (Figure 1). The EU Member States that have adopted the Target Model have a Single Day-Ahead Coupling mode (SDAC), while the Intraday Market is gradually being coupled on a pan-European level. Continuous Intraday Trading or Single Intraday Coupling (SIDC) is in almost full force among most EU member states. Furthermore, Greece is directly coupled with the Italian and Bulgarian electricity markets, giving access to other coupled EU countries.

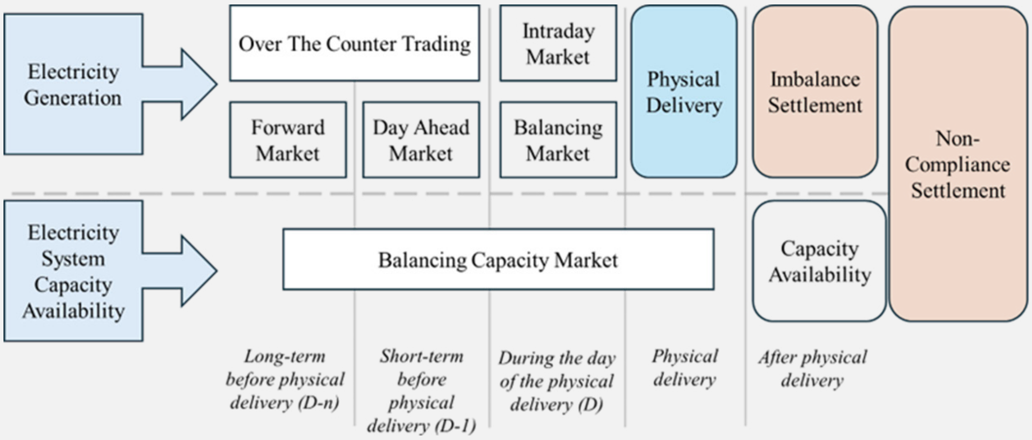

Figure 1. Target Model structure in Greece.

The main institutions in the formation of the Target Model include the Independent Power Transmission Operator (IPTO), the Hellenic Energy Exchange (HEnEx) and the Clearing House (EnExClear). EnExClear acts as the Clearing House both for the Day Ahead and the Intraday Markets, intervening among the counterparties of the settled transactions, assuming the role of buyer to each seller and the opposite. The Clearing House is responsible for the financial settlements and transactions, to reduce credit risk for the market. The Clearing Members, following the Clearing Regulations, are split into two categories, Direct Clearing Members that are Market Participants (MPs) who may only clear their own transactions and positions, and General Clearing Members who are Fi-nancial Institutions that undertake the clearing of the position and transactions of other participants.
Finally, considering the Derivatives Market, which was established in March 2020, ATHEXClear is responsible for clearing all transactions and acting as a Central Counter-party. For the efficient supervision of the legal structure, overseeing the daily function of the markets are the Regulatory Authority for Energy, Waste and Water (RAEWW) in Greece and the Hellenic Capital Market Commission (HCMC). As Figure 2 illustrates, op-erators of the power system also include Hellenic Electricity Distribution Network Opera-tor (HEDNO), acting as the Distribution System Operator (DSO) and the Operator of RES and Guarantees of Origin . Eventually, in 2022, the Target Model came into full force in Greece, implementing the final step of the BM and the non-compliance charges for BM re-sponsible parties.

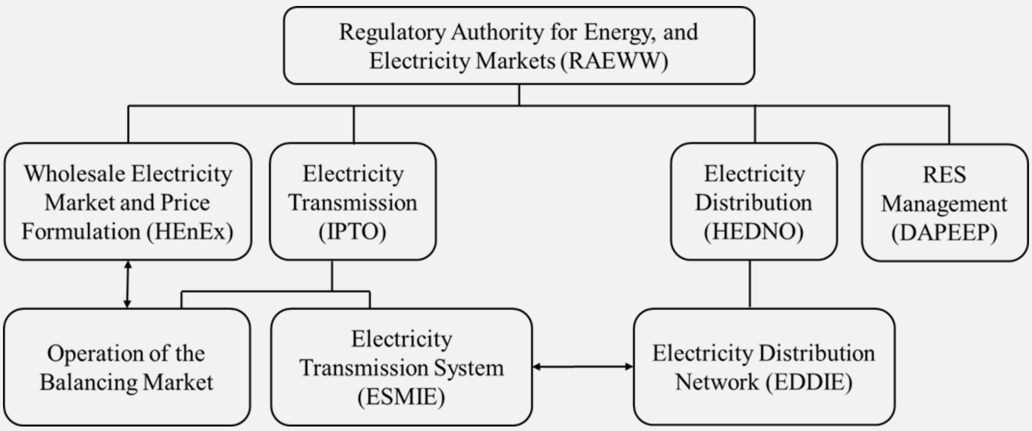

Figure 2. Main institutional entities and operators of the Greek power system.

3. Spot Market Analysis

3.1. Power Exchange

In line with [1], a Power Exchange (PX) refers to a competitive wholesale trading fa-cility designed for the exchange of energy commodities like electricity and natural gas. All PXs share a similar structure with common rules and operating mechanisms. A power exchange serves as a centralized platform characterized by standardized attributes, prin-ciples, regulations, quality benchmarks and transaction terms for energy-related financial product trading. This marketplace is a central electronic auction platform connecting buy-ers and sellers through fully transparent rules and procedures, with the main task match-ing demand and supply, and continuously determining a Market Clearing Price (MCP).

3.2. Day Ahead Market

The DAM refers to transactions occurring the day before physical delivery. The pro-cedure allows market participants and the TSO to arrange a balanced timeframe of the physical aspects of the delivery (Figure 3). The orders are submitted one day before the de-livery day with hourly time units and refer to the market schedule. Based on the assessed load for that hour and the prices of the technologies offered, the MCP is calculated. At the DAM closure time, in each market schedule, generation should be equal to estimated de-mand, respectfully to the interconnection balance, considering net imports and exports of electricity. When the balance is secured, offers that are above the balance are declined, while priority is given on a first-come first-served basis respectfully to the lowest price. When submitting an order, each participant submits a balanced portfolio (nominations) to the system operator, providing information on generation or forecasted consumption in each market schedule (time unit) [23].

In DAM, only electricity products with physical delivery within the Hellenic Trans-mission System Bidding Zones are traded. The eligible products, supported by the Price Coupling Algorithm, are in accordance with Article 40 of Regulation (EU) 2015/1222 by a joint proposal of Nominated Electricity Market Operators (NEMOs), and are in line with the available Buy and/or Sell Orders. Additionally, bilateral Over the Counter (OTC) trades are taken into consideration as volumes in the DAM, but their prices can remain undis-closed, while they do not affect the final MCP. Figure 4 illustrates the traded volumes in the Day-Ahead market of HENEX from 2021 until 2024, reflecting the constantly rising demand for electricity (24% slope) along with the apparent electrification trend since 2021.

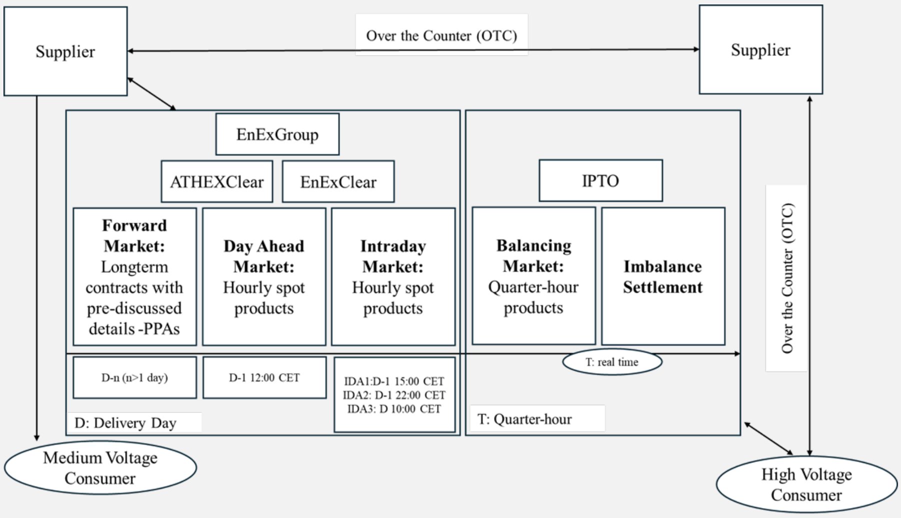

Figure 3. Power exchange market design in Greece.

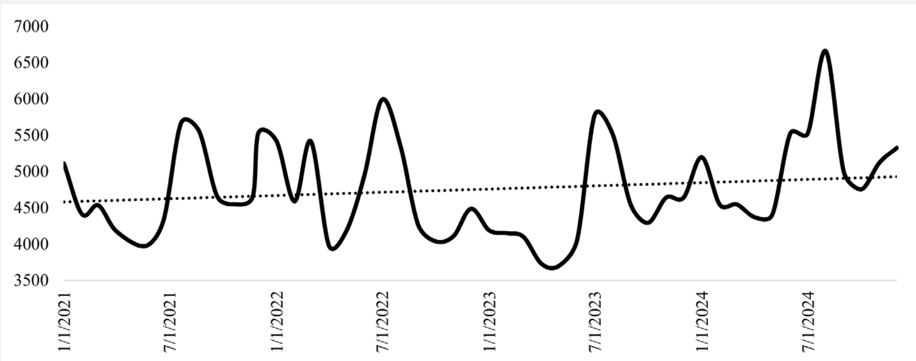

Figure 4. Traded volumes in the DAM of HENEX (1 January 2021–31 December 2024).

As Figure 5 depicts, even though DAM prices during 2024 are significantly lower compared to 2022, they are still higher compared to the respective levels during the im-plementation of the Mandatory Pool (2007–2019), supporting the argument of increased electricity prices since the introduction of the Target Model in Greece. Considering price volatility, as expected during evening hours, an upward trend is evident. Interestingly, as illustrated in Figure 6, during 2021, we observe increased levels of volatility compared to the following years.

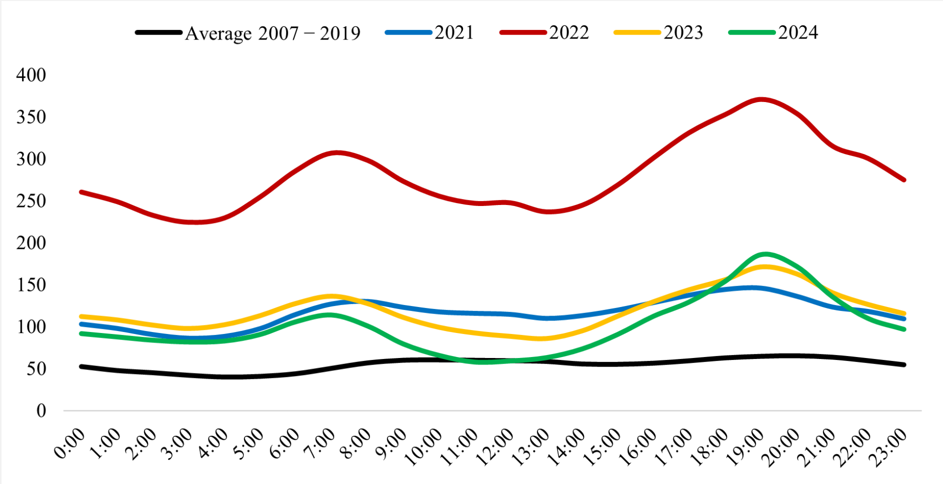

Figure 5. Average hourly DAM prices (EUR/MWh).

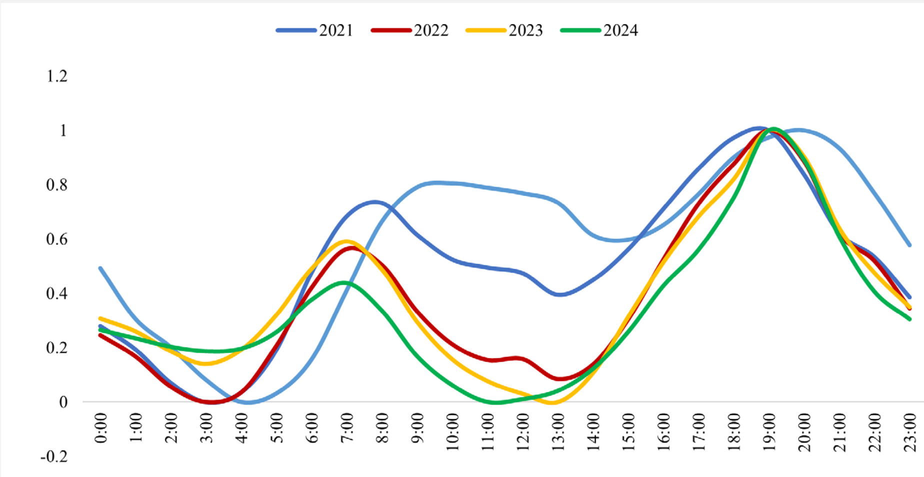

Figure 6. Price volatility in DAM.

OTC trades and contracts with obligation of physical delivery, taking place in the FM, can use DAM for fine-tuning. One of the main objectives for the EU is the adoption of a single pan-European cross-zonal DAM for electricity. The goal is to increase overall effi-ciency by promoting competition, increased liquidity and enablement of more efficient uti-lization of generation resources across Europe [30]. SDAC was initiated in 2014 by NEMOs and TSOs in the framework of Capacity Allocation and Congestion Management, enabling cross-border trading through implicit auctions for next-day power delivery.

In February 2014, the "first go-live" took place, including Belgium, Denmark, Estonia, Finland, France, Germany, Austria, United Kingdom (UK), Latvia, Lithuania, Luxembourg, the Netherlands, Norway, Poland, Sweden, Portugal and Spain. A couple of months later, in November 2014, Czech Republic, Hungary, Romania and Slovakia joined the initiative. In February of 2015, Italy and Slovenia coupled. Next, in 2018, Croatia and Ireland cou-pled, while the German–Austrian bidding zone split into two separate ones [31]. The Greek DAM has been integrated into the pan-European DAM since December of 2020, through the Greek–Italian border, with Bulgaria joining later in May of 2021, through the Greek–Bulgarian border. Across this coupling of regions, it was made possible to imple-ment implicit capacity allocation on each border. Nevertheless, in the same year, the UK decoupled from the EU, almost one year after Brexit.

3.3. Intraday Markets

Following the completion of DAM, the IDM allows participants to correct the sub-mitted positions in DAM as the time of the physical delivery approaches. This can be es-pecially useful when there are changes in the energy demand, power plant availability, or changes in the non-dispatchable RES plant forecast, as short-term forecasts are more ac-curate for RES plants. The IDM allows participants to submit buy or sell orders on the day of physical delivery, after the gate closure of the DAM. Results for the FM and DAM are considered, as well as the BM restrictions. As for the case of DAM, there is no guarantee that the submitted orders will be matched and thus executed [32].

Until September 2021, the Greek IDM performed in three local intraday auctions (LIDAs), as it was not yet coupled in intraday terms with neighboring markets, since the cross-border capacity was not recalculated after DAM. In September of 2021, the Greek and Italian IDMs were coupled, initially through complimentary intra-day auctions (CRIDAs).

On 13 June 2024, Intraday Markets (IDAs) took their place via the SIDC. During the execu-tion of IDAs and until the results are published, the coupled borders included in IDAs are paused and all orders in IDAs are verified and validated. Results of IDAs comprise the acceptance status of each order, a single net position for each bidding zone and market time unit as well as the MCP for each time unit. After publication, the results are forward-ed to the Clearing House-EnExClear. As depicted in Figure 7, similarly to the case of DAM volatility, the three Intraday Markets follow identical patterns to 2021, maintaining in-creased levels compared to the following years.

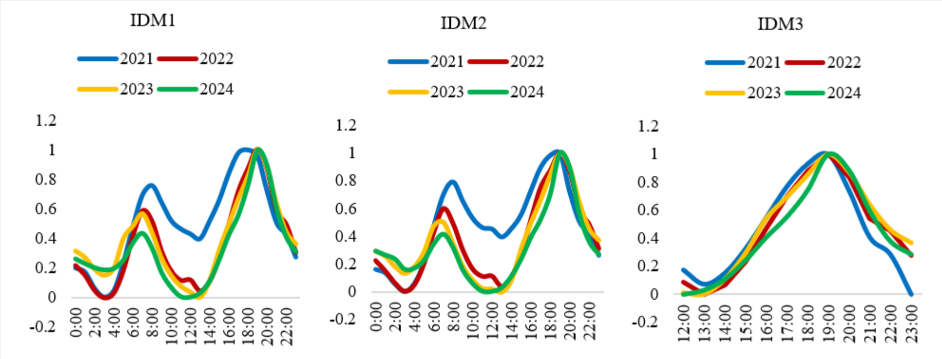

Figure 7. Price volatility of intraday markets (2021–2024).

In a similar manner to SDAC, the EU's plan is for all member states to adopt the XBID project (Cross Border Intraday). XBID was established in 2018, aiming to construct a single EU cross-zonal intraday electricity market, where market participants can trade electricity continuously. SIDC is constructed on a common system with a Shared Order Book (SOB), a Capacity Management Module (CMM) and a Shipping Module (SM) (Figure 8). The benefit of a common system means that market participants from different coupled regions can match their orders with complementary orders, if the available transmission capacity al-lows this act. In such cases, order matching results in implicit capacity allocation and the SOB and CMM are updated immediately, while the trading principle remains the same. Updating the SOB means matched orders are removed and the available capacity is up-dated in the CMM. The number and location of the borders where the capacities are up-dated follows the cross-border flows of the matched orders [33].

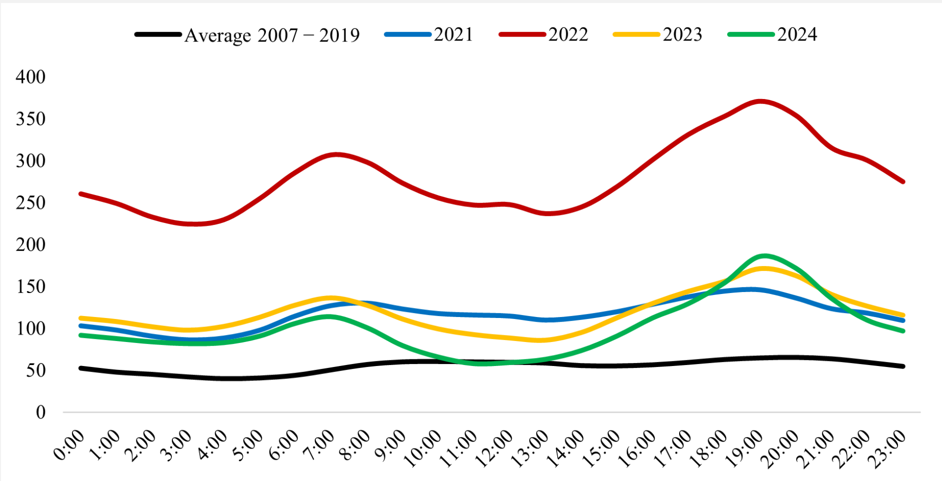

Figure 8. SIDC matching solution architecture.

The initiative of an integrated intraday market serves the purpose of increasing mar-ket liquidity and thus the overall efficiency of intraday trading. Liquidity increase refers to orders that did not have a chance to match prior to integration and since the adoption of XBID, facing greater probability in matching an order. With the overall growth of RES, the interest in intraday trading has increased, as it is rather challenging for RES producers to remain balanced after the closing of DAM. Holding a balance closer to the delivery time is beneficial for all MPs, and for power systems alike. This is of particular interest for RES aggregators, which constantly try to minimize their deviations, and thus the non-compliance charges. The intraday solution supports both explicit and implicit con-tinuous trading, while being in line with the EU Target to unify all EU power exchanges into one.

The SIDC's CMM in the most basic form consists of the Market and the Delivery Are-as. The Market Area represents a "price area" in the delivery grid, containing one or more Delivery Areas, and the transport capacity between Market Areas is subject to congestion. The Delivery Area represents an area in the delivery grid and is managed by the respective TSO. Order entry takes place into the Delivery Area, meaning a commodity is received or delivered.

The Delivery Area is a subset of the Market Area, as seen in Figure 9. In SIDC's CMM, apart from the Market and Delivery Areas, the role of interconnectors and borders is crucial. An interconnector is the connection between two

Delivery Areas, while a Border is a connection between two Market Areas. An Interconnector is implied to have a separate configuration. The configuration includes characteristics such as opening and closing time, capacity resolution along with default capacity and validation. At the same time, a common configuration per Border is essential. A broader schematic of the CMM configura-tion is depicted in Figure 10.

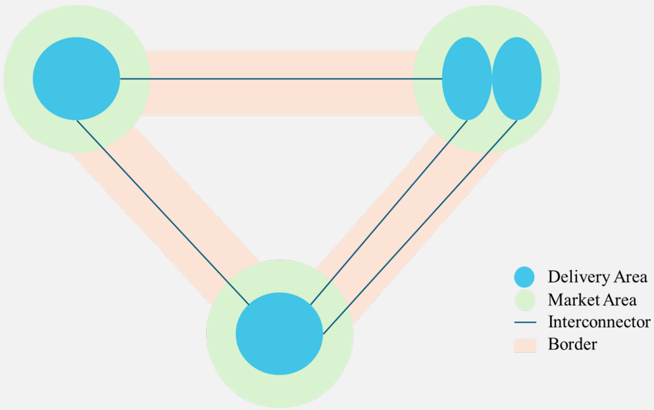

Figure 10. CMM schematic.

On 13 June 2024, Intraday Auctions were introduced to EU member states that have already adopted the SIDC. In the case of Greece, CRIDAs have been replaced by IDAs. IDAs allow for the accumulation of offers and efficiently allocate scarce transmission ca-pacity, compared to continuous intraday trading, where allocation takes place on a first-come first-served basis. The purpose of IDAs is to harmonize the computation of cross-border capacity and assign a price to that capacity concurrently with its allocation and determine the price of cross-border capacities that can be realized through XBID [34]. Ultimately, IDAs further strengthen the competitiveness of EU electricity markets, trading, and supply through Regulation (EU) 2015/1222.

Figure 11 illustrates the waves that took place in terms of the SIDC for each country. As for the case of Greece, SIDC run through the XBID live platform allows for more free-dom and flexibility for a more accurate trade, especially for RES aggregators [35]. During the continuous trading, participants can submit buy and sell orders for all market sched-ules, with time unit of 60 min. Initially, it was expected for 15 min time units to be intro-duced in Greece during 2023, though it is estimated to be accomplished by June 2025.

While XBID provides a platform for continuous trading, IDAs provide a mechanism for allocation and pricing cross-border capacity in the intraday markets via the EUPHE-MIA algorithm. The IDA solution is organized as an implicit auction; orders are matched, and the cross-zonal capacity is instantly allocated for different bidding zones. All valid submitted orders for the respective auction are taken into consideration, and a clearing price for the specific bidding zone is determined. It is not possible to simultaneously allo-cate cross-zonal capacities for IDAs and XBID. To resolve this issue, the XBID orders are suspended for a limited period of 20 min before and after the Gate Closing Time (GCT) of IDAs. The GCT as well as the allocated period for IDAs and DAM, along with the suspen-sion intervals of XBID, are shown in Figure 12.

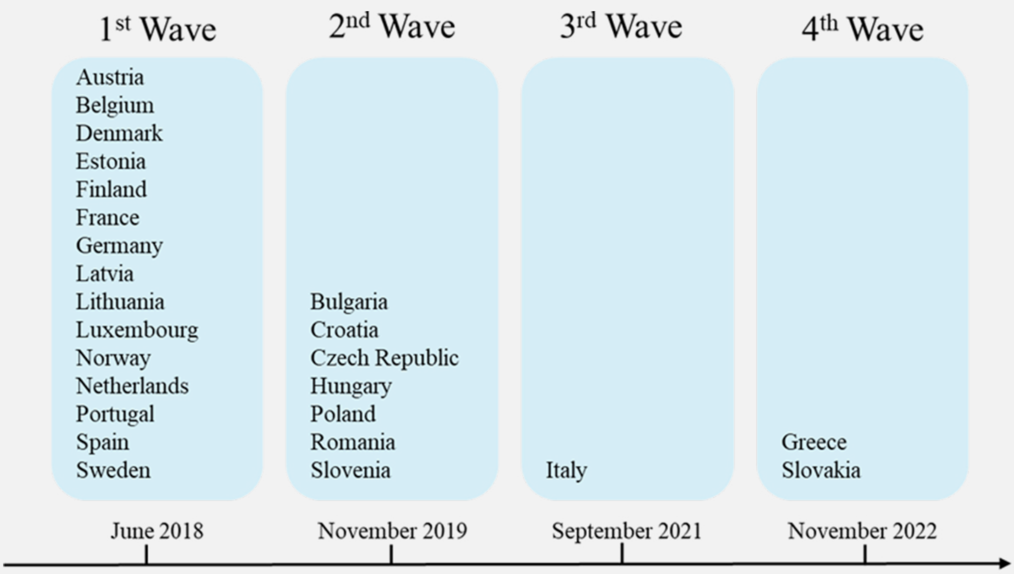

Figure 11. SIDC country introduction.

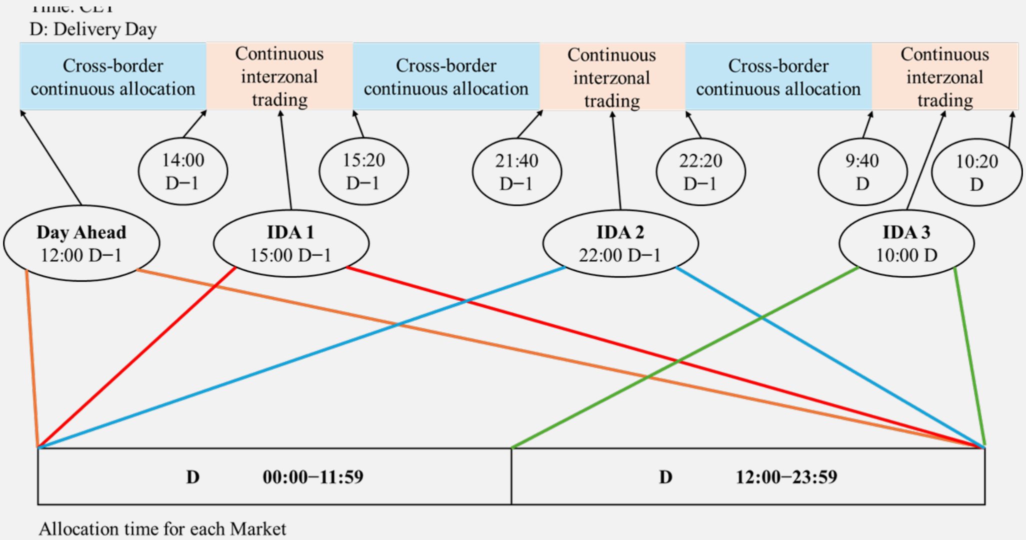

Figure 12. Trading periods in different markets of the Target Model.

For the case of Greece, Gate Opening and Closing Times for IDAs remains the same as they were formed in CRIDAs. XBID and IDAs are closely affiliated. The only XBID module affected is the CMM; the remaining two modules remain non-functionally impacted. XBID's CMM serves as a connecting link between the TSO of the country and the NEMO's IDA trading solution. Pre-coupling, XBID's CMM is used as a source of network constraint data for the IDA; this is needed to determine the available capacity per region, and after that, in the coupling phase to validate the IDA results (allocated capacity does not exceed the network constraints). Regarding the DAM results, they are provided by the NEMOs to the EUPHEMIA algorithm via PMB (Price Coupling of Regions (PCR) Matcher and Broker) and the PCR along with the allocated capacities are provided to the IDA platform. The PMB service provides anonymized orders and electricity network constraints. Data are distributed along all PXs, to calculate bidding zone prices, along with other reference prices and net positions for all bidding zones.
IDA results are submitted back to XBID's CMM in the form of allocation requests. In case the flows coming from IDA are compatible with the CMM data, they are accepted, or else they are denied. The back and forth transferring process is made available by imple-menting the IDA Central Interface Point (CIP), developed specifically for IDA operations; both NEMOs and TSOs have access. IDA CIP is a solution to work between NEMO's sys-tem and XBID's CMM. Functionalities include data transfer between the two platforms, processing of the data received from XBID's CMM and giving the processed data to NEMOs, accepting the resulting data from NEMOs after the IDA GCT and transferring back these data to XBID's CMM, while ensuring consistency between the platforms. Nota-bly, IDA Local Trading Solutions could potentially be the same as in the Day-Ahead auc-tion with small adaptations for the IDAs, or completely new, depending on the NEMO in each instance. The high-level architecture is provided in Figure 13.

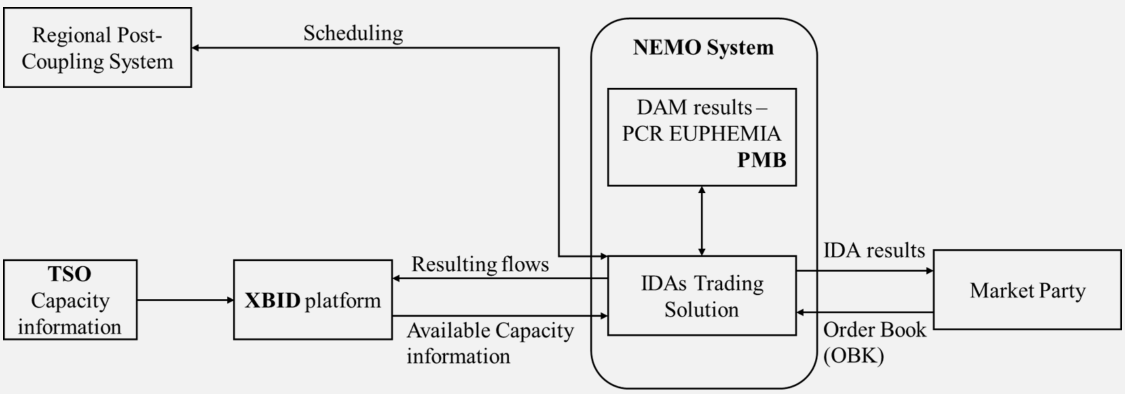

Figure 13. High-level architecture of IDA data transferring.

3.4. Calculation of Market Clearing and Market Coupling

Following Gate Closure, for the DAM and the IDMs, respectively, the algorithm for calculating the MCP is set into action. The submitted buy and sell orders should have in-formation on volume and price, in the relevant price ranges of the auction, determined by EnExGroup. The Buy-Orders establish the demand curve in the PX, while the Sell-Orders establish the supply curve; these two refer to the aggregation curves for each market schedule of the following day. The MCP reflects the demand and supply, serving interest for both curves. As illustrated in Figure 14, the interception point of the two curves deter-mines the MCP and the Market Clearing Volumes (MCVs). For each market schedule, there is a unique MCP and MCV, both applying for Buyers and Sellers. This price is never high-er than the price fixed by the buyer or lower than the price fixed by the seller. The MCP is determined in a pay-as-cleared manner, meaning that all sellers with accepted orders no matter the submitted price will get paid the MCP, as during these auctions, the buyers and sellers are not matched one-on-one but rather in an aggregated manner.

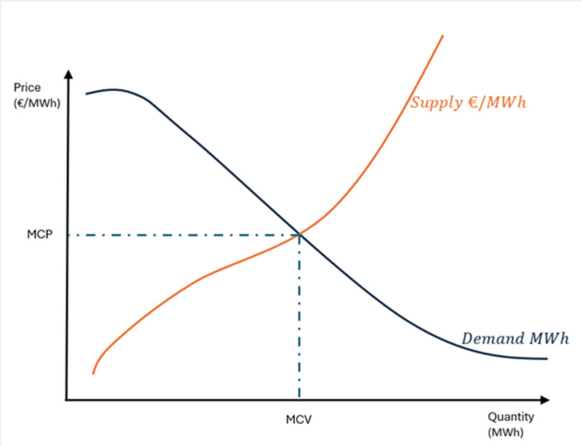

Figure 14. Supply and demand aggregation curves

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Market Coupling (MC) is a way to join and integrate energy markets from different re-gions into one single coupled market. As such, buy and sell transactions are possible through different areas, while benefiting from more attractive prices. The main benefit of MC is the improvement of the market liquidity combined with less volatile electricity prices via healthy competition, price convergence, mitigation of market power abuse and grant-ing easier access to the market for smaller participants [20]. In Figure 15, the advantages of MC can be observed. Quantities from Market A that would not be otherwise realized in this market could be partially or even completely exported to Market B. On the other hand, Market B has access to lower prices due to imports from Market A. The EUPHEMIA algo-rithm was developed to solve the problem of coupling of the DAM markets in the PCR. Market participants submit their orders to the respective PX; these orders are collected and submitted to EUPHEMIA. Next, it is up to EUPHEMIA to decide which orders are to be executed and which to be rejected. The main objectives of EUPHEMIA include maximiza-tion of social welfare generated by the executed orders and optimization of the capacity of the relevant network elements [36].

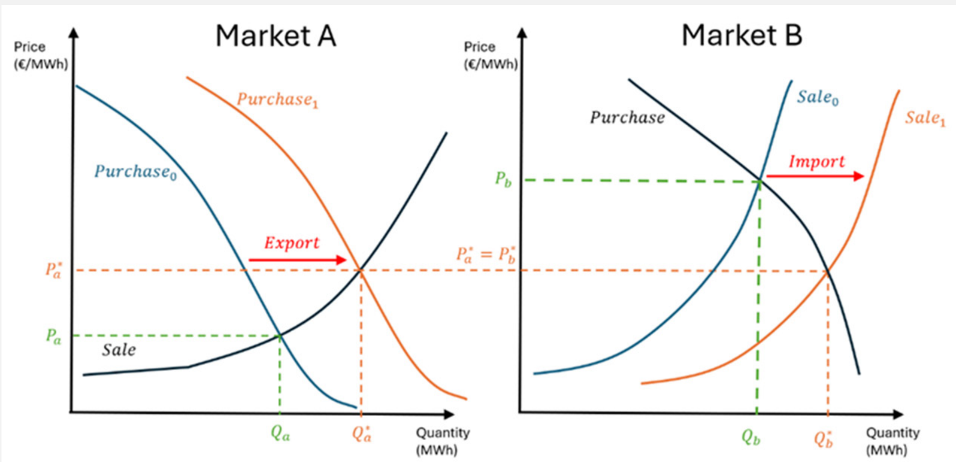

Figure 15. Market coupling.

EUPHEMIA handles a variety of order types simultaneously as well as their require-ments, which are available to market participants according to the local market rules. Such order types include Aggregated Hourly Orders, Complex Orders (Minimum Income Con-dition and Load Gradient orders), Block Orders (Linked Block Orders, Exclusive Groups of Block Orders, Flexible Hourly Orders) and Merit Orders. The hourly orders (de-mand/supply) from all market participants belonging to the same bidding zone will be aggregated into one single curve, called the aggregated demand/supply curve, defined for each period. Demand orders are sorted from highest to lowest price, while supply orders are sorted from lowest to highest price, in the opposite manner to demand orders.

In line with the main principle of the algorithm, Figure 16 shows that any orders that are in-the-money should be accepted, while orders that are out-of-the-money should be re-jected. Orders that are at-the-money can be either accepted fully, or partially, or rejected. The algorithm aims at rapidly finding a good first solution and continuously improving it if possible. Also, all submitted orders of the same type by market participants are treated equally. Information about the Power Transmission network of each PX provided by the TSOs is taken into consideration as constraints, meaning that each bidding zone applies different constraints. Accordingly, all submitted orders in the same bidding zone will have the same clearing price. EUPHEMIA calculates the MCP for each bidding zone and period along with the corresponding net position. For this reason, the MCP in the Greek bidding zone and the MCP for exports are different. Finally, Figure 17 illustrates an overview of the wholesale market timeframe available in the spot market of Greece.

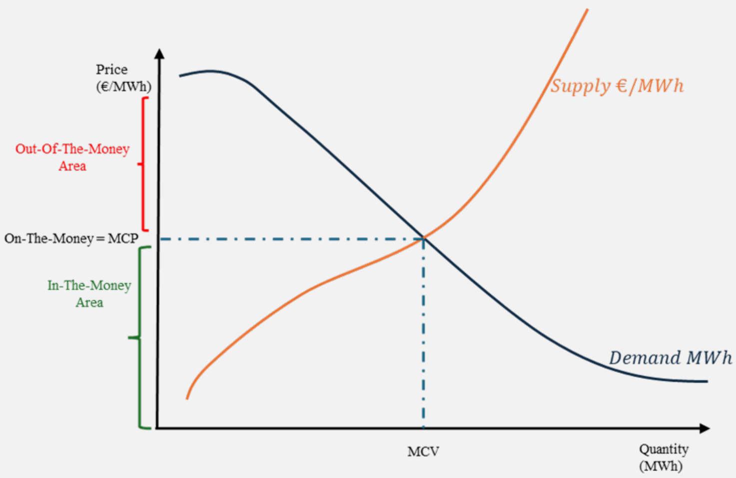

Figure 16. EUPHEMIA solution.

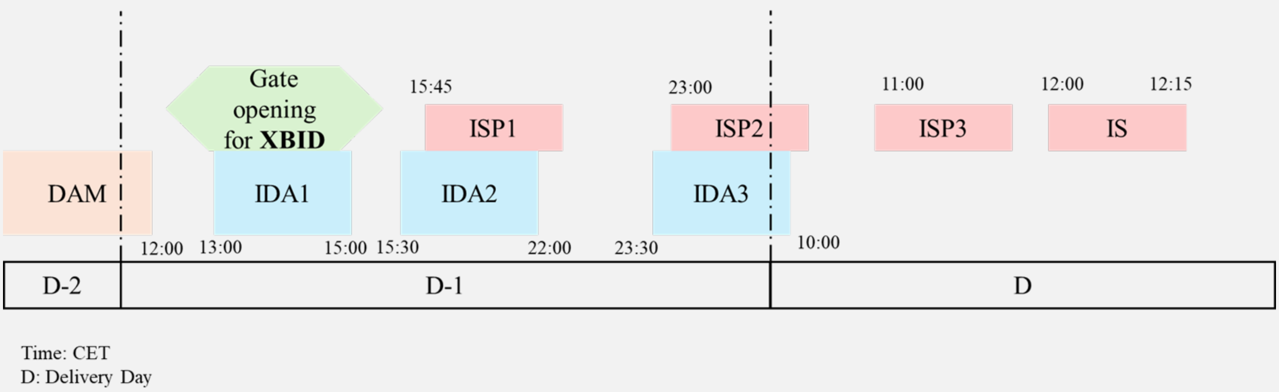

Figure 17. Spot market timeframe.

3.5. Operating Aid for Battery Energy Storage Systems in Greece

The updated NECP includes a target for substantial 3.1 GW battery energy storage by 2030. A total of 900 MW of Battery Energy Storage Systems (BESS) has been awarded across the three auctions that have already taken place. The first auction, in August 2023, awarded 411.8 MW across 12 projects (2 MWh per MW), with bid prices ranging from EUR 33.9 to EUR 64.1 per MW annually with an average of EUR 49. per MW annually. The subsidy included a one-time capital expenditure (CAPEX) grant of EUR 200,000 per MW. The second auction in February 2024 awarded 300 MW across 11 projects (again, 2 MWh per MW), with bid prices ranging from EUR 44.1 to EUR 49.9 per MW annually with an average of EUR 47.6 per MW annually. The subsidy included a one-time CAPEX grant of EUR 100,000 per MW, which was significantly reduced compared to the first auction. The third auction in March 2025, awarded 188.9 MW across nine projects (4 MWh per MW). The subsidy included a one-time CAPEX grant of EUR 200,000 per MW.

The following analysis is in line with the detailed framework published by RAAEY on the calculation of the operating aid towards BESS in Greece. The intention of the framework is to incentivize the owners of subsidized BESS to participate in the relevant energy markets actively and effectively. Policymakers aimed to minimize risk and uncertainty of the revenue streams of BESS and at the same time ensure minimum technical characteristics throughout the Contract for Difference (CfD) duration. The duration of each Regulatory CfD period is set at 3 full calendar years beginning on 1/1/2026. Operational support will be disbursed annually from DAPEEP. The incentive scheme, which is designed to last for 10 years, is based on the relative performance of the awarded project within a Group of other similar Projects (the Reference Group). Both subsidized and merchant BESS with similar technical characteristics will be part of the same Reference Group. Each subsidized BESS will be categorized in different Groups based on their minimum guaranteed injected capacity (MWh/MW). Subsidized BESS from the first two auctions will be part of the same Groups, while subsidized BESS from the third auction will be grouped separately. The operational aid (EUR/MW) is equal to the ex ante operating aid plus the ex post operating aid minus the various penalties due to deviations from technical requirements.

Ex Ante Operating Aid = RR - EMR - EAR + ERL (1)

where RR is the Reference Revenue of each BESS, Estimated Market Revenue (EMR) is calculated before the beginning of each CfD period by RAAEY, and it is based on different economic data from IPTO, DAPEEP and HEnEx. Estimated Additional Revenue (EAR) considers any investment, operational or other type of aid besides the CfD. Estimated Revenue Losses (ERL) represents any decreases in the net market revenue related to a forced supply of additional services which may not be provided. Next, the ex post Operating Aid will be calculated separately for each BESS and year based on the difference between the Estimated and Actual Group Net Market Revenues plus any Actual Additional Revenues and Losses. Group Net Market Revenue is considered the sum of each individual BESS of the Group divided by their accumulated capacity.

Finally, specific technical characteristics will be inspected every 2 years, such as Power Capacity, Energy Capacity, Round Trip Efficiency, Standby Auxiliary Consumption, Technical Availability. In the case of any deviations from the standard technical requirements as per RAAEY's official call, penalties will be imposed based on the magnitude of the deviations. Figure 18 below illustrates the BESS incentive scheme under two different Reference Groups. Furthermore, Figure 19 depicts the scenario of positive adjustment when reported Group Revenue is lower than the Estimated Revenues and Figure 20 the negative adjustment, when Reported Group Revenue is higher than the Estimated Revenue.

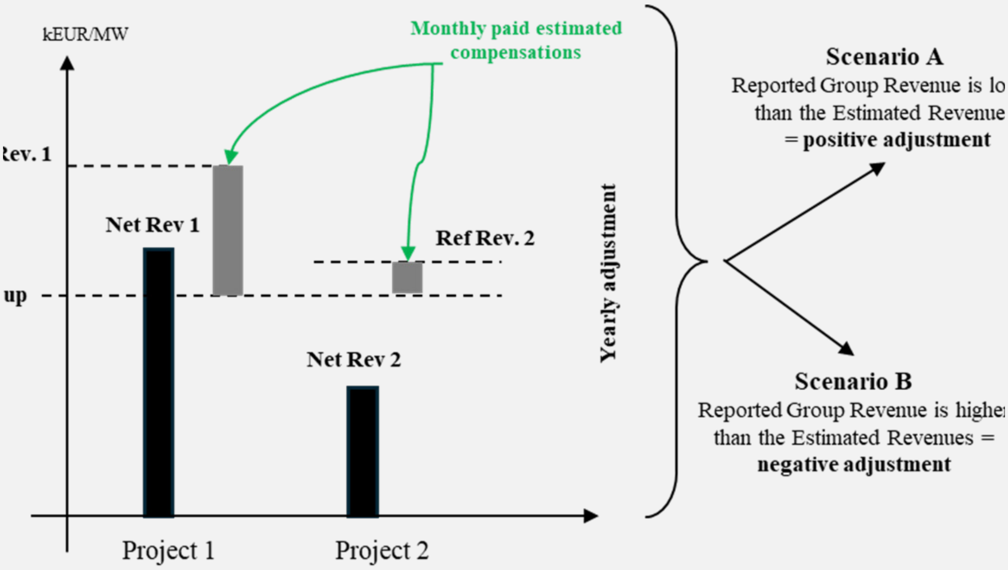

Figure 18. Incentive scheme under two different Reference Groups.

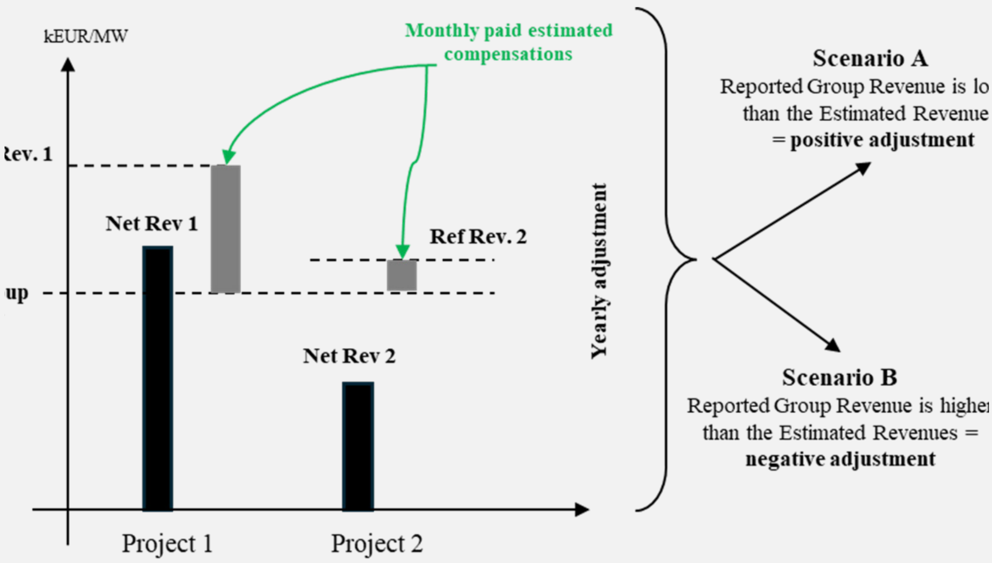

Figure 19. Scenario A, positive adjustment of operational aid.

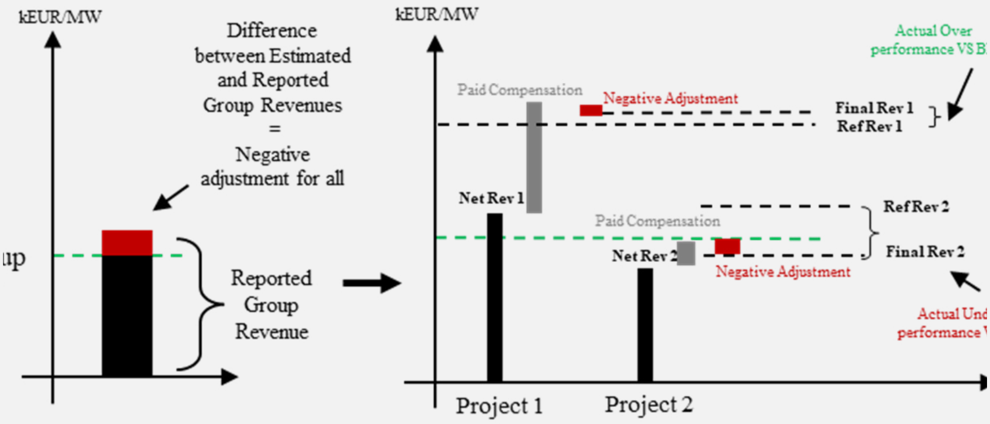

Figure 20. Scenario B, negative adjustment of operational aid.

4. Balancing Market Analysis

Since the introduction of the Target Model, the electricity mix in Greece has changed significantly. In line with [37], storage units could act as assets and support the further penetration of RES even in the BM. The operation of the BM is handled by the local TSO, which is responsible for determining the imbalance settlements for the balancing actions, as well as the balancing costs that derive from those actions, ensuring a balanced and secure electricity grid. BM plays an essential role in the PX, especially with the constant integration of renewable energy into the power grid [38]. For a BM to be efficient, it should ensure supply at the lowest cost possible, provide real-time system monitoring, while delivering environmental benefits by reducing the requirement for back-up generation. One of the core functions of the BM is compensation for the ancillary services provided to ensure a balanced grid operation.

As for the case of Greece, IPTO is responsible for the operation of the BM. In the same context, IPTO is responsible for providing sufficient available capacity for the balancing services for the System and is required to issue the appropriate dispatch instructions to the Balancing Service Entities. The BM is divided into three individual procedures, the Balancing Capacity Market, the Balancing Energy Market and finally the Imbalance Settlement. With the full integration of the BM, the balancing costs were expected to reduce [39]. Yet according to [40], for the case of Greece, and specifically for RES aggregators, imbalance costs soared.

In the Greek BM, apart from the Imbalance Settlement, non-compliance charges are calculated monthly, based on the certified production data, the corrected Imbalance Prices and the submitted production. The non-compliance charges use three main indexes with the respective tolerance limits for their calculations. They are applied to all Balance Responsible Parties, while the tolerance limits are declared by the TSO based on the size of the participant. The main difference between conventional units and RES is that, for the case of the former one, non-compliance charges are applied when the significant imbalances between the measured energy and the corresponding Market Schedules of the same participant occur systematically.

According to the Electricity Market Code, non-compliance charges are applied:

- For Conventional Unit Portfolios in case:
    - The normalized absolute deviation in a month m exceeds the tolerance margin $TOL_{(ld,ADEV)}$.
    - The normalized RMS value of deviations in month m exceeds the tolerance margin $TOL_{(ld,RMSDEV)}$.
- For both Dispatchable and Non-Dispatchable RES Unit Portfolios, a third condition is added
    - The normalized absolute deviation in a month m exceeds the tolerance margin $TOL_{(r,ADEV)}$.
    - The normalized RMS value of deviations in month m exceeds the tolerance margin $TOL_{(r,RMSDEV)}$.
    - The absolute normalized deviation in month m exceeds the tolerance margin $TOL_{(r,DEV\_NORM)}$.

The first two tolerances for conventional and RES portfolios are the same, but for RES portfolios, the normalized deviation is also considered.

To calculate those values, we set:

- The Market Schedule of Participant p for the MTU t: $MS_{(p,t)}$;
- The offtake in MWh that corresponds to the consumers of the Interconnected System per participant p for the MTU t: $MQ_{(p,t)}$;
- Deviation in each MTU t for the participant p.

$$DEV_{(p,t)} = MS_{(p,t)} - MQ_{(p,t)} \quad (2)$$

The tolerances are determined by IPTO. They should be published at least two months prior to their implementation and are calculated based on the monthly $MQ_{(p,t)}$. For a conventional portfolio, $NCBALR_{(p,m)}$ corresponds to the charge that is implied in case a significant imbalance occurs in an MTU of month m between the amount of energy dispatched and the corresponding Market Schedule of the seller p.

For a conventional portfolio, a significant imbalance is considered when:

$$NADEV^{NORM}_{(p,m)} > TOL_{(r,ADEV)} \quad (3)$$

$$NRMSDEV_{(p,m)} > TOL_{(r,RMSDEV)} \quad (4)$$

$TOL_{(r,DEV)}$ and $TOL_{(r,RMSDEV)}$ are determined by IPTO.

Computational method for $NADEV_{(p,m)}$:

$$ADEV_{(p,m)} = \sum_{t\ m} |DEV_{(p,t)}| \quad (5)$$

is the absolute deviation within the month MTU m.

$$NADEV_{(p,m)} = \frac{ADEV_{(p,m)}}{\sum_{t\ m} MQ_{(p,t)}} \quad (6)$$

is the normalized absolute deviation within the month MTU m.

Computational method for $NRMSDEV_{(p,m)}$:

$$RMSDEV_{(p,m)} = \sqrt{\sum_{t\ m} (DEV_{(p,t)})^2} \quad (7)$$

is the Root Mean Square (RMS) value of Deviations within the month MTU m.

$$NRMSDEV_{(p,m)} = \frac{RMSDEV_{(p,m)}}{\sqrt{\sum_{t\ m} (MQ_{(p,t)})^2}} \quad (8)$$

is the normalized $RMSDEV_{(p,m)}$ within the month MTU m.

For the calculation of Equations (4)–(7) the understanding of the below values is crucial:

1. UNCBAL_ADEV is the unitary charge corresponding to non-Compliance Charges to Suppliers for the normalized monthly absolute deviation.
2. UNCBAL_RMSDEV is the unitary charge corresponding to non-Compliance Charges to Suppliers for the normalized monthly RMS value of deviations.

3. $TOL_{ld,ADEV}$ is the tolerance margin for imposing non-Compliance Charges on Suppliers for the normalized monthly absolute deviation.
4. $TOL_{ld,RMSDEV}$ is the tolerance margin for imposing non-Compliance Charges on Suppliers for the normalized monthly RMS value of deviations.

These quantities are determined by RAE following a proposal by Hellenic Electricity Transmission System (HETS) Operator.
Computational method of $NCBAL_{p,m}$:

$$NCBAL_{p,m}=\max\left\{(UNCBAL_{ADEV}\times ADEV_{p,m})\times(NADEV_{p,m}-TOL_{ld,ADEV}),\ (UNCBAL_{RMSDEV}\times RMSDEV_{p,m})\times(NRMSDEV_{p,m}-TOL_{ld,RMSDEV}),\ 0\right\} \quad (9)$$

For dispatchable and non-dispatchable RES portfolios, additional tolerance is implemented as TOL_{r,DEV_NORM}. The tolerances $TOL_{r,ADEV}$ and $TOL_{r,RMSDEV}$ are calculated in a similar manner as for conventional portfolios.
Computational method for $NRMSDEV_{p,m}^{NORM}$:

$$RMSDEV_{p,m}^{NORM}=\sqrt{\sum_{t\in m}\left(DEV_{p,t}^{NORM}\right)^2} \quad (10)$$

is the Normalized Root Mean Square (RMS) value of Deviations within the month MTU m.

$$NRMSDEV_{p,m}^{NORM}=\frac{RMSDEV_{p,m}^{NORM}}{\sqrt{\sum_{t\in m}\left(MQ_{p,t}^{NORM}\right)^2}} \quad (11)$$

is the normalized $RMSDEV_{p,m}^{NORM}$ within the month MTU m.
In addition to the above quantities, $ANDEV_{p,m}^{NORM}$, the normalized absolute monthly deviation of RES Units Portfolios in normal operation represented by the Balance Responsible Party p for month m, also plays a significant role.

$$ANDEV_{p,m}^{NORM}=\frac{DEV_{p,m}^{NORM}}{\sum_{t\in m} MQ_{p,t}^{NORM}} \quad (12)$$

At the same time, additional tolerance is added to the solution in the form of an additional constraint, where

$$ANDEV_{p,m}^{NORM}<TOL_{r,DEV\_NORM} \quad (13)$$

The calculation method for $NCBAL_{p,m}$:

$$NCBAL_{p,m}=NCBAL_{C1_{p,m}}^{NORM}+NCBAL_{C2_{p,m}}^{NORM} \quad (14)$$

where,

$$NCBAL_{C1_{p,m}}^{NORM}=\max\left\{(UNCBAL_{ADEV}\times ADEV_{p,m}^{NORM})\times(NADEV_{p,m}^{NORM}-TOL_{r,ADEV}),\ (UNCBAL_{RMSDEV}\times RMSDEV_{p,m}^{NORM})\times(NRMSDEV_{p,m}^{NORM}-TOL_{r,RMSDEV}),\ 0\right\} \quad (15)$$

$$CBAL_{C2_{p,m}}^{NORM}=\begin{cases}(UNCBAL_{DEV}\times DEV_{p,m}^{NORM})\times(1-TOL_{r,DEV}), & \text{if } ANDEV_{p,m}^{NORM}>TOL_{r,DEV\_NORM}\\ 0, & \text{if } ANDEV_{p,m}^{NORM}\le TOL_{r,DEV\_NORM}\end{cases} \quad (16)$$

Furthermore, non-compliance charges do not apply to the Supplier of Last Resort, as defined in the relevant regulation. The non-compliance charges are only implemented in Greece, acting as an additional charge to the imbalance charges. The main issue with the introduction of non-compliance charges is that the power output of non-dispatchable RES can only be forecasted and estimated, but never accurately predicted. Combined with the lack of storage technologies, either being short or long term, non-dispatchable RES portfolio participants are facing huge non-compliance charges.
Another important issue that will become apparent in the following period in Greece is the electricity storage requirements to support the transition towards high renewable penetration levels. Currently, IPTO implements the Integrated Scheduling Process (ISP) for the Balancing Capacity Market. This process aims to compel the required Balancing Capacity needed in the short term while ensuring the schedule is in line with the technical constraints of the HETS and the Balancing Service Entities. In practice, IPTO keeps some capacity reserves for quick response for introducing additional energy generation. Currently, only conventional quick response plants can be implemented. Another usage of the reserves is for additional energy consumption during peak RES production hours with low consumption periods. Essentially, IPTO keeps capacity reserves that can generate ad hoc the required energy or limit their energy consumption to keep the grid in balance (ancillary services).
The Balancing Energy Market has the responsibility of determining quantities and prices for the activation of the Balancing Energy by the Balancing Service Providers, considering both the Market Schedule and HETS's real-time state. Two main processes take place in the Balancing Energy Market, manual Frequency Recovery Reserve (mFRR) and automatic FRR (aFRR). Through the mFRR process, IPTO estimates in close to real time whether upwards or downwards activation of the mFRR is mandatory. After the type of mFRR is determined, relevant Dispatch Orders per time unit (15 min) are issued. On the other hand, in the aFRR process, real-time automatic Dispatch Orders to the Balancing Service Entities are issued. This process takes place with a frequency of 4 s, through the Automatic Generation Control Function.
The determination of entities occurring in the BM is conducted through a bidding competition for mFRR and aFRR processes, distinctly per direction. Regarding the remuneration for entities for the activation of mFRR Energy, which is implemented for purposes other than balancing, it supports the pay-as-bid principle and considers the activated offer steps in the related direction, while the reimbursement of entities for the activation of aFRR Balancing Energy is dependent on upward or downward activation.

- For upward activation, the greater value between the price for upward Balancing Energy for mFRR and the price of the Balancing Energy Offer for aFRR arranged by the Balancing Service Entity, matching the quantity of upward Balancing Energy activated for aFRR.
- For downward activation, the inferior value between the price for downward Balancing Energy for mFRR and the price of the Balancing Energy Offer for aFRR arranged by the Balancing Service Entity, matching the quantity of downward Balancing Energy activated for aFRR.

Contracted Balance Responsible Parties are assessed. A single Imbalance price per settlement is established. The calculation process is the weighted average price of the activated Balancing Energy in the predominant direction (upward or downward) for mFRR and aFRR for the specific Imbalance Settlement Period. The Settlement Procedures are issued for the first time one week after real-time procedures and are performed on a weekly basis. Finally, the Settlement includes Balancing Energy Settlement, Balancing Capacity Settlement and the Imbalance Settlement.

5. Conclusions

The introduction of the Target Model in Greece was anticipated to enhance cross-border trading, lead to more competitive electricity prices and lower emissions. Yet, the huge penetration of RES poses several challenges for the wholesale electricity market, such as increased price volatility and massive curtailments in generation. This issue is mainly attributed to the oversaturation of photovoltaic generation bringing prices close to zero or even negative during daylight hours. In contrast, increased prices are evident dur-ing night hours accompanied by lower production from photovoltaic plants and increased demand. This inverted supply–demand relationship is seeking means of storage to exploit the remaining and curtailed renewable energy. Eventually, this would directly lower the price volatility and smoothen the price curve during the day. In that sense, aiming to avoid the curtailment of renewable generation, the installation of storage units along with mas-sive investments in the upgrade of grid interconnection are vital.

This paper provides an extensive overview of the market design and formation of the Target Model in the Greek wholesale electricity market. Our analysis investigates the spot market structure by highlighting the architecture of the different markets. Furthermore, the Balancing Market along with the corresponding non-compliance charges are scrutinized. Additionally, the foremost contribution of our study is the detailed description of the re-cent support mechanism to facilitate the integration of BESS into the system. This is broadly considered by market participants as a key policy incentive enabling cost recovery for storage.

Future research should be directed towards the assessment of the regulatory frame-work to ensure compliance with the EU Directives along with a dynamic sensitivity anal-ysis on key parameters. Furthermore, related to policy implications, aiming to address grid congestion caused by the rapid penetration of RES, a fast-track approval process for new transmission lines and interconnections should also be considered.

Author Contributions: Conceptualization, E.N., F.I., K.K. and K.A.; Methodology, E.N. and F.I.; Software, E.N.; Validation, F.I.; Formal analysis, E.N., F.I., K.K. and K.A.; Investigation, E.N.; Re-sources, E.N.; Data curation, F.I.; Writing—original draft, E.N.; Writing—review & editing, E.N., F.I. and K.A.; Visualization, E.N. and F.I.; Supervision, F.I., K.K. and K.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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

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In-depth Research

Improving Energy Security through Electricity Storage in Open and Semi-Open Markets

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Overview

The current view holds that an increasing variable renewable energy (VRE) share creates a problem for energy security due to the non-dispatchable nature of VRE. This paper shows under what conditions electricity storage can become a solution to this issue. It first recalls the four pillars of energy security, of which storage is one of them, and analyses some important framework conditions for independent or economically profitable storage to develop. The theoretical background analysis of the spot and futures market is put in relation to storage. The paper shows under what conditions day-night and seasonal storage can be profitable, and why other forms of storage such as long-term strategic storage can for the moment not be profitable. The paper then analyses market conditions of 10 open or semi-open electricity markets and assesses in which of them independent or profitable storage is likely to develop. Thereafter, the paper describes the potential contribution of storage to the ancillary market, focusing on primary, secondary and tertiary power regulation. The paper argues that one of the factors of the 2025 Iberian blackout may have been the prohibition of PV to contribute to primary regulation, combined with insufficient storage. The paper shows why hydropower storage without pumping is the least cost solution for the regulatory power supply. PV-production combined with storage can possibly also be a low-cost supply. The paper also shows why the supply of regulatory power should be strictly separated from commercial markets. It then touches on the potential to develop an over-the-meter market involving prosumers. It concludes with recommending some measures to favour storage in both, open and semi-open markets.

Energy Security in a Renewable Electricity Context

Energy security can be defined as the absence of power outages. In a world powered to a large extent by renewable energy, energy security depends on four pillars:

- Sufficient renewable electricity generation: In a power grid with a high proportion of intermittent energies, sufficient installed renewable energy capacity is especially important. Only energy that has been produced can be stored. In the Asia-Pacific Economic Cooperation APEC, e.g., the renewables share in TPES has increased from 4.79% to 7.32% and the renewables share in TFC from 6.02% to 9.51% between 2010 and 2020, the renewables share in electricity from 15.58% in 2010 to 24.69% in 2020[1], whereas the share of installed renewable capacity in total installed capacity increased from 20% in 2010 to 38% in 2022[2].
- Sufficient before-the-meter-storage capacity, including long term storage, seasonal storage, disaster-related storage and strategic storage: Storage is the key factor to bridge the time gap between generation and load. According to IRENA[3], pumped hydro storage (PHS) was the largest single source of electrical storage capacity in the world in 2017, comprising 4.67TWh or 169GW of installed storage capacity, accounting for 96% of global installed capacity of which half was in three countries China, Japan and the US. A recent Workshop on PHS[4] identified around 10,200TWh unused PHS potential, sufficient to store total annual final energy consumption of 221000PJ[5] (or 61390TWh) for about 60 days. The location of PHS storage is, however, not optimal as storage should ideally be located near load centres to increase energy security. Keles and Holland (2021)[6] show that it may be profitable to locate storage at renewable production sites. IRENA, in the quoted report, expects battery energy storage (BES) to increase by at least 17-fold by 2030. COP29 held in November 2024 in Baku, Azerbaijan[7], pledged to deploying 1,500 GW of energy storage in the power sector globally by 2030, more than six times the level of 2022.
- Sufficient transmission capacity: Transmission capacity is the key factor to overcome the distance between generation, or far away storage, and load centres. Transmission capacity is e.g. required to use the complementarity between solar energy and wind energy which are usually located in different geographical locations. COP29 pledged to adding or refurbishing 25 million kilometres of grids by 2030[8]. Interconnecting e.g. archipelago or islands (Greece, Croatia, Indonesia, Japan, New Zealand, the Philippines, Papua New Guinea, Taiwan) is a special challenge requiring subsea cables at higher cost than for land-based transmission.
- Sufficiently well informed and forward-looking or smart consumers: Consumers may have the technical means to manage their own energy security by installing behind-the-meter-batteries. If this generalizes, electricity becomes a storable good similar to other consumer goods. For zero carbon or positive energy settlements, behind-the-meter-batteries are a must, often within microgrids. Such batteries are usually small-scale day-night storage devices, but if they are installed in big numbers, they may have an impact on the grid. Behind-the-meter-batteries may have a positive impact on grid stability, or may, on the contrary, pose a threat to the electricity grid if consumers get into panic because of (mis)information about a (supposedly) coming supply crisis driving them to hoard storable goods. The market dynamics observed on markets of non-perishable commodities having a cost of carry may occasionally go from normal markets to inverted[9] (or panic driven) markets. This may in future also be the case of electricity markets.

Theoretical Elements Underlying the Commercial Viability of Storage

This section develops some theoretical elements related to the commercial viability of electricity storage and answers the question how independent electricity storage operators can contribute to support the development of renewable energy. The focus on independent operators goes beyond the purely technical questions of how much storage is needed to achieve a wanted energy security level. Such wanted energy security level can be defined as storage-to-consumption ratio, expressed e.g. in number of consumption days of the wanted storage, and implemented in electricity planning. But the question raised in this section is, whether the wanted storage will be commercially feasible, so that it becomes commercially interesting, either for an independent storage operator to invest and start storage operation, or for an integrated grid system operator to invest in storage as a profit (as opposed to a loss) centre.

The primary source of revenue for a storage operator is the buyer-seller price difference. For e.g. a short-term day-night storage operator, the relevant price difference is the day-night price difference. This is normally traded in the tomorrow-next markets. During sunny or windy days, generation may be higher than load, so that the prices can come down to zero (or even become negative[10], leading to curtailment[11]). At this moment the storage operator ideally can fill up storage to be released in after sunset. Let Pin be the buying price and Ein the corresponding energy stored by an operator during daytime and Pout the selling price and Eout the corresponding energy sold by the operator after sunset. Variable cost is then given by $P_{in} E_{in}$, and revenue by $P_{out} E_{out}$. The commercial viability condition for this most simple storage case can be stated as follows:

$$P_{in} E_{in} \le P_{out} E_{out}, \quad \text{where all terms} \ge 0 \qquad (1)$$

By adding gross margin Mg, this inequality can be written as equality:

$$P_{in} E_{in} + M_g = P_{out} E_{out}, \quad \text{where } M_g \ge 0 \qquad (2)$$

Operators producing below this gross margin condition accumulate immediate short-term losses that are very difficult to cover in the long term. Defining now the variable cost C_v as:

$$C_v = P_{in} E_{in} \qquad (3)$$

and expressing fix cost C_f as a proportion of variable cost:
$C_f = c_f \; P_{in} E_{in}$ (4)

and total cost C_{tot} as a function of variable cost:
$C_{tot} = P_{in} E_{in} (1+c_f)$ (5)

inequality (1) becomes:
$P_{in} E_{in} (1+c_f) \leq P_{out} E_{out}$, where all terms ≥ 0 (6)

Defining Mn as net margin, then equation (2) transforms to:
$P_{in} E_{in} (1+c_f) + M_n = P_{out} E_{out}$ where $M_n \geq 0$ (7)

Inequality (6) and equation (7) state the net margin condition. Operators producing below this net margin accumulate mean term and long-term losses due to undercovering fix costs. This may happen from time to time provided that the gross margin condition in (1) and (2) is always satisfied and that the net margin condition in (6) and (7) is satisfied in average over the mean and long term. The net margin condition of inequality (7) can be rewritten in a different form:
$P_{out} E_{out} - P_{in} E_{in} (1+c_f) \geq 0$, where all terms ≥ 0 (8)
Inequality (8) can be transformed to show the dependency between cost and price ratios and energy efficiency:
$(P_{in} (1+c_f))/P_{out} \leq E_{out}/E_{in}$, where all terms ≥ 0 (9)
The ratio between total cost and selling price must be smaller than the roundtrip energy efficiency ratio of the storage system. It is now worthwhile looking at the efficiency ranges of common storage technologies[12].

ESS Type	Technical Maturity	Efficiency Ranges (%)
Pumped Hydro	Mature	65–85%
Compressed Air	Developed	40–65%
Lithium-ion Battery	Mature	85–95%
Zn-air Battery	R&D Demonstration Commercial	~50%
Redox Flow Batteries	Developed	60–85%
Hydrogen Storage	R&D Demonstration Commercial	30–70%
Ammonia Storage	R&D Demonstration Commercial	30–70%
Reversible Fuel Cell	R&D Demonstration Pre-commercial/commercial	50–70%
Super Magnetic Storage	R&D Demonstration Pre-commercial	90–95%
Super Capacitor	R&D Demonstration Pre-commercial	90–95%
Hot Water Storage	R&D Demonstration Commercial	20–90%
Molten Salt Thermal Storage	R&D Demonstration Commercial	30–95%

Fig. 1: Energy storage types, technical maturity and efficiency ranges (%)
Source: Manal AlShafi, Yusuf Bicer (2021)

From equations (1) to (9) it can be inferred that highly efficient technologies with roundtrip efficiencies over 80% can be commercially profitable even if the cost-price spread is small. Conversely, a small cost-price spread will exclude those storage technologies from commercial viability that show insufficient roundtrip efficiency. Inequality (9) can be transformed to express a condition linking the selling price to the buying price and fix costs and inverse roundtrip efficiency:
$P_{out} \geq P_{in} (1+c_f) \; E_{in}/E_{out}$, where all terms ≥ 0 (10)

We introduce now the price elasticity of demand defined conventionally as:
$PE_d \; (((E_{in}-E_{out}))/E_{in})/(abs(((P_{in}-P_{out}))/P_{in}))$

Applied to the day-night storage market, the subscript "in" is interpreted for "day", and the subscript "out" is interpreted for "night", so that the elasticity expresses the day-night price elasticity of demand. From equations (1) to (9), it is immediately evident that for a given efficiency loss rate $((E_{in}-E_{out}))/E_{in}$, the absolute value of the corresponding price increase rate $abs(((P_{in}-P_{out}))/P_{in})$ must be greater or equal than this efficiency loss rate to satisfy the viability condition (1). This means, that consumers must be ready to consume electricity and pay for it during evenings and nighttime in spite of relatively higher prices. This illustrates the sometimes-forgotten truth, that fundamentally, the commercial viability of storage depends on consumers and is paid by them.

The above is valid without considering fix costs. If fix costs are introduced, the above can be spelled out as:
((E_in-E_out))/E_in ≤ abs(((P_in (1+c_f)-P_out))/(P_in (1+c_f))) (11)

Graphically this can be illustrated in the figure below which is interpreted as follows: With a given efficiency loss rate of ((E_in-E_out))/E_in , the storage operation is profitable as long the day-night elasticity of demand to that operator is less than unity. In the figure below, this is the case as long as P_out≥P_outcritical. The figure shows the family of lines of unit elasticity of demand.

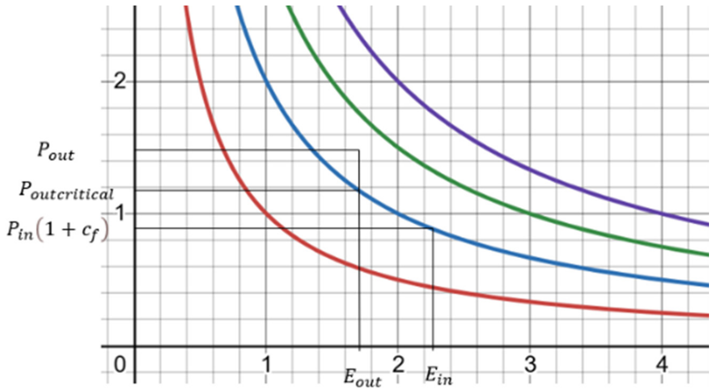

Fig. 2: Quantity-price condition for day-night profitability of storage
Source: The author (using Desmos graphic calculator)

To illustrate this, take an example from a market where the prices are set for each hour of the next day. It is well known that the Nordic market sets not only an hourly general systems price, but also a different hourly system price for each one of its balancing zones, depending on the hourly supply-demand balance and interconnection capacity of each zone. Taking e.g. the zone around Copenhagen (DK2), the price chart of 30 November shows that a day-time price of around 40EUR/MWh, caused by a high share of solar, contrasts with evening and night prices of 100EUR/MWh and above, allowing for margins of well over 150% which is an attractive environment for storage.

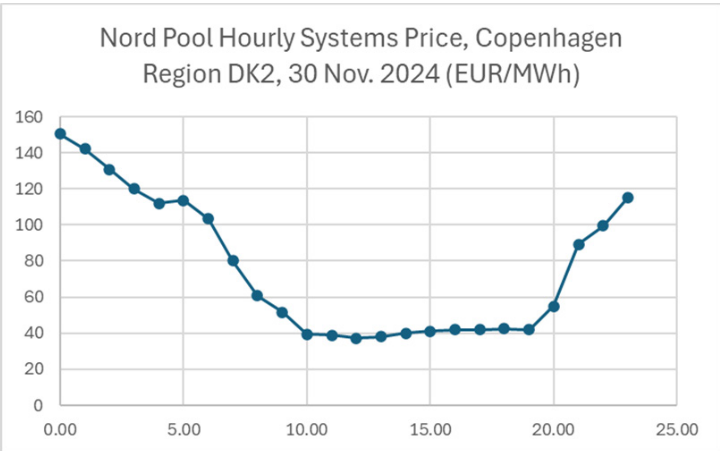

Fig. 3: Hourly price chart of the Nord Pool region DK2, Copenhagen, 30 Nov 2024
Source: The author, based on data from Statnett

The above formulae (1) to (11) may in principle describe the short term as well as the long-term storage, depending on what is included or not under fix cost c_f. If c_f includes mainly wages and taxes, the formulae apply to the short-term market (e.g. daily storage). If c_f also includes interests, these formulae describe long term storage (e.g. annual storage). The futures market is the type of market where the long-term is being traded. On a futures market, agents conclude futures agreements today for delivery of a certain amount of the commodity E_(out 0,T) at a specified time (T) and place in the future. The future price of electricity is the price agreed by a seller and a buyer in a contract concluded today (t=0) for delivery of the commodity at a later date (t=T). The time intervals may range from a minimum of 1 month to 5 – 10 years (60 – 120 months) ahead. To describe the future market, future prices agreed today (t=0) for delivery at time t=T will be noted as F0,T, replacing the short time storage prices P_out of earlier equations. It is common knowledge that the future price of any commodity at time T (F0,T) depends positively on the spot price of this commodity at the present time 0 (P_(in,0)) and the risk-free interest rate (r).

$F_{(0,T)}=P_{(in,0)} e^{rT}$ (12)
This relationship can be derived easily by showing that any other future price level ($F_{0,T}$) of the commodity, given its spot price ($P_{(in,0)}$), would allow agents to make illimited profits, a situation that would be immediately corrected by arbitrage.

If a commodity, like e.g. electricity, needs to be stored and incurs fix storage cost C_f, this formula becomes:
$F_{(0,T)}=(P_{(in,0)}+C_f)e^{rT}$ (13)

It is sometimes preferable to express the storage cost as the corresponding continuous compounding yield, noted c_f, and include it into the exponent:
$F_{(0,T)}=P_{(in,0)} e^{(r+c_f)T}$ (14)

In a more general case, the formula expressing the future price of seasonal commodities such as electricity, gas and oil, is more complicated. It does not have be developed here in detail as the results can be taken from other sources . The figure below shows the future electricity prices actually observed on 30 March 2012 UK Base Electricity Futures at the Intercontinental Exchange (ICE, London). The quoted study is based upon 26,057 empirically observed prices. The blue line shows actual price quotations, the red line their theoretical estimates and the green line the de-seasonalized trend. According to the theory, one would expect a slightly exponential growth of the green line rather than a linear growth. Probably the estimation would also fit an exponential growth (shown by the added black line), had the authors wanted to fit the data to exponential growth (in spite of the increased difficulty to find a sufficiently good estimator for this highly non-linear case). Remark that in the Northern Hemisphere, a seasonal minimum price is found at the end of March and a seasonal maximum price in December, whereas on markets around the Equator, such as at the Singapore quarterly, a seasonal maximum is observed in September at the beginning of the typhoon season.

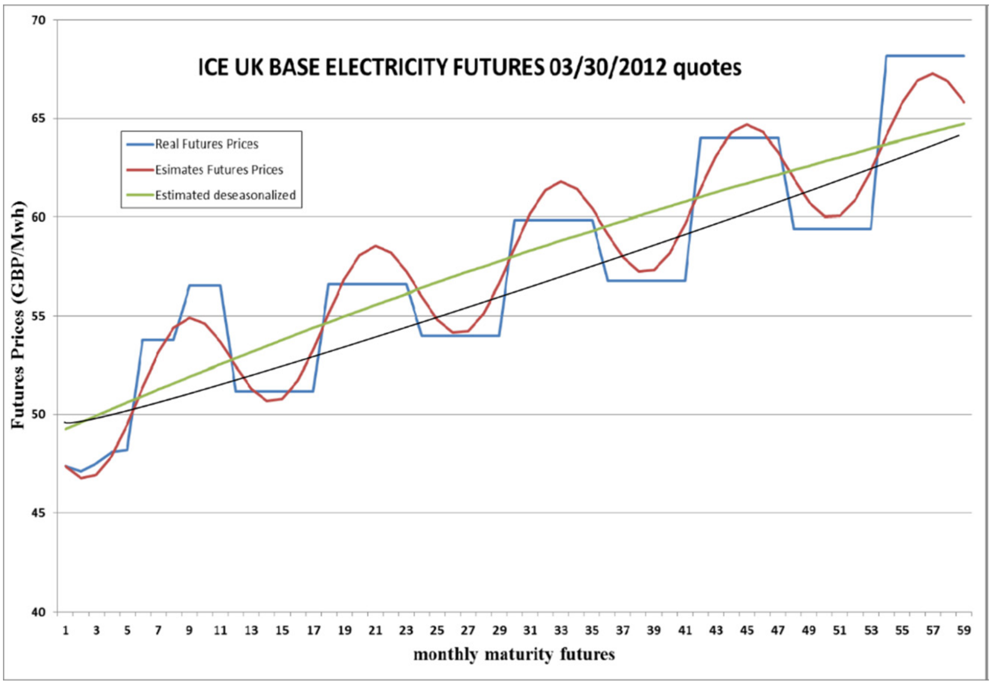

Fig. 4: Real and estimated 60-month futures prices of the UK, 30 March 2012
Source: Abadie and Chamorro (2014), adapted by the author

The green trend line shows that on this future market, the buyers pay around 30% storage premium (from around GBP50 to around GBP65) over 60 months, or around 6% per year, of which part of it is due to the (annual) risk-free interest rate r = 2.05%, which corresponds to the 10-year UK government debt in January 2012, and the other part, i.e. around 4% per year, is due to storage costs. 4% for storage cost other than interest is too little to be profitable as hardly any storage technology can be found having a roundtrip efficiency loss rate of 4% (see inequality 11). For a long-term multiannual storage market, commercial viability does not look good.
Viability looks better for an annual storage market. According to the above figure, an operator could have bought a 9-month future contract in March 2012 for GBP 47 with maturity in December 2012 for GPB 57. The absolute value of the price increase rate is 21,3%, of which 1.54% is due to risk-free interest over 9 months. The remaining just under 20% allows for storage technologies having a roundtrip efficiency loss rate of less than 20%, bearing in mind that wages and taxes still have to be included in this margin. It is better than the multi-annual storage market, but still hardly sufficient for today's technologies.

The point made here is that it is favourable for the storage market to introduce a futures market that allows market operators to hedge against price fluctuations happening between now (t=0) and the maturity (t=T). A large producer or storage operator requiring high stable prices will sell electricity today on the futures market to hedge against falling prices. A big industrial or services enterprise requiring low stable electricity prices will buy electricity today on the futures market to hedge against price increases. The futures market allows having contractually guaranteed future prices. The larger share the futures market has in the total market, the more the futures market contributes to make the price evolution foreseeable. Futures markets are a necessary, or at least a highly welcome tool to facilitate storage. Futures markets are traded in highly liquid exchanges (as opposed to over-the counter markets) and delivered physically, at a specified future place, date and quality . In futures markets, both parties (buyer and seller) have the obligation to buy/sell the underlying asset at the predetermined price on the expiration date. The gains and/or losses made from the operator's futures positions are debited/credited by the clearing house to the operator's account in cash after each trading day, meaning that the so-called settlement of futures contract is usually by cash[20].
While futures market in their "normal" state (see further down) favour storage, the inverse can also be said: sufficient long-term storage capacity will allow the futures market to have the above shape and be profitable. If the offered long-term storage capacity or the offered long-term storage duration is limited, the price shape of the futures market may flatten (or it may even come down) for the period beyond the offered storage duration. The figure below shows the natural gas futures settlement price on 7 July 2023, for the period starting in August 2023 and ending in December 2035, where the curve is flattening beyond about 30 months ahead, beyond which not yet produced gas is stored in underground storage for free.

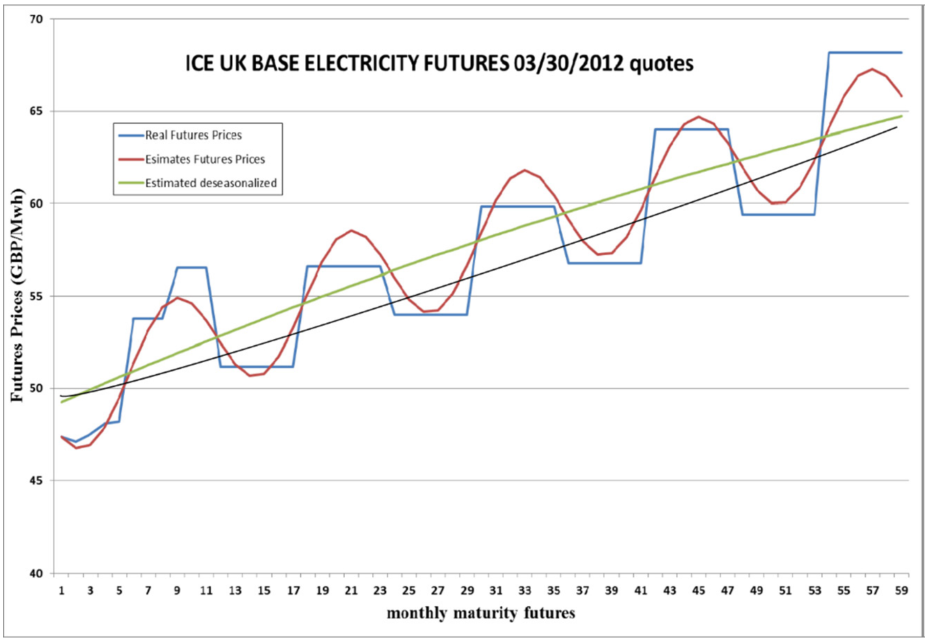

Fig. 5: Futures price of natural gas August 2023 to Dec 2035
Source: The author, based on Diversegy (2023)

The above figure shows the situation in a normal market. A normal market or carrying-cost market is called a "contango"[22] market. Normal futures markets are characterized by the fact that the future price $F_{(0,T)}$ is higher than the spot price $P_{(in,0)}$ (see equation 14). This implies also that the future price of this contract will gradually diminish as the contract approaches maturity, following the so-called contango price process, converging at the level of the spot price $P_{(in,T)}$ at time T: $F_{(0,T)} \geq F_{(1,T)} \geq F_{(2,T)} \geq \ \geq F_{(T,T)} = P_{(in,T)}$. This contango price process prevails if the spot prices drop or are stable during the maturity period $P_{(in,0)} \geq P_{(in,T)}$. The contango price process can also exist in a moderate increase of the spot price during the maturity period; many authors associate contango with upward expectations of prices. As contango pays for storage cost, storage will be filled up during contango.
The opposite market situation called "inverted" market. An inverted market occurs if an unexpected event (natural disaster or other market disturbance) happens during the maturity period. This creates a supply disruption with unsatisfied demand, leading to a sudden price shock at e.g., period t=7 (blue line in the above figure), with $P_{(in,7)} = P_{(in,0)} + \sum_{t=1}^{t=7} \Delta P_t$. Instead of the expected price drop at t=7, the price rises to $P_{(in,7)}$. The price rise benefits those agents who hold the physical good, whereas those who hold a future contract are relatively penalized, resulting in a negative sign in the expression of the future price that had been concluded at time (t=0), so that equation (13) becomes

$$F_{(0,T)} = \left(P_{(in,0)} + C_f - \sum_{t=1}^{t=7} \Delta P_t\right) e^{rT} \quad (15)$$

If the penalty is expressed as a so-called loss of convenience yield $\Delta p=\sum_{t=1}^{t=7} \Delta P_t$ and taken into the exponent, this becomes, similar to equation 14:

$$F_{0,T}=P_{in,0}\, e^{(r+c_f-\Delta p)T} \quad (16)$$

If this price increase is sufficiently large, we get a situation in which the new spot price $P_{in,7}$ exceeds $F_{0,T}$ so that, for most of the periods t=1…T, we have $P_{in,7}>F_{0,T}$, which is a situation of "inverted markets". Inverted markets are characterized by the fact that the future price $F_{0,T}$ is lower than the spot price $P_{in,7}$, meaning that demand today is stronger than expected demand in the future. An "inverted" market does not pay for storage but instead incentivises storage holders to empty their storage to satisfy the unsatisfied demand[23].
One of the conditions of a prosperous storage market is that storage is sufficiently large to avoid that the market falls into an "inverted market", given that both happen under the effect of seasonal or disaster-related fluctuations or simply of "bad news". If there is sufficient storage, the market is less likely to fall into the state of "inverted market". The less well the agents are prepared to face supply disruptions by holding storage, the bigger the price shock. In the ideal world where all market participants are fully prepared to face any supply disruption by holding corresponding storage, a disaster or similar event becomes an expected event that causes neither supply disruption nor price shock. In the real world, some agents are always unprepared to face a supply disruption. Concerning the terminology, the oil and other commodity markets use the term "backwardation" to describe the "inverted market". For historical reasons[24], many authors still call this situation "normal backwardation" despite the fact that the normal or most often prevailing market situation is in fact the "contango" market[25], and that the "inverted" or "backwardation" market prevails less often and usually in exceptional situations.
The right-hand side of equation (14) can be interpreted as levelized cost of renewable electricity including storage and systems cost (LCOESST). It has been shown[26] that LCOESST has a trend to diminish in time due to learning curves. Within the next three to four years, the unsubsidized levelized cost of renewable electricity including short term storage and systems cost (LCOESST) is expected to be the cheapest energy form in practically every part of the world (see figure below). The levelized cost is the reference cost for large-scale electricity generation. This development might favour renewable electricity storage technologies that up to now have still a too low roundtrip efficiency, provided P_{out} does not decline at the same speed as the LCOESST.

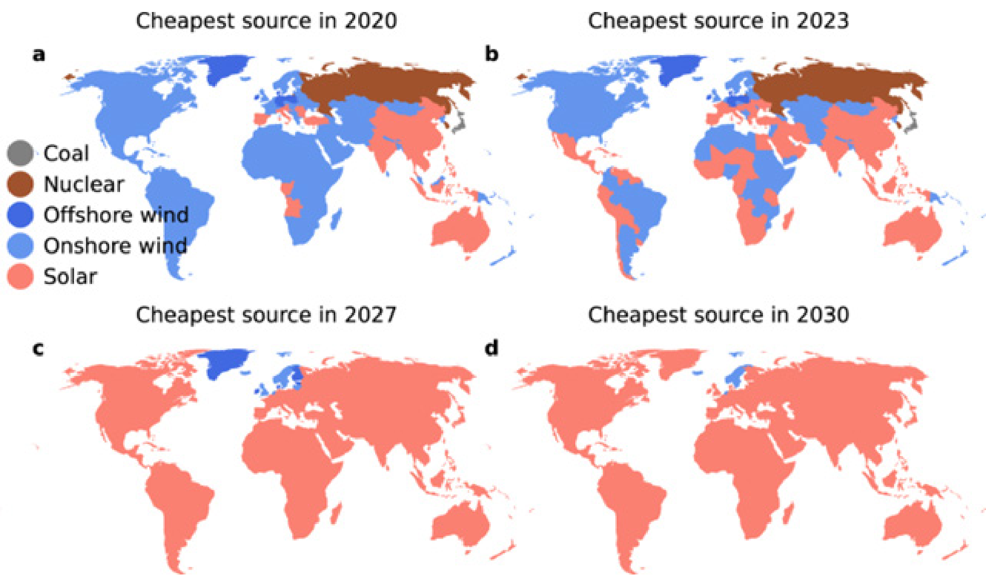

Fig. 6: Technology with the lowest LCOEssc by year and region
Source: Femke J. M. M. Nijsse (2024)

Application to Selected Electricity Markets

This section applies the above theory to selected electricity markets and analyses them for their capability to favour a storage market. A first requirement is that a storage market is part of a wholesale or retail market. This, in turn, requires wholesale or retail markets to exist in first place.
Electricity markets have not been reformed or liberalized to favour electricity storage, but to improve economic efficiency (i.e. diminish electricity prices) and to attract private sector investment[27]. To the extent that independent storage operators fall under the category of private sector investment that is to be attracted, reformed electricity markets can fulfil the task of favouring storage. However, the way how markets attract storage investors is not necessarily by their theoretical or practical degree of openness, nor by the existence of an electricity futures market.

For a market to be a good market for storage, it is sufficient that the market offers a sufficient price spread to attract private investors (even if that market may involve administrative price setting, hence not be completely competitive). On the other hand, a market may be wholly competitive without offering sufficient price spreads to attract storage investors. Both will be exemplified further down.
Even though market openness is not the main criteria for attracting storage investors, the discussion needs to include some remarks about market opening to be clear in substance. The World Bank has analysed the extent to which the developing world has implemented different elements of electricity sector reforms in the period 2005 – 2015. The World Bank study uses the following quantification metric for market openness:

Competition	Monopoly = 0	IPPs = 25	Single Buyer Model = 50	Bilateral Contracts = 75	Competitive market = 100

Table 1: Market openness quantification table
Source: World Bank (2017)

A study made in 2005 within the framework of CIGRE[29] mentions nodal priced markets as optimal pricing type and adds a further precision by considering liquidity as desired quality and defining liquidity as the part of electricity traded through power pools relative to the total electricity consumption. Korea and Australia have highly liquid markets as they trade 100% of their electricity on mandatory centralized power pools, whereas the Nordic Scandinavian market is less liquid and trades only 30% through a voluntary pool and the rest through bilateral contract markets (OTC). The Philippines is even much less liquid as spot market transactions in WESM make up only about 8.2% or about 5.2 TWh in 2015, while the rest are through bilateral contracts (BCQ) and distributors transacted even less on the spot market, opting instead for long-term contracts[30]. The mentioned World Bank study finds that up to 2015, only 20% of developing countries have implemented competitive power markets. Developing countries having implemented competitive power markets are e.g. the Philippines, Peru, China and Mexico. For Viet Nam, Malaysia, Thailand, and Indonesia, the World Bank study finds that power markets are not fully competitive.
Viet Nam is an interesting case for studying the market potential for storage. Viet Nam has introduced a wholesale power market (VWEM) in 2019[31]. Foreign investors can now participate in BOT schemes while domestic investors use the IPP scheme, both under the Single Buyer Model[32]. Wholesale and retail prices are set by decree . The example of Viet Nam shows that in an electricity market, in which prices are set by law or decree, day-night storage can be sufficient to achieve commercial viability. In Viet Nam, the day-night price difference exists in retail markets, except for residential uses, but not on wholesale markets where in general there is no day-night differentiation, except at wholesale markets at industrial zones and industrial clusters (i.e. transformer substations). The two tables below show the high voltage retail prices for production sectors as well as the medium voltage wholesale prices for transformer substations as examples, both offering 184% maximum margins.

1	**Retail electricity price for production sectors**	
1.1	**Voltage level from 110 kV and above**	
	a) Normal hours	1,728
	b) Off-peak hours	1,094
	c) Peak hours	3,116

8.2	**Wholesale electricity price at the medium-voltage side of the 110/35-22-10-6 kV substation**	
8.2.2	**Voltage level from 6 kV to below 22 kV**	
	a) Normal hours	1,779
	b) Off-peak hours	1,155
	c) Peak hours	3,284

Table 2: Two examples of hour-dependent electricity prices in Viet Nam
Source: Lawnet.vn, 11. October 2024

In 2024, around 48% of electricity of Viet Nam originated from baseload coal and 8.5% from solar[34]. Viet Nam currently has only one 1200MW PHS (pumped hydropower storage) plant under construction and plans to double PHS capacity by 2030 and to add further 300MW BES (battery energy storage) by 2030[35]. The discussion on storage is at the moment under way.

The Philippines electricity system is composed of three physically separate grids in Luzon, Visayas and Mindanao, respectively with plans to interconnect them in the near future. In 2001, the Philippines has created a competitive wholesale market (WESM), which started operation in Luzon in 2006 and in the Visayas in 2010[36]. For each separate grid, information on battery charging and discharging power (in MW) is being published, along similar information from other energy sources[37]. Each grid has its own market price, but a central systems price is also formed at time intervals of 5 minutes in all three grids as well as in the central system[38]. However, the Philippines is often quoted for its high electricity prices. Philippines residential electricity prices are 132.22% of the world average electricity price and 247.86% of the average price in Asia[39], likewise, the shares of renewables dropped between 2008 and 2019 in spite of feed-in tariffs[40], casting doubt about the effectiveness of the electricity market reforms. In 2024, 62% of electricity of the Philippines originated from baseload coal, and only 3% from solar[41]. The picture below shows the systems price of the Philippines for 30 November 2024[42].

Fig. 7: Systems Price of the Philippines, 30 November 2024
Source: WESM Weekly Market Watch 25 Nov – 1 Dec 2024

In Japan, Japan Electric Power Exchange (JEPX) was established in November 2003 and commenced trading in April 2005[43]. The JEPX power exchange trades around 40% of all electricity traded in Japan. The spot market price for the tomorrow-next market is fixed at 30 minutes intervals. The futures market is still young and smaller in volume than the spot market. The Japanese power system is fragmented among 10 regional companies of which three are operating at the 50Hz and the others at 60Hz. DC links exist except for Okinawa. The figure below represents the system price chart for 30 November 2024[44] .

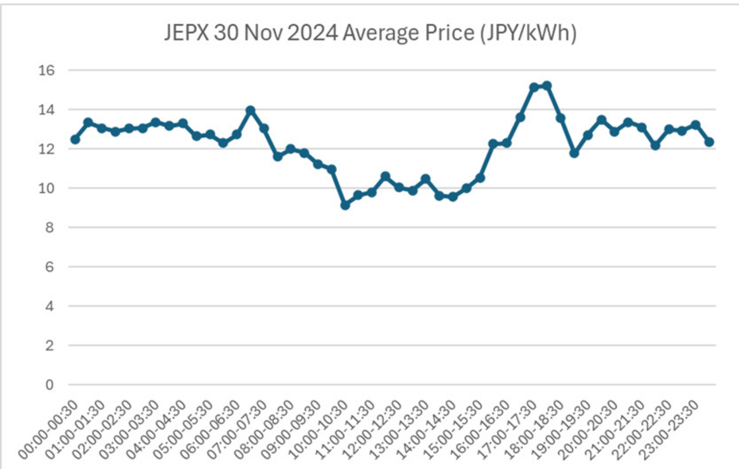

Fig 8: Intraday system price chart of Japan, 30 November 2024
Source: The author based on JEPX electric power market data intraday

The low-price level around 10JPY/kWh that prevails for around six hours from 9:00 to 15:00 contrasts with a peak price of 15JPY/kWh (offering 50% margin) which is, however, limited to about one hour in the late afternoon, followed by a nighttime price of around 13JPY/kWh (30% margin). The relatively narrow price spread might be due to the fact that the solar energy share is still low (around 10%, 2024), preventing the day price to fall sufficiently, while the baseload energy (oil, coal, nuclear) share is still high (around 43%, 2024)[45], keeping the night price too low, diminishing the profitability of storage. Both factors make large scale storage superfluous and diminish the price spread for storage. This might change once the share of solar grows, and the share of baseload diminishes consequently.

In Singapore, the Uniform Singapore Energy Price (USEP) is set at half-hour rhythm, fixing 48 prices every day. On 30 November 2024[46], the price has varied during the 48 half-hourly time intervals between approximately SGD80/MWh and SGD120/MWh, hence the absolute value of the price increase between the minimum and the maximum price is around 50%, allowing in principle for technologies with a roundtrip efficiency of up to 50% to be commercially viable, bearing in mind that fix costs such as wages and taxes also need to be included in this margin. A particularity of this market to have two peaks and two valleys per day: low prices between 2:00 and 5:00 in the night as well as from noon to early afternoon, and high prices in the morning and evening, respectively. Singapore produces 94% of its power from gas[47], which is easily interruptible at night hours, leaving the waste-to-energy (3% or 393 MW) as base load and price maker during the night. However, technology cannot explain the binary price curve. Energy storage systems make up 2% or 200 MW of the production mix, which are likely to produce electricity during peak hours.

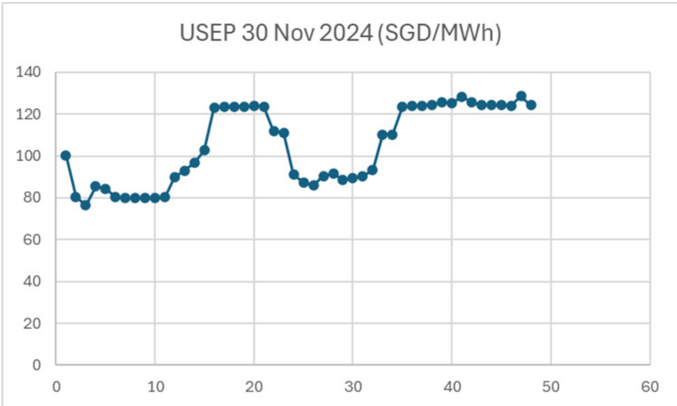

Fig. 9: Singapore half hour intraday prices, 30 November 2024
Source: The author based upon USEP data

In the US, electricity can be traded at more than two dozen trading hubs[48]. Taking as example the Southern California region SP-15 on 30 November 2024[49], the price chart shows daytime prices of around 30USD/MWh and 55USD/MWh in the evening, dropping to 45USD/MWh at nighttime, representing a margin of 83% or 50%, respectively. Price charts for other locations all over the US can show very different patterns. In California (2021), the share of non-fossil energy has reached 59%, with the share of solar photovoltaic (15.9%) exceeding the share of nuclear (10.8%), and energy storage attaining around 5GW with a plan to decuple energy storage by 2045[50].

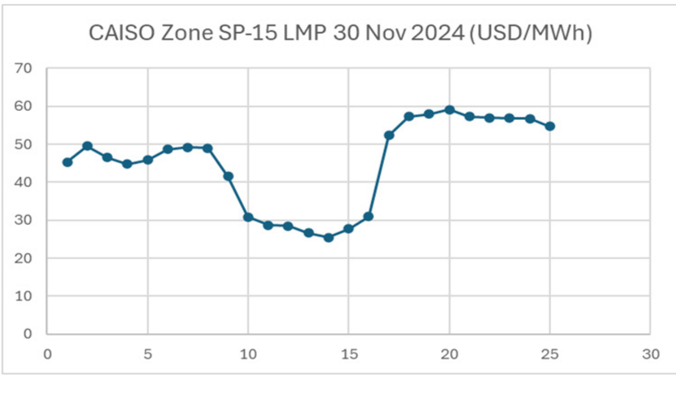

Fig. 10: Intraday price chart of the Southern California Region, 30 November 2024
Source: The author, based on CAISO data

The electricity system of Peru determines marginal prices at altogether 201 nodal market points. The picture of intraday prices may vary between these points, most of which share, however, low night prices and high day prices, characteristic for an electricity system with a low share of solar power (2%, 2024)[51]. The example of the intraday price chart of the westernmost city of Talara at the node Talara 13.2, on 30 November 2024 is shown in the figure below[52]. This market does not allow for a price spread that would favour storage of solar energy. However, the high daytime price offers good potential to develop solar energy production.

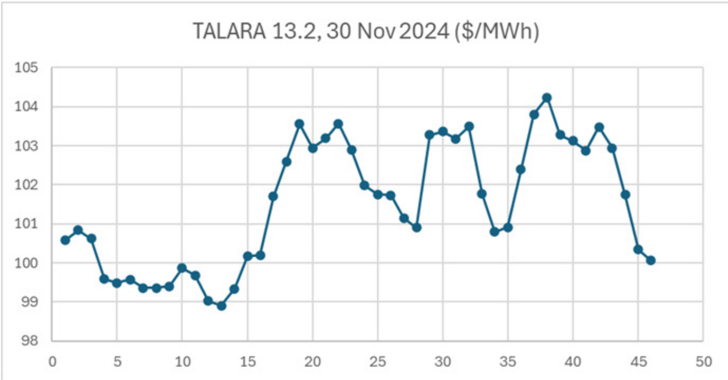

Fig. 11: Intraday price chart at node Talara 13.2., 30 November 2024
Source: The author based on Coes data

In Chile, the share of baseload coal has diminished to 16% (2024)[53], while solar (22%) and wind (12%) are rapidly growing, with hydropower reaching 30%. Chile is in rapid energy transformation which will see substantive decommissioning of fossil power combined with the commissioning of new solar power plants in the coming years, especially in the northern regions. Most of the electricity is supplied through long-term bilateral contracts[54]. The wholesale market only trades marginal quantities. This can be seen from the marginal cost data of the programmed operations as published by the Chilean transmission operator[55]. The 110 nodes whose hourly marginal costs are published usually all show zero cost between 9:00 and 19:00. This is a market imperfection which might be due to the facts that the Chilean transmission operator does not publish an hourly systems price, and that the wholesales market is only a small part of the total market which includes all OTC contracts. The figure below on the left shows the example of hourly marginal cost at the node Temuco 220, close to the town of the same name, on 30 November 2024. The right-hand figure shows the hourly programmed nationwide demand on that day. For an independent solar producer with storage, this information points to a reasonably good market condition, possibly tarnished by the narrow space offered by the existing bilateral OTC long term contracts against which any new market entrant has to compete.

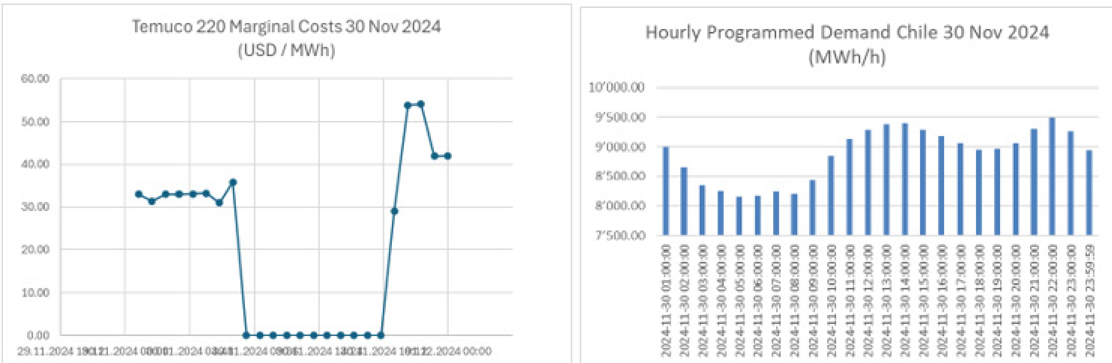

Fig. 12: (l) Intraday marginal cost at the node Temuco 220, Chile, 30 November 2024;
(r) hourly programmed demand of Chile, 30 November 2024
Source: (l) The author based on data from Coordinador; (r) Chile system operator

Theoretically, not each country needs to have its own wholesale market. Regional power pools combined with cross-border trade could suffice to cover the participating neighbouring countries. ASEAN has been discussing the introduction of a regional power market for many years and looked at other regional markets such as the Nord Pool, the Australian National Electricity Market (NEM), the South African Power Pool, or the Central American Electrical Interconnection System (SIEPAC) as examples. Up to the present, the conditions are not met to realize an ASEAN regional power market[56].

Market for Ancillary Services or Regulatory Capacity

The electricity system has as a particularity that the produced amount of electricity in a grid or balance zone must at all times be exactly equal to the consumed amount of electricity. There is no queuing in the electricity system, contrary to what we have for all other goods. The above-described day ahead markets all require exact supply and demand forecasts for the next day. However, forecasts always contain a certain error due to unexpected demand, wrong weather forecasts or unplanned system outages. At least one power plant in the balance zone (usually hydropower) needs to adapt its production second by second (i.e. supply the so-called regulatory power) to keep supply in the balance zone exactly equal to demand (so-called spinning reserves, primary regulation). Other power plants may be on standby and ready to be brought online within minutes (non-spinning reserves, secondary regulation). A third category of power plants may be switched off in a reserve mode ready to be started within hours (black start services, tertiary regulation). In AC systems, regulation is frequency regulation, in DC systems (e.g. microgrids) it is voltage regulation.

Insufficient primary regulation may have been a factor causing the Iberian blackout of 28 April 2025. Considerable confusion still exists around the root cause of this event. The ENTSO-E webpage[57] which is still being updated mentions three power and frequency swings oscillations, the third one of which caused the blackout. Under FAQ, it states that the causes are still under investigation. Concerning the possible lack of inertia, it states that the "Iberian system was operating with sufficient reserves to manage usual imbalances between generation and demand." The irrelevance of inertia is also echoed in the Redelectrica report of 18 June 2025[58,59] : "The incident was NOT caused by a lack of system inertia". A summary[60] of the said Redelectrica report mentions three causes: 1) insufficient voltage control capacity, 2) oscillations creating difficulties to stabilise voltage and 3) 'apparently improper' disconnections of generation plants. This summary also mentions that "Solar PV already has the capacity to control voltage, but regulations did not allow its application." As a consequence, PV generation dropped from 18GW to 8GW in just five minutes[61] . The urgent Royal Decree Law enacted by Spain on 26 June 2025[62,63] updates operating procedure PO 7.4, allowing solar plants to actively contribute to grid voltage control.

In Spain, a widespread dissemination of decentralized as well as grid-scale battery energy storage should now follow. It goes without saying that all batteries should contribute to grid voltage control. Once installed, batteries should fulfil the role that diesel generators take at present for supplying emergency electricity at specific locations such as hospitals. A sufficiently dense battery system in the grid may avoid most of the blackouts or at least shield the equipped communities from being drawn into blackout.

This being said, ancillary markets are and should remain totally different from commercial markets. The supply of primary regulatory power should be automatic for all producers as well as for storage facilities, wherever technically possible. As for secondary and tertiary regulatory power, to show the difference between the ordinary storage market and the ancillary market, recall first what the ordinary market implies for a storage operator. As described initially, the source of income for storage operators is the day-night or summer-winter price differential. To apply this to the example of Chile, all nodes show a daily price pattern with daily minima (zero) and nightly maxima. In this market, it is optimal to have one charging-discharging cycle per day. Discharge should be during the night (high prices) and charging during the day (low prices). The figure below shows the trajectory of the storage cycle of a Chilean storage engaged in commercial storage (i.e. not in regulation), showing the real maximum and minimum storage levels as observed on 30 November 2024[65].

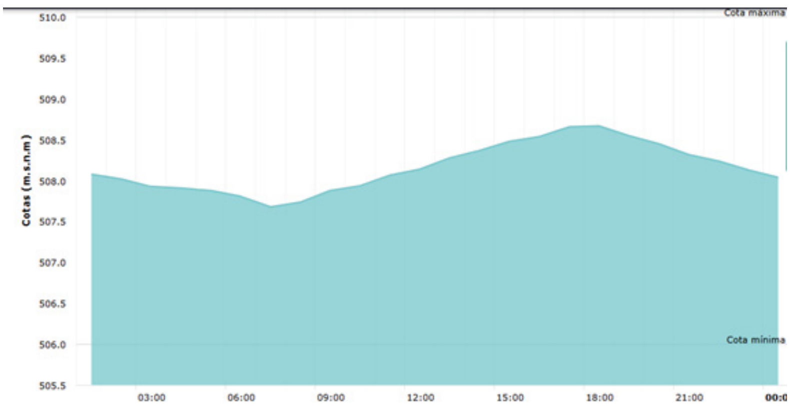

Fig. 13: Storage level trajectory of a commercially oriented storage in Chile, 30 Nov 2024
Source: Coordinador

In contrast, the economics of ancillary markets can be explained by referring to the figure below. It shows a storage operator engaged in supplying secondary regulatory power. Four periods of energy production (discharge, downward slopes) and five periods of pumping or water inflow (charging, upward slopes) happened during that day. The example refers to the storage profile of a hydropower lake in Chile, taken on 30 November 2024[65]. The red lines show the optimal trajectory if this operator was a commercial market operator (not engaged in regulatory services).

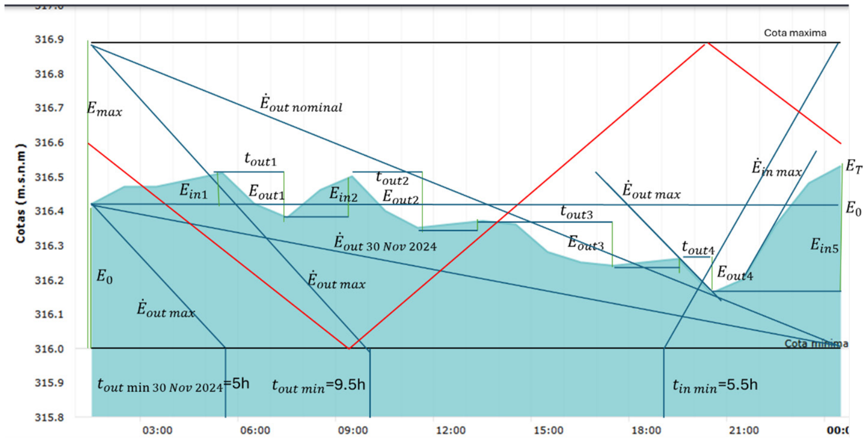

Fig. 14: Storage used for primary and secondary regulation, Chile, 30 November 2024
Source: The author, adapted from Coordinador

In this picture, E_0 is the initial storage level and E_T the final storage level at the end of the day. E_T-E_0 is an increase in storage achieved during the day. In the long run (after many days of operation) this difference has an expected value of zero. The storage capacity is E_{max} and the nominal discharging power is $\dot{E}_{out\ nominal}$, the maximum discharging power (speed) is $\dot{E}_{out\ max}$ and the maximum charging power is $\dot{E}_{in\ max}$. The minimum discharging time of the full storage capacity E_{max} is 9.5h, the minimum discharging time of the initial storage level E_0 is 5h. The minimum charging time of the total storage E_{max} is 5.5h. The four discharged quantities of energy are $E_{out\ 1}$ … $E_{out\ 4}$, and the five charged quantities are $E_{in\ 1}$ … $E_{in\ 5}$, respectively.
For further comparison, tertiary regulation is stored electricity on stand-by, whereby market participants are paid for not producing. An example is shown below[66]. As the secondary regulation shown in the figure above did not reach its minimum level during the day, this tertiary storage below remained idle at its maximum level during the whole day of 30 November 2024.

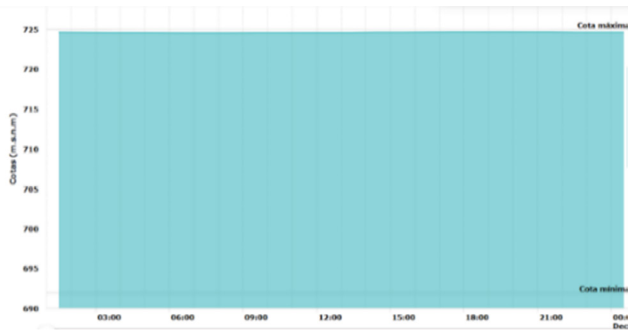

Fig. 15: Storage used for tertiary regulation, Chile, 30 November 2024
Source: Coordinador

On the basis of the above three examples, the economics of ancillary markets can be explained; the explanation below is technology neutral and valid for any type of storage, including battery storage.
The cost of regulation C_R for the above case can be stated using some of the given elements; the variable cost C_v is the cost of storing energy, where P_i is the market price of each amount of energy at the time it was bought. Total cost is variable cost C_v plus fix cost C_f. Fix cost comprises financial cost, wages and taxes.

$$C_R=\sum_1^5 P_i E_{in\ i} + C_f \quad (17)$$

A decisive advantage of hydropower as a storage form is that the energy is directly collected in the storage, which sets all $P_i=0$ in equation 17, meaning that there is only fix cost. This advantage is lost for the case of pumped hydropower storage (PHS) and for all the other storage technologies which have a non-zero storage cost in form of pumping or charging and, therefore, $P_i\neq0$. If battery storage is, however, combined with PV or wind energy within one single production and storage location and operator, the loss incurred when charging the battery can in practice be combined with the efficiency factor of the PV or wind energy equipment, reducing the cost of regulation to fix cost also for these storage forms. This means that a transmission system operator can provide for regulatory energy by tendering for it in a separated cost-based capacity market comprising both, production and storage combined.

On this separated capacity market, only fix cost need to be paid for. Capacity is not just nominal power $\dot{E}_{out\ nominal}$, but is also characterized by the three other parameters, namely the total storable E_{max}, the maximum output (discharging) power $\dot{E}_{out\ max}$ and the average charging speed over the year, given by the sums of charging amounts during a year, noted $\sum_i E_{in\ i}/8766h$. This is the resource availability, determined by precipitation, sunshine, wind etc. No storage can operate in the long term above its resource availability, unless it receives supplementary input by commercial energy bought on the market.

If only fix cost matters, the question does not have to be answered as to when the operator of regulatory storage should buy its energy if he is to follow a least cost strategy. This question has no clear answer; no least cost market-oriented supply strategy exists for a regulatory operator having to buy the energy on the market, as explained hereafter. On the one hand, this storage operator should buy his electricity at the moment the prices are low to save cost. On the other hand, he cannot buy at a minimal price on a futures contract as he cannot guarantee that he needs the electricity at a precise future moment as he may need it instead any time between now and the indeterminate future. If he cannot buy electricity at minimum price on a futures market, he should buy it at the tomorrow-next spot market. Again, he cannot predict the exact hour when he needs to have the energy, nor how exactly much he needs. If he fixes an arbitrary buying schedule, he creates an erroneous forecast against which he should shield all the other operators. He may be the problem instead of the solution.

The same is true for the regulatory operator's production schedule. He cannot optimize his production as a function of prices as, in that case, he would be following the red trajectory in the figure further above. Instead, he is forced to produce in dysfunction of the market (i.e. the prices), he must produce only as a function of the instantaneous supply demand gap. Tertiary regulation is paid for not producing energy.

The above describes a model of least cost provision of ancillary market services. Other models are possible but are not least cost. The example shows that ancillary markets are not commercial markets financed by electricity trading. Instead, they are public service markets and are financed by grid users within the framework of systems taxes. The transmission system operator together with the operators on the ancillary market play the role of being an integrated supplier of last resort. The systems taxes are not temporary support measures like e.g. feed-in tariffs but relate to the provision of energy security. Like most other security services, the electricity regulation on the ancillary markets satisfies the two classical criteria characterizing public goods or public services, namely non-rivalry and non-excludability . Non-rivalry means that if one electricity consumer profits from energy security, he does not rival with any other electricity consumer profiting from energy security. Non-excludability means that even if a consumer did not want to profit from the offered energy security, he would still profit from it against his will, hence he is obliged to contribute to the systems cost.

The question of increasing the decentralized provision of regulatory storage by means of battery energy storage merits to be looked at. Hydro power may be the least cost option to provide regulatory storage capacity, but such capacity may be far away from consumption centres such as cities. If extreme weather situations happen, the transmission grid between the hydropower regulatory storage and the city may be interrupted. Therefore, decentralized PV combined with battery energy storage may offer an interesting contribution towards setting up decentralized regulatory storage capacity.

As explained above, regulatory energy is a public good that cannot be produced nor used by consumers, it is the role of the local and provincial administrations to invest in decentralized regulatory production and storage units. Municipal and provincial administrations and their local public enterprises are often large energy consumers; hence they will invest in regulatory storage to increase their own energy security. To minimize investment cost, such investment can be done by procuring the installation in local public procurement using open competitive tendering. The facilities built are then leased to the transmission system operator to provide regulatory energy.

Above it was mentioned that local and provincial administrations could set local energy security levels in form of storage-to-consumption ratios, expressed in number of consumption days of the local storage, to be implemented in local electricity planning. It has been articulated that 30% of the total surface of a city, including built-up surface, or the equivalent of 5MWh/inhabitant/year, should be covered with solar panels[68] to maintain decentralized energy security. Battery storage should be an integral part of such a target. A certain proportion of this battery storage target can then be leased to the transmission systems operator who will use it as regulatory storage capacity.

An important question is the optimum level of regulatory capacity in a balance zone, indicating how much regulatory capacity should be installed in a balance zone to avoid blackouts at all times while also avoiding curtailment of renewable energy and overinvestment in storage. The solution of this problem depends on the following elements:

- Forecasting error: The bigger the forecasting error in a balance zone, the more regulatory energy is needed. Introducing intra-day markets diminishes the forecasting error. With intra-day markets, the major sources of forecasting errors are demand uncertainty and unforeseen weather events.
- Demand uncertainty: Demand uncertainty in a balance zone is smaller if aggregate storage (i.e. market based plus regulatory storage) is sufficiently large so that the consumers remain confident that blackout or shortage can be avoided. With high aggregate storage levels, consumers are less likely to panic and to feel the need to charge their batteries all at the same time.
- Generation-load disequilibrium: Balance zones that are in structural deficit (generation < load) face bigger blackout risks and need more aggregate storage (commercial plus regulatory) to remain resilient. For this reason, densely populated consumption centres such as cities need to monitor their energy security and install combined PV production and storage plants within their balancing zones.

- Peak situations: At maximum power of the balancing zone, expressed in MW, the following should be satisfied: generation + aggregate storage output + net imports ≥ load, reflecting the four elements of energy security as stated in the introduction.
- Perfect security does not exist, but sufficient aggregate storage (commercial and/or regulatory) will make the frequency of blackouts rarer and shorten their duration.

The detailed analysis of the question of optimal level of regulatory capacity goes beyond the scope of this paper and will not be answered here.

Regulatory Measures to Improve the Supporting Role of Storage

Feed-in-tariffs (FIT), green certificates, power purchasing agreements (PPA), tax rebates and subsidies for storage: The mentioned instruments, as well as investment support schemes are examples of measures that have been used by different authorities around the globe[69]. Due to their efficiency to boost renewables, feed-in tariffs (FIT) are one of the most popular of these measures. As FIT may be expensive policies, they are usually being provided to incite small consumers to feed renewable electricity into the grid. In most of the cases, the FIT did not include support to battery storage. However, on some small islands, FIT for battery energy storage have been successfully introduced to develop local electricity storage[70]. A project carried out on the Corvo Island in the Azores Archipelago shows the way how batteries increase the PV energy injected into the grid and reduce the curtailment of PV powe[71].

The main problem in providing FIT for battery energy storage (or for pump hydro storage) is to ensure that the stored energy is originating from renewable sources. If battery energy storage is combined with the renewable source in what is sometimes called hybrid[72] production-storage facilities, this is directly guaranteed.

If production and storage are separated and managed by two different operators, the usual way to guarantee that all stored energy is originating from renewable sources is to request the FIT supported battery storage operator to prove the origin of the stored energy by way of energy attribute certificates[73] (renewable energy certificates REC, guarantees of origin GO) certifying that the stored energy is effectively renewable. Many countries have introduced the possibility to certify renewable energy and trade the certificates issued[74].

Green finance to support storage: International organizations including the UN[75] , the IEA[76] and IRENA[77] have stressed the need to scale up finance to drive the attainment of sustainable development goals in general or the energy transition in particular. The global finance flows destined to clean energy production must be multiplied by five during the current 2020 – 2030 decade to stay on track for meeting the Paris Agreement targets[78]. Especially high is the need to direct supplementary finance towards the developing world[79]. To finance clean energy, the international community has created so-called green finance, geared at preferential conditions towards green activities or green sectors as defined in so-called taxonomies of green activities. Clean energy investors of all size should be enabled to have access to green finance (equity, bonds, loans and credit risk guarantees) to accelerate the transition towards carbon neutrality.

The global discussion on the conditions under which electricity storage is to be considered as a green activity from the perspective of investment facilitation has focused on a global taxonomy of green sector activities[80]. The global voluntary standard has been taken as a model for many countries who have elaborated their taxonomy of green activities. In this standard, energy storage, whether pumped hydro or battery and other new storage forms, is included among the green activities if it satisfies certain so-called screening criteria. Thus, batteries, capacitors, compressed air storage, flywheels and large-scale energy storage facilities (other than pumped hydropower storage) are considered as green activities if the infrastructure to which they belong:

- is a dedicated connection to a power production plant eligible under one of the renewables criteria (e.g. solar, wind), or
- is a dedicated connection to a power production plant operating under the low carbon power threshold (100g CO_2/kWh), or
- the infrastructure is located on a system with a grid factor at or below 100g CO_2/kWh, or
- the infrastructure is located on a system for which at least 67% of its added generation capacity in the last 5 years falls below the low carbon power threshold

Pumped hydropower storage in particular, is considered as green activity:

- If it has been in operation before 2020 and has power density > 5W/m2; or GHG emissions intensity of electricity generated < 100gCO_2 e/kWh.
- If it has been commencing operation in 2020 or after, if it has power density >10W/m2; or GHG emissions intensity <50g CO_2 e/kWh. In this case, it must either perform an assessment, based on recognised best practice guidelines, of environmental and social risks and incorporate measures to address risks, or must show that the facility is contributing to a grid which has at least 20% share of intermittent renewables.

Storage Facilitating Over-the-Meter Transactions

Decentralized PV production combined with storage and appropriate software can enhance the role of users in exchanging electricity among each other. Users in this case can be households or enterprises. They share the common characteristic of having formerly been pure consumers who now become producers as well as consumers (sometimes called prosumers).

Their batteries are installed behind the meter, serving in priority to store their own production. The battery is the decisive instrument allowing them to choose the best moment to sell electricity – namely when the daily prices are at their highest. The battery in this sense here is deemed to include the inverter. To be able to allow spotting the moment when the daily prices are highest, the system also needs a software with access to the hourly price information of the surrounding local distribution system operator (DSO) at the corresponding voltage level. The software should be able to analyse recent shapes of the price curve and be able to infer this information for the day ahead; in a similar way, it should be able to analyse the prosumer's own hourly consumption profile and to make an inference for the day ahead. Furthermore, it should have an interface enabling the prosumer to manage the battery in consequence.

When installing PV and batteries, users have a choice to be made concerning the size of the PV and battery. If a user's local useable solar resource allows him to produce more than his average individual daily consumption (typically if the user resides in a low-density settlement with sufficient available PV area and has low individual consumption), he may choose the size of the PV and battery to exceed his daily consumption. In that case, the user will become a predominant producer and be able to regularly sell excess production to the local grid. The grid will only supply him at those occasions when his own resource and stored energy are insufficient. For the local distribution service operator (DSO), this user is perceived as a producer with occasional needs to be supplied from the grid.

If, however, the user's local useable PV area is smaller than his average individual daily consumption (typically if the user resides in a high-density settlement and has high individual consumption), the size of the PV will be smaller than his average daily consumption. In that case, the user will be a predominant consumer who is able to support only part of his consumption by self-produced renewables. Only in special circumstances will this consumer have a surplus to feed into the main grid. This user can then still choose the size of his battery to be larger than his PV production, equalling or exceeding his daily consumption instead, so that he would store his surplus production in his battery whenever possible instead of feeding it into the grid. If the battery is sufficiently large, he can even store electricity from the grid and avoid feeding back into the grid altogether, using the battery as security device instead. For the local DSO, this user is perceived as a consumer having reduced his energy consumption by investing into energy conservation (for the local DSO, self-production and storage by users have the same effect as energy conservation).

To make a quick check whether inhabitants of a given settlement are likely to be in the first (predominant producer) or in the second (predominant consumer) category, the following table may help. It shows the percentage of the settlement's area that needs to be covered by PV to satisfy the settlement's energy needs, as a function of the settlement's population density (in persons/ha) and the settlement's total final per capita energy consumption (in MWh/person/year). The table has been calculated for an annual solar irradiation of 1736KWh/year/m2, equalling the global annual average irradiation, also equivalent to 4.752kWh/day/m2 and to 198W/m2[81], and using a technical PV efficiency of 5.3m2/kWp. Example: a settlement having density of 150persons/ha with consumption of 5MWh/person/year requires covering 23% of its area by PV to satisfy its consumption. The table should be adapted for specific locations by using the global solar atlas[82]. The mentioned 150persons/ha density is at the lower end of the density bandwidth of 150 to 600persons/ha recommended for sustainable neighbourhoods by UNHabitat[83]. This threshold density of 150persons/ha emerges, therefore, as a quite ideal density of sustainable habitats. In practice, the above table is useful for settlements located within ±60° latitude. In higher latitudes, solar radiation has less than 50% of its equator intensity (arccos(60°)=0.5) and becomes secondary, but wind energy becomes the dominant renewable energy form. Below ±60° latitude, wind energy is often available at times when solar energy is missing, hence storage can bridge the time-gap between solar and wind energy. Note that wind energy is practically absent near the equator in the so-called Intertropical Convergence Zone (ITCZ)[84]. In this zone, storage is mainly bridging the time-gap between two different solar episodes.

		Pop. density (pers/ha)											
		50	100	150	200	250	300	350	400	450	500	550	600
TFC (MWh/person/year)	3	5	9	14	18	23	27	32	37	41	46	50	55
	4	6	12	18	24	31	37	43	49	55	61	67	73
	5	8	15	23	31	38	46	53	61	69	76	84	92
	10	15	31	46	61	76	92	107	122	137	153	168	183
	15	23	46	69	92	114	137	160	183	206	229	252	275
	20	31	61	92	122	153	183	214	244	275	305	336	366
	25	38	76	114	153	191	229	267	305	343	382	420	458
	30	46	92	137	183	229	275	321	366	412	458	504	550
	35	53	107	160	214	267	321	374	427	481	534	588	641
	40	61	122	183	244	305	366	427	488	550	611	672	733
	45	69	137	206	275	343	412	481	550	618	687	756	824
	50	76	153	229	305	382	458	534	611	687	763	840	916

Fig. 16: PV Area requirement (%) as a function of TFC and population density
Source: The author

Settlements in green cells in the above table are likely to be predominantly producer settlements (needing, however, to be supplied during bad weather periods), whereas settlements in the yellow and orange cells are likely to be predominantly consumer settlements (wishing to feed into the grid at occasional net surplus periods). Settlements in orange cells need more than 100% of their own area as PV area to cover their electricity needs.

As interactions between users are still a relatively new phenomenon, this section terminates by mentioning the factors and conditions favouring the existence and development of interactions between users. Such factors have been analysed and compared for China and the EU by Uhde[85], reflecting on policy documents of China and the EU originating from the period 2016 – 2019. These are listed below.

Household preparatory organization for microgrids: In many jurisdictions, households are not supposed to engage in regular economic activity. The preparatory steps to be undertaken to run a microgrid may include not only the investment in a microgrid, but also the creation of a small company engaging in trade as well as steps to organize several prosumers of a same settlement into a prosumer community in a microgrid that can act more effectively on the market by using pooling mechanisms. Literature largely focuses on this aspect and on trade within a given microgrid[86,87,88]. The more heterogenous the ecosystem behind the meter, the more users will interact among themselves behind the meter.

User participation in the over-the-meter market: This requires corresponding market access for users and is a further development of market opening, beyond private sector participation mentioned earlier. Users need to be able to supply from behind the meter to compete with incumbent suppliers in front of the meter. For this, users need to be able to receive the hourly price information and should be able to participate in, or at least to be visible by, the day ahead program maker. In the day ahead plan, behind the meter users will be a category of non-dispatchable producers. The availability of supply from their side may depend on weather conditions.

Last mile grid tariffs: When users start using the grid as producers or prosumers, the grid tariffs for using the last mile of the grid should normally be revised as electricity will start flowing in both directions and hence the net flow through the last mile is expected to diminish.

Example of a community claiming to be the world's largest Virtual Power Plant (VPP): The above factors can be illustrated by an example of a decentralized energy community. A community of solar energy traders has been created in Germany in 2015 under the name "sonnen" community. The sonnen community aims to make the household the new centre of the energy system[89]. It has received new impetus with the arrival of cheaper and more powerful batteries. Users acquire a battery with inverter and a software that allows trading electricity with other community members. From Germany, the community has expanded to Italy, Spain and UK, with further branches now in Australia and in the US. To be operational, the equipment and software of this community requires a fully opened market environment, a condition which all the mentioned jurisdictions offer.

The "sonnen" community claims to be the world's largest virtual power plant (VPP)[90]. This suggests that a VPP can actually overcome the lack of physical infrastructure. This argument merits discussion. In general, a purely virtual power plant is limited to financial delivery and cannot satisfy energy needs of buyers by physical delivery. This limitation can, however, be overcome if the VPP contains at least two production-consumption systems that may be physically disjoined but must instead be linked by a combination of two local contracts. By combining two local contracts, the VPP may allow a community member of, say, a continent A to physically supply a community member on a continent B, even if the two continents are not linked by a power transmission line. This is illustrated by the figure below. On the left, a predominantly producing sonnen community A resides on continent A and is connected to grid A. On the right, a predominantly consuming sonnen community B resides on continent B and is connected to grid B. The discussion comprises two cases.

Under a first case, a physical connection between the continents exists, but no VPP, and a predominantly producing community A wishes to supply electricity to a predominantly consuming community B. In this case, a supply agreement is necessary between community A and community B, defining the route for physical delivery and the modalities of payment. If the two communities are geographically far apart but linked by a physical transmission line, the delivery route can be very complicated, the delivery charge substantial, and the difficulty of negotiation can easily surpass the negotiating skills of small prosumers.

Virtual Power Plant Combining Two Local Contracts

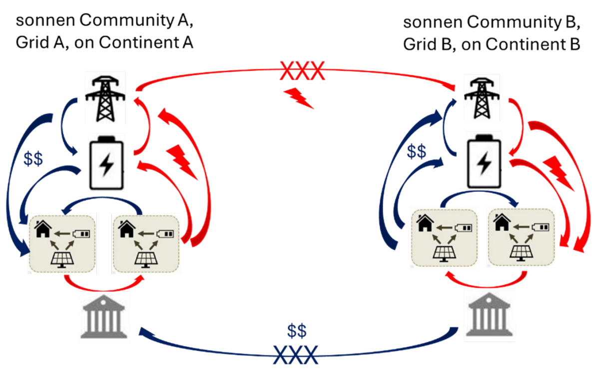

Fig. 18: Virtual Power Plant combining two local contracts
Source: The author

Take now a second case when the two continents are not physically connected (shown as "XXX" in the intercontinental interconnector of the figure), but where instead a VPP exists that combines two local contracts, one of each continent. In the above case, these contracts involve four partners, namely community A, grid A, community B and grid B. In the first contract, community A sells a certain quantity of electricity to grid A and receives financial compensation. In the second contract, community B buys exactly the same quantity of electricity from grid B and pays the corresponding price. The VPP combines the two local contracts and allows physical deliveries to happen, in the above case from community A to community B, simultaneously without need of an intercontinental transmission from A to B. In the ideal case where the prices are the same in grid A and in grid B, there will not even be an intercontinental financial transaction from B to A. This is shown as "XXX" in the financial flow in the above figure. In a less ideal case, where the price levels are different in A and B, there should be a compensation payment from one community to the other.

Summary and Conclusions

To summarize, the following points may merit to be mentioned again.

The four pillars of energy security are sufficient generation, sufficient storage, sufficient transmission and smart consumers. The theoretical elements underlying the commercial viability of storage show that on the day ahead spot market, the essential factor procuring income to storage operators is the day-night price spread. Futures markets offers further commercial viability for seasonal storage, but not for long term storage. Solar energy, together with short term storage, are at the brink of becoming the cheapest electricity source worldwide within the next two to three years.

The countries analysed in this study that offer viable day-night storage markets are countries whose solar share is sufficiently high to create low prices during the day (NordPool, California, Chile). Peru offers insufficient day-night storage conditions due to an insufficient share of solar. Japan and the Philippines offer mediocre day-night storage markets due to insufficient share of solar, but also due to high shares of cheap baseload, keeping night prices too low to make storage profitable. Viet Nam, in spite of low shares of solar and high shares of coal baseload offers good conditions for storage as the government sets prices with large day-night spreads. Singapore, for the moment, has an atypical bimodal price curve that cannot be explained by technology, but which offers good conditions for storage.

One of the factors causing the Iberian blackout of 28 April 2025 may have been the prohibition of PV to supply primary regulatory power. The role of storage for the market for secondary regulation is analysed by referring to an example of Chile. It is pointed out why a given storage cannot be used simultaneously for the ancillary market and for the commercial market, as the ancillary market may pay storage for not producing at the time when the commercial market incentivises storage to produce. The ancillary market satisfies both criteria applying to public goods, namely non-rivalry and non-excludability. Municipalities are advised to set up tenders for renewable energy capacity and thereafter lease the capacity either for the ancillary or for the commercial market.

In the analysis of storage facilitating over-the-meter transactions, two categories of users – predominantly producers and predominantly consumers have emerged. The difference between the two has been shown to depend on density of the settlements and on per capita final energy consumption of the settlement. Regulatory measures favouring inter-user transactions include facilitating the creation of microgrids in domestic settlements. The sonnen-community has been referenced as an example of a solar community claiming to be the world's largest virtual power plant (VPP). It has been shown under what conditions the VPP can overcome the lack of physical infrastructure between two continents.

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Improving Energy Security through Electricity Storage in Open and Semi-Open Markets

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Keywords
LCCA, Cost optimal, nZEB, Heating, Condensing Gas boiler, Hybrid heating system, Energy measures, EPBD

Abstract
The present study evaluates the interrelation between cost effectiveness and energy and environmental performance of a range of technologies, focusing on those have the potential to upgrade space heating and domestic hot water (DHW) production in three individual categories of typical buildings of Greece. Life Cycle Cost Analysis (LCC) is a well-established methodology which provides reliable results on a long-term basis and has drawn a lot of attention by the scientific community. For Greece, previous studies have assessed and identified the financial gap between energy efficiency interventions and the Nearly Zero Energy Building (nZEB) thresholds [11,12]. A significant financial gap was quantified for different building types – Single-Family House (SFH) buildings, Multi-family House (MFH) apartment blocks and office buildings – depending on construction period and Climate Zone. The current study, not only compares the techno economic performance of competitive interventions, but also reevaluates their results, taking into account updated energy prices, primary energy factors and emission factors, reflecting energy market multiverse. The results of the financial assessment for the residential buildings show that intervention packages with natural gas appliances are more cost effective while packages with electrical driven systems (heat pumps) achieve less primary energy consumption. Synergies with other interventions such as passive measures, cooling and renewable energy systems are necessary for optimal results depending on the construction period and climate zone. On the other hand, findings for office buildings, with lighting and cooling as the dominant energy uses, show very similar results for the cost effectiveness of technologies under investigation, while the greatest impact is achieved with the combined measures of photovoltaics and lighting upgrade with LED fixtures.

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Nomenclature

CAPEX	capital expenditure
COP	coefficient of performance
CP	construction period
CZ	climate zone
DHW	domestic hot water
DPP	depreciated payback period
EPBD	Energy Performance of Buildings Directive
GHG	Greenhouse gas
HP	heat pump
IP	intervention package
LCC	life cycle cost
MFH	multi-family house
nZEB	nearly zero energy building
NZEB	net zero energy building
ZeB	zero emission building
PEC	primary energy consumption
PV	photovoltaic
RES	renewable energy sources
SFH	single-family house
VRF	variant refrigerant flow

1. Introduction

Buildings are at the core of the European Union (EU) energy efficiency policies [1]. This is absolutely reasonable since they take up around 30-40% of final energy consumption and 36% of greenhouse gas (GHG) emissions [2, 3]. Improving the energy efficiency of the building stock in Europe is, therefore, a major goal for achieving not only the EU's 2030 targets but also the long-term objectives under the EU's Roadmap to a low carbon economy by 2050 [4]. Furthermore, the Directives 2010/31/EU (Energy Performance of Buildings Directive-EPBD) [5] and the 2012/27/EU (Energy Efficiency Directive – EED) [6] introduced specific measures for improving the energy performance of the European building stock. In this context, their amendments, 2018/844 [7], 2018/2002 [8], focused on definition of nZEBs for both new and renovated buildings, as well as on long-term renovation strategies through cost-effective approaches. Taking into account that nZEBs constitute one of the main pillars of the EU energy policy, EPBD requires Member States to formulate policies and establish specific measures for promoting the refurbishment rate of existing buildings in order to diminish their energy consumption to nZEB levels. An annual average EU-wide renovation rate of 3% of the building stock needs to be accomplished in a cost-effective manner.

The obligation of all EU member states for all newly constructed buildings to be nZEBs has been already applied since 2021 for all building (since 2019 for public ones) but existing buildings, especially those constructed before 1980, remain the majority of the building stock and the most energy intensive due to lack of envelope thermal insulation and very low efficiency energy systems (mostly oil boilers for heating). In addition, the latest amendment of the EPBD, 2024/1275 [9] introduces Zero Emission Buildings (ZeB), a standard that sets a stricter policy for the areas of both energy consumption and renewable energy share. Effectively, this means that the "ZeB" standard will be mandatory for all new buildings from 1 January 2030, while new public buildings will have to comply even earlier, from 1 January 2028. The aim is for the entire building stock to be zero-emission by 2050. Specific definitions of ZeB are expected to be further provided by each member state, however, the directive itself acts as a driver for the classification of a building as "ZeB", corresponding to zero on-site carbon emissions and zero or very low amount of operational GHG emissions. Even though directive about ZeBs does not impose (at least not in the short future) an obligation for existing buildings, it shows the pathway that EU policies are following, especially about on-site use of fossil fuels. Finally, the revised EPBD includes policies to increase the renovation rate in the EU and especially for the worst-performing buildings. It sets a binding target for the increase of the average energy performance of the national building stock by 16% by 2030 and be 20-22% by 2035 while it enhances long term renovation strategies with the new Building Renovation Plans and the introduction of the building renovation passports.

Since "nZEBs" has been officially adopted by EU policies as a term, and consequently, Member States have provided respective national definitions, many studies on the cost-effective feasibility of nZEBs were carried out. In a critical review about cost-optimal analysis for achieving nZEB [10] it was found that the cost-optimal approach was an effective method. Commission has already amended EPBD twice since then and EU is in the verge of moving forward to the next building energy efficiency milestone for the near future, the ZeBs. Nevertheless, cost-effectiveness remains a significant tool especially for existing buildings and the renovation process.

In a previous study [11], the authors investigated the cost-effectiveness and primary energy saving potential of intervention packages (IPs) consisting of single or multiple measures on existing single and multi-family house buildings (SFH and MFH) erected in two climate zones (B and C) of Greece prior to 1980 and within 1980–2000. To this end, the calculation of the investment as well as the operating and maintenance costs for a wide range of energy efficiency measures, were carried out.

The considered energy efficiency measures were based on the four principles of NZEB design: 1) reducing the energy demand, 2) improving the indoor environmental quality, 3) increasing the share of RES and 4) reducing the primary energy emissions. It was found that the financial gaps between cost-optimal and nZEB scenarios fall within 120–180 €/m2 (climate zone B) and 200–250 €/m 2 (climate zone C), to 140–180 €/ m2 (climate zone B) and 180–220 €/m2 (climate zone C), for SFH and MFH buildings, respectively. Given the aforementioned results, it can be concluded that only if substantial economic incentives are provided, it will be possible to attain the nZEB targets at reasonable costs in the case of older buildings located in climate zone B.
In another study [12], the same approach was used for investigating LCC and PEC relationship in typical office buildings, both for existing (built prior to 1980 and within 1980–2000) and new ones. The goal at this work was to discover the impact of various energy saving measures and the feasibility of leading to nZEB and NZEB in a cost optimal manner. A successful attempt to reduce the computational load with multi-objective genetic algorithm for optimizing energy efficiency measures in the case of SFHs in Greece is also presented in a recent study [13]. It is proven that faster, yet reliable, methods can be utilized when the number of investigating energy measures combinations is large.
Regarding the main object of interest of the current study, this is considered to be the cost effectiveness analysis of heating systems (both space heating and DHW) for three building types and for all the CPs and CZs of Greece. The analysis is based on the primary energy consumption and the Life Cycle Cost (LCC) for a number of energy efficiency IPs while the framework of the assumptions for the techno-economic calculations is similar to the previous studies. The packages are categorized according to the heating and DHW system combined with cooling systems, insulation (passive) measures and renewable energy systems (solar thermal for DHW and PVs). The key goal of the study is to compare the LCC (€/m2) and the PEC (kWh/m2) of the different heating systems for three building types in all CPs and CZs. In addition, the payback period will determine the feasibility of the specific packages of measures, while at the same time the rest of the measures (passive, cooling, RES) are also categorized in terms of being part of the IPs with low LCC or not.
As the study focuses on the heating systems and consequently the fuel (electricity & natural gas), IPs are selected in order to account for realistic combinations of measures and limit the total scenarios created. The study is based on the methodology and the tools of the previous studies with two major upgrades. The first is an updated cost database to represent the most recent market status for all systems and interventions included in the study. The second is an upgrade to the energy pricing tool which calculates the energy cost for the specific consumption of each intervention scenario by applying the latest billing trends of local energy providers, thus improving the accuracy of the overall calculations.

2. Methods

2.1 Overview

As already stated, a cost effectiveness analysis of energy efficiency interventions is performed within this study with special emphasis on heating and DHW systems for three typical buildings that are the most common throughout the Greek building stock. The analysis is carried out for all the major CPs and for all four CZs. The selection of the typical buildings, CPs and CZs are explained below and, in general, are all based on the previous studies [11], [12] and it is explained were differentiated. Energy efficiency IPs, mainly focused to heating & DHW systems, were established, in some scenarios also combined (i.e. insulation measures) so as to allow for synergies due to reduced heat losses – further details on following paragraph 2.4-. Energy simulation and economic assessment framework was also based in the previous studies with several updates and upgrades.

2.2 Typical buildings

The typical buildings are:

1. SFH – single floor house with an unheated basement and a pitched roof and heated floor area of 80 m2
2. MFH (apartment) building – three storey building with nine apartments over a commercial use (shops) at the ground floor and a heated floor area of 705 m2
3. Office Building – five storey building with a heated floor area of 1,505 m2

The total of the above buildings represents almost 85% of the country's building stock and numbers more than 610,000,000 m2 of heated spaces [14]. All simulation parameters (schedules, internal gains, set points etc.) are predefined for each building use according to Technical Directive 20701-1/2017 of the Technical Chamber of Greece [15] which is the handbook of the Energy Performance of Buildings Regulation of Greece (KENAK). Details about the geometry and other characteristics of the typical buildings can be reviewed in the previous studies [11], [12] in which the same typical buildings are simulated.

2.3 Construction Periods (CPs) & Climate Zones (CZs)

Typical buildings are categorized in four CPs:
P1: prior to 1980 (no insulation regulation)
P2: 1980 – 2010 (thermal insulation regulation - ΚΘΚ 1979)
P3: 2011 – 2017 (energy performance of buildings regulation - KENAK 2010)
P4: 2018 – 2023 (revised energy performance of buildings regulation - KENAK 2017)

Each CP dictates the level of thermal insulation at the building envelope and the type and efficiency of the technical systems of the buildings (heating, DHW, cooling, ventilation, lighting) while the geometry remains the same.
In previous studies, existing buildings prior to 2000 were examined, as they are the majority of the building stock and more suitable for energy upgrade. In this study however, all periods are covered.

In Greece, there are four CZs (A, B, C and D) depending on the number of annual heating degree days as specified in the Technical Directive 20701-1/2017 [14], and illustrated in Figure 1. Detailed information about the climate of different cities in Greece can be found in the corresponding Technical Directive 20701-3/2010 of the Technical Chamber of Greece [16]. Previous studies analyzed cost effectiveness only for zones B and C as being the most populated ones. In the current study all climate zones are fully covered.

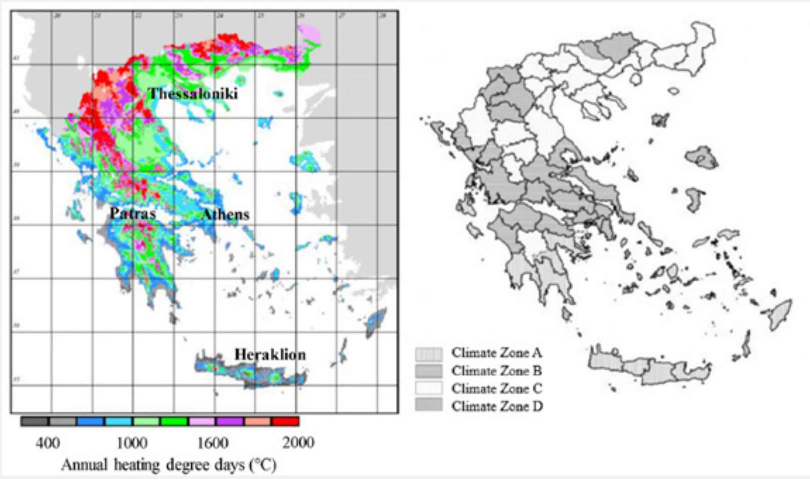


Figure 1: Climate zones and annual heating degree days in Greece

The IPs for improving the energy performance of the typical buildings were made by firstly selecting a new heating system and DHW production system and then combined with supplementary measures both passive and active. Passive measures include replacing windows (both frame and glazing) and reinforcing thermal insulation of the rest of the building envelope and have been evaluated, looking forward to synergies of reduced installed capacity and consequently lower Capital Expenditures (CAPEX) for the heating appliance. The latter, will also address the necessity of reaching nZEB status for buildings in the near future, as a prerequisite EU Fit for 55 targets. Active measures include the replacement or upgrade of the rest of the systems and installed PVs. Finally, other measures like CHP, biomass, and geothermal systems and shading systems were omitted in order to keep the number of the combinations as low as possible and in the aftermath of the previous studies showing that they are not very cost effective and it's not always feasible to be implemented as a retrofit solution.

The competitive heating and DHW systems (if applicable) to be evaluated and are proposed for the replacement of the existing respective systems are:

1. A modern condensing gas boiler system (central installation or individual system per apartment)
2. A high temperature heat pump (maxTsupply = 75 °C and only as a central system)
3. An individual low temperature heat pump (maxTsupply = 55 °C) with fan coil units per apartment or central for office building
4. A hybrid system as a combination of low temperature heat pump and condensing gas boiler technology. Heat pump operates only when external temperature is above a threshold temperature in order to maintain high COP.
5. A VRF system (only for offices)

The supplementary measures that are combined with the heating & DHW systems above and are evaluated as IPs are:

- a package of passive measures (thermal insulation and windows replacement)
- replacement of the cooling system (if applicable),
- a solar thermal system for DHW only (in residential uses only),
- replacement of the ventilation system
- replacement the lighting system (office use only)
- a PV system, considered under net-billing regime that was recently introduced in Greece replacing net-metering.

All interventions are presented in a comprehensive table (Table 1) that also includes some basic energy efficiency factors and coefficients (COP, EER, U-values etc.). Detailed properties of existing systems performance and envelope of the typical buildings can be reviewed in the previous studies [11], [12].

	Construction period	Existing systems (heating/DHW/cooling)	Envelope (U-values W/m²K)	New heating/DHW systems	Other Measures	Number of simulated IPs
Single-Family House	CP1	Oil boiler eff:68% Electric heater Split Units EER:1.7	No insulation U_{wall}=2.32, U_{roof}=1.95 U_{floor}=1.73, U_{win}=3.7-4.28	1.Condensing gas boiler eff: 1.05 2. High T HP COP: 3.0-3.8 3. Medium T HP COP: 3.8-4.5 4. Hybrid system*	1. New Split Units – Cooling 2. Insulation & Window Replacement U_{wall}=0.4-0.45 U_{roof}=0.4-0.43 U_{floor}=0.6-0.8 U_{win}=1.80 3. Solar thermal system for DHW (2.1-2.8 m² collector) 4. PV system (8 m² PV panels)	224
	CP2	Oil boiler eff:73% Electric heater Split Units EER:2.1	U_{wall}=0.9, U_{roof}=0.7 U_{floor}=0.9-1.73, U_{win}=3.9-4.05			224
	CP3	Oil/Gas boiler eff:81.2/90.3% Split Units EER:3.0	U_{wall}=0.5-0.7 U_{roof}=0.45-0.6 U_{floor}=0.8-1.30, U_{win}=2.6-3.2			56
	CP4	Oil/Gas boiler eff:98.4/102% Split Units EER:3.5	U_{wall}=0.45-0.65 U_{roof}=0.40-0.55 U_{floor}=0.7-1.20 U_{win}=2.2-2.8			56
					Total	**560**
Multi-Family House	CP1	Oil boiler eff:71% Electric heater Split Units EER:1.7	No insulation U_{wall}=2.42, U_{roof}=3.41 U_{floor}=2.29, U_{win}=3.7-4.65	1.Central condensing gas boiler eff: 1.05 2. Individual condensing boiler eff: 1.05 3. Central High T HP COP: 3.0-3.8 4. Individual Medium T HP COP: 3.8-4.5 5. Central Hybrid system*	1. New Split Units – Cooling 2. Insulation & Window Replacement U_{wall}=0.4-0.45 U_{roof}=0.4-0.43 U_{floor}=0.6-0.8 U_{win}=1.80 3. Solar thermal system for DHW (16-21 m² collector) 4. PV system (66 m² PV panels)	288
	CP2	Oil boiler eff:77% Electric heater Split Units EER:2.1	U_{wall}=0.9, U_{roof}=0.7 U_{floor}=0.9-1.73, U_{win}=3.9-4.05			288
	CP3	Oil/Gas boiler eff:83.8/91.2% Split Units EER:3.0	U_{wall}=0.5-0.7 U_{roof}=0.45-0.6 U_{floor}=0.8-1.30, U_{win}=2.6-3.2			72
	CP4	Oil/Gas boiler eff:98.4/102% Split Units EER:3.5	U_{wall}=0.45-0.65 U_{roof}=0.40-0.55 U_{floor}=0.7-1.20 U_{win}=2.2-2.8			72
					Total	**720**
Office building	CP1	Oil boiler eff:68% Chiller EER:1.7 T8 Fluorescent 17 W/m²	No insulation U_{wall}=2.32, U_{roof}=1.95 U_{floor}=1.73, U_{win}=3.7-4.28	1.Condensing gas boiler eff: 1.05 2. High T HP COP: 3.0-3.8 3. Medium T HP COP: 3.8-4.5 4. Hybrid system*	1. Chiller 2. Insulation & Window Replacement U_{wall}=0.4-0.45 U_{roof}=0.4-0.43 U_{floor}=0.6-0.8 U_{win}=1.80 3. Ventilation – AHU replacement/upgrade 4. LED 5. PV system (150 m² PV panels)	96
	CP2	Oil boiler eff:73% Split Units EER:2.1 T8 Fluorescent 17 W/m²	U_{wall}=0.9, U_{roof}=0.7 U_{floor}=0.9-1.73, U_{win}=3.9-4.05			176
	CP3	HP COP:/EER:3.0 T5 Fluorescent 12 W/m²	U_{wall}=0.5-0.7 U_{roof}=0.45-0.6 U_{floor}=0.8-1.30, U_{win}=2.6-3.2			72
	CP4	HP COP:/EER:3.0 LED 5.7 W/m²	U_{wall}=0.45-0.65 U_{roof}=0.40-0.55 U_{floor}=0.7-1.20 U_{win}=2.2-2.8			72
					Total	**416**

Table 1: Existing systems & envelope basic properties and energy upgrade measures of the typical buildings

**Efficiency of the hybrid system: when the condensing gas boiler operates it has typical efficiency. But when the heat pump (HP) operates, its COP is higher than a typical heat pump system as it operates only in optimal external temperature.*

2.5 Energy and economic assessment framework

Energy simulations and cost effectiveness assessment were conducted following the same framework as the previous studies. Simulations are performed by a specialized simulation tool structured according to the defined and calculated parameters of the National TEE-KENAK 1.31 software version. All input parameters for the calculations are in accordance with the corresponding technical guideline (TOTEE 20701-1:2017) [15]. For each intervention, the primary energy consumption is calculated as the main energy performance index:

- PEC – Primary Energy Consumption in (kWh/m2 of conditioned floor area)

In an effort to make the current evaluation as up to date as possible the electricity primary energy factor as well as the electricity CO_2 emission factor were updated (Table 2) with the latest values according to the revised version of the National Energy and Climate Plan (NECP), officially adopted in December 2024 [17].

The primary energy factors for electricity consumption from the grid and for natural gas consumption on site are presented in the following table:

Energy carrier	Primary energy conversion factor	Greenhouse gas emissions factors
Electricity from the grid	1.489	327.4 g/kWh
Natural gas	1.050	196.0 g/kWh

Table 2: Primary energy and emissions factors

The economic evaluation of each intervention is carried out with a calculation tool that meets the requirements of EN 15459-1 "Heating systems and water-based cooling systems in buildings - Energy performance of buildings Part 1: Economic evaluation procedure for energy systems in buildings". For each intervention, the corresponding capital cost as well as the annual costs and savings (benefits) are calculated from a financial perspective. The interest rate used for the economic calculations is set at 7%, while an annual energy price increase rate of 2.8% is also considered - both consistent with values used in previous studies.
The database of the capital cost of IPs was fully updated to reflect the latest developments of the respective market of energy retrofitting. These include insulation, windows replacement, solar thermal and PV systems, LED lighting fixtures, as well as all the basic technologies for heating and DHW systems investigated. As an example, Figure 2 depicts the specific cost of the latter ones as a function of the heating capacity. In the HP systems a change of trend is evident at capacities of around 35 to 50 kW which is explained by the change of technology as the shift from domestic scale to high-capacity units disrupting the overall economy of scale.

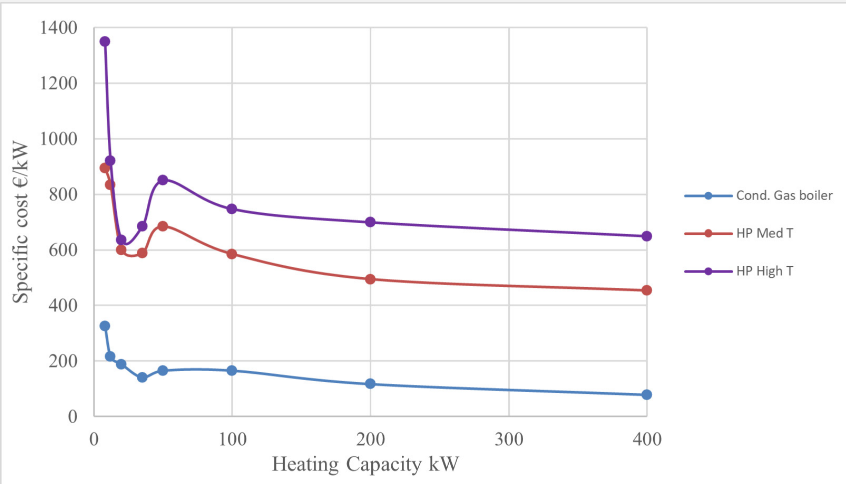


Figure 2: Specific initial investment cost for Gas boilers & Heat Pumps

In addition, new tools were developed for the energy pricing (natural gas and electricity) according to the latest tariffs of the providers. Figure 2: Specific initial investment cost for Gas boilers & Heat PumpsAn innovative aspect of the techno-economic evaluation, enhancing its accuracy, is that the baseline prices for natural gas and electricity are directly derived from the simulated energy consumption of each scenario. As is generally well known, the natural gas prices tend to decrease as consumption increases, reflecting bulk pricing benefits and tiered tariff structures. In contrast, electricity prices generally rise with higher consumption, mainly due to progressive tariff schemes. These opposing trends emphasize the need for targeted energy policies and efficient consumption planning across different energy sources.

Under the methodological framework set above, all the IPs for all construction periods and climate zones for the three typical buildings are simulated and assessed. For every package, two major economic performance indexes are calculated:

- LCC – Life Cycle Cost (in Euro/m2) which corresponds to the present value of the total cost of the building usage per conditioned floor area for an assessment period of 30 years for residential buildings and 20 years for private/ commercial buildings as defined in Regulation 244/2012 [18].
- DPP – Depreciated Payback Period (in years) which corresponds to the amount of time (in years) that is required for the cumulative LCC to become equal to zero

$$LCC=\sum_j \left[C_{inv,j}+\sum_i \left(C_{a,j}\left(\frac{1}{1+p}\right)^i\right)+C_{disp,j}-C_{val,j}\right] \quad \textbf{Eq 1}$$

Where:
Cinv : the initial investment cost,
Cdips: the final disposal cost,
Cval: the residual value,
Ca: net annual operation and maintenance cost (includes energy cost)
p: discount rate for deduction of the Ca (7% for the current study)

$DPP=ln(SPB(p+1)(r/(p+1)-1)+1)/ln(r/(p+1))$ **Eq 2**

Where:
$r=((\delta+1))/100$ **Eq 3**

r: annual variation of energy prices
δ: annual increase rate of the energy prices (2.8% for the current study)
SPB: simple payback time

In addition to the economic benefits, the simulation results allow the estimation of the environmental benefits from the reduction of CO2 emissions per year of use and during the life time of the installation/system. However, these benefits do not affect the financial perspective that is under evaluation in this paper.

3. Results

As explained in the methodology section, the key performance indexes of the IPs' assessment are PEC, LCC and DPP. Based on these, a series of charts are plotted for all typical buildings in order to facilitate the evaluation. PEC vs LCC and PEC vs DPP charts are the major ones that depict the two basic financial indicators vs the energy performance indicator. In these charts the IPs are grouped i) based on the heating system (and DHW if applicable) and ii) based on the installation of a PV system or not.
In PEC vs LCC charts, the "cost optimal region" can be distinguished under the dashed horizontal line. It's a region of significance under which an intervention package (IP) could be considered cost optimal. The threshold Lec,LCC (Eq. 4), is set as the 10% of the range of the minimum and the maximum cost and is provided as a recommendation taking into account the overall distribution of the result. Another dashed line, vertical to the first, sets the boundary from the primary consumption perspective. The threshold LnZEB,PEC (Eq. 5) is the primary consumption of the cost optimal IP (the one with the lowest LCC) increased by 50%.

$L_{ec,LCC} = LCC_{min} + 0.1(LCC_{max} - LCC_{min})$ **Eq 4**

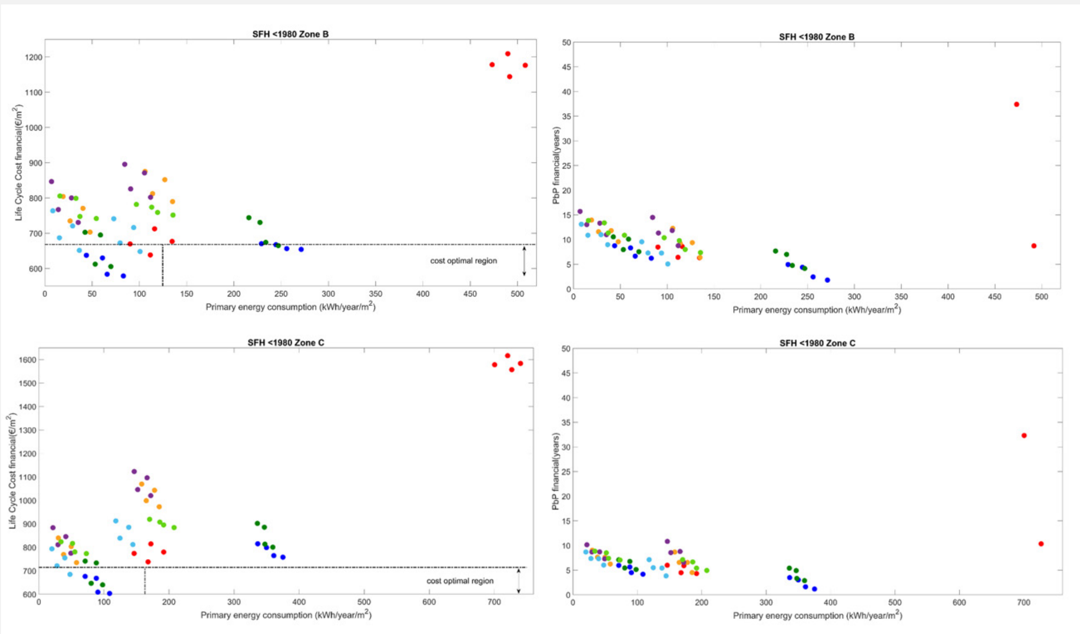
$0 \leq PEC_{individual\ scenario} \leq L_{nZEB,PEC} = PEC_{LCCmin} + 0.5PEC_{LCCmin}$ **Eq 5**

Secondary bar charts are also plotted to depict the frequency of specific interventions in the packages that are within cost optimal region. These charts are categorized by the type of system that they include (horizontal axis) and with the different colour show if they include one of the following interventions.

a) for residential buildings: PVs, insulation and solar thermal system for DHW
b) for office building: PVs, insulation, LED lighting, ventilation upgrade

Indicative charts as were described above, are presented for each typical building. A short discussion follows with the basic observation and findings before the more analytical conclusions at the last chapter.

3.1 SFH building



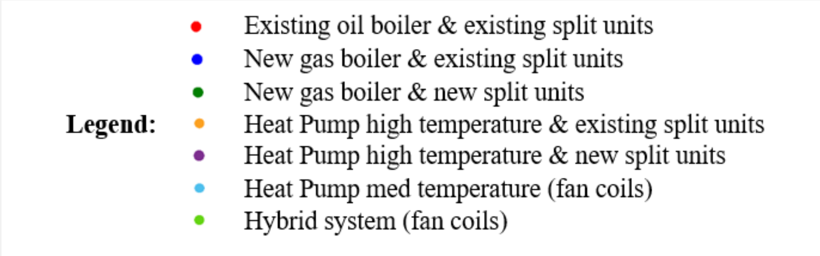


Figure 3: LCC vs PEC and DPP vs PEC charts for Single Family House in CP1(-1980) and climate zone B & C

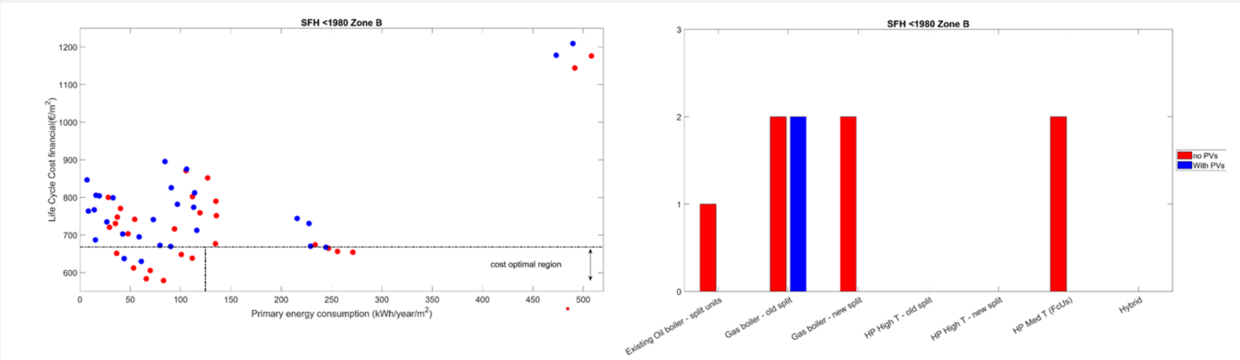


Figure 4: LCC vs PEC chart based on PVs or no PVs in the intervention package & respective frequency bar chart for SFH in CP1(-1980) and climate zone B

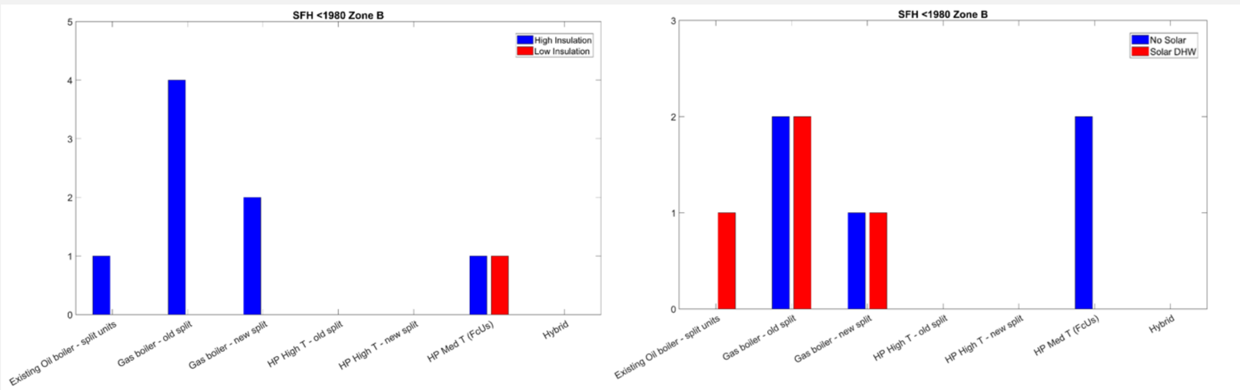


Figure 4: LCC vs PEC chart based on PVs or no PVs in the intervention package & respective frequency bar chart for SFH in CP1(-1980) and climate zone B

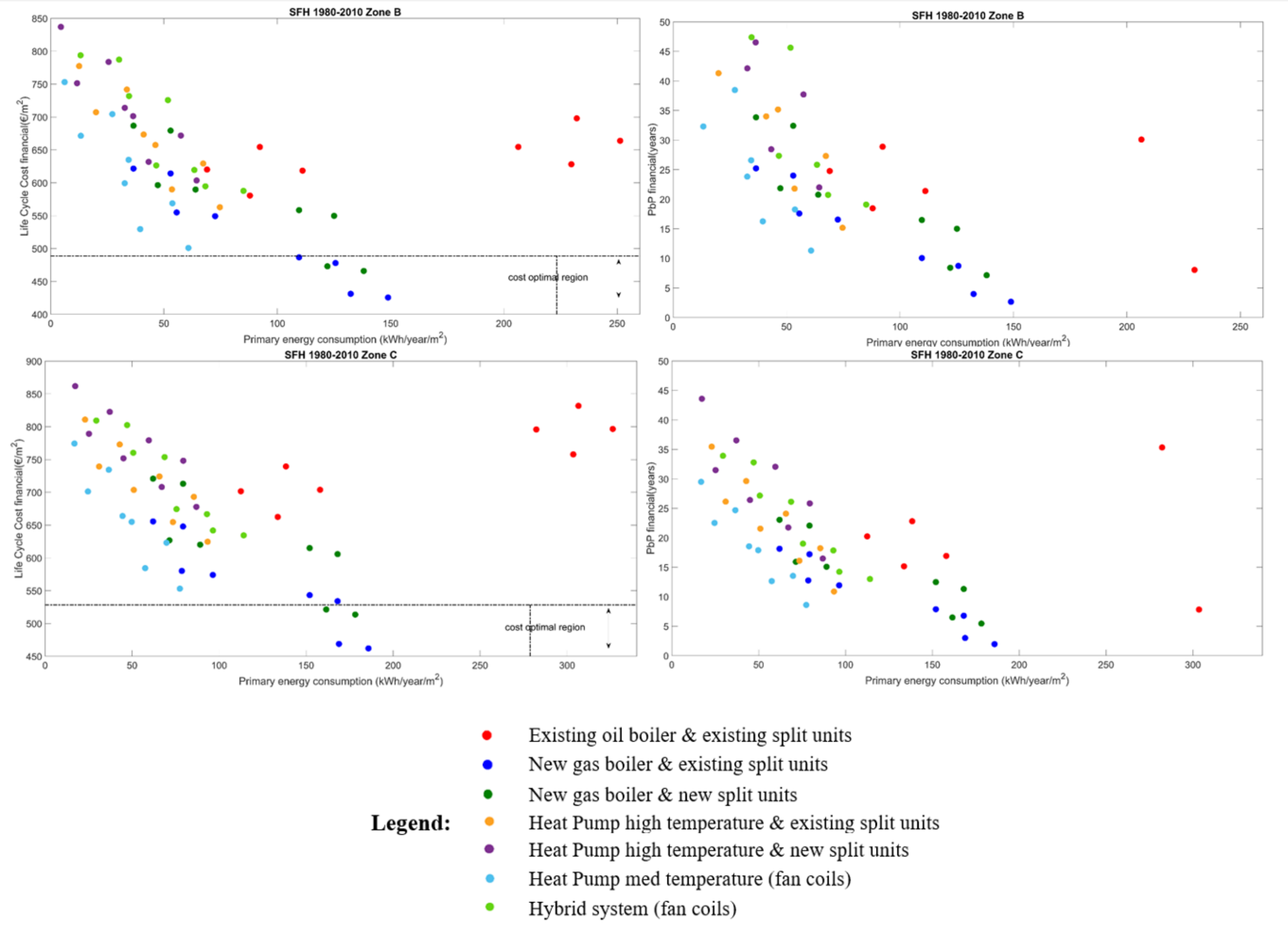


Figure 6: LCC us PEC and DPP us PEC charts for SFH in construction period 2 (1980-2010) and climate zone B & C

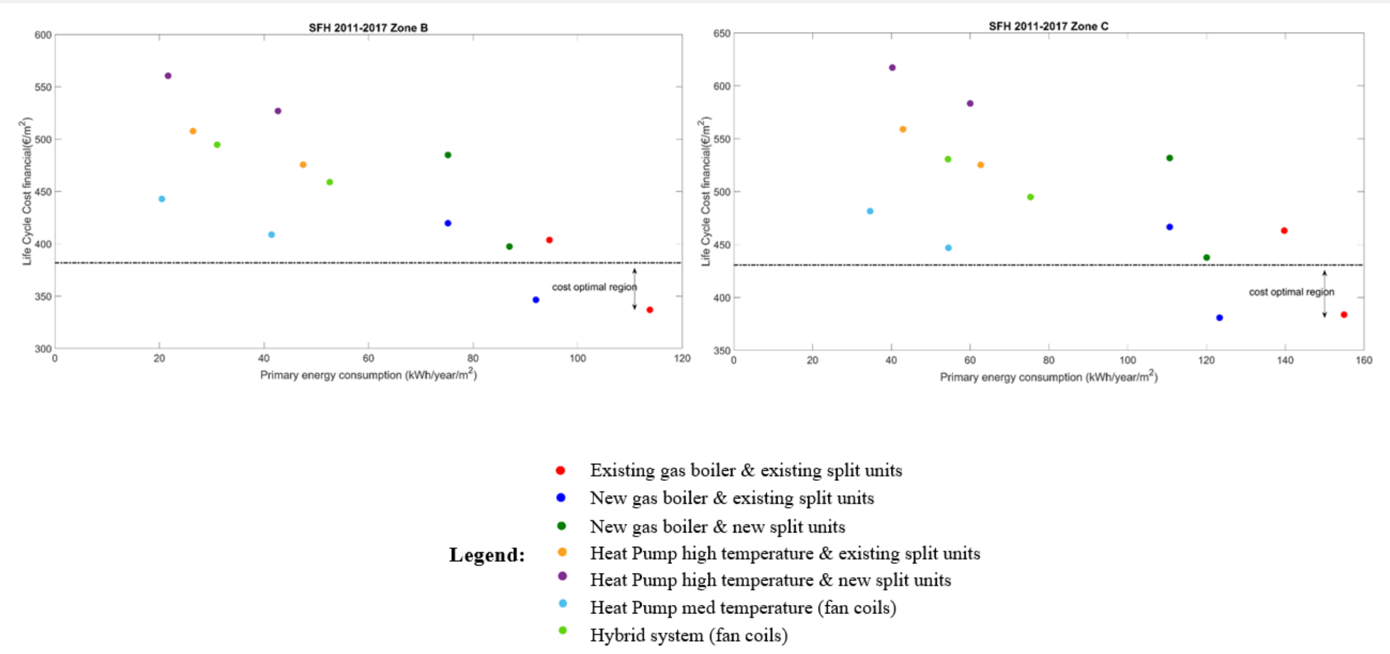


Figure 7: LCC us PEC and DPP us PEC charts for SFH in CP3 (2011-2017) and climate zone B

3.1.1 SFH - General remarks

A general conclusion that stands for all CPs is that LCC and PEC increase as climate zones goes from coastal to continental, from A to D. This happens due higher consumption for heating and DHW which is caused by the higher heating demand. This remark is in line with the fact that the major energy use in single family houses is heating and for this reason affects significantly the total PEC. Next, conclusions are derived separately for each CP.

CP1: prior to 1980

In Figure 3, LCC and PBB vs PEC charts are presented for CP1 and climate zones B & C which represent the oldest buildings in the climate zones and where the majority of the Greek population lives. As it is obvious from these charts, for all different energy systems technologies there are several IPs that enable the typical building to operate within a low to very low range of PEC (in many cases, even below50kWh/m2). This highlights that no single solution is universally optimal and rather all technologies can substantially reduce annual energy costs while achieving the same indoor quality. Across all climate zones (A to D), retrofit packages that include natural gas appliances offer the best performance in terms of LCC (€/m²). However, electrically driven systems achieve the lowest PEC values, meeting nearly Zero Energy Building (nZEB) standards.

In terms of DPP, almost all IPs fall under 15 years in zone B and under 10 in C due to the fact that energy performance of the existing buildings is really poor due to uninsulated building envelopes and low efficiency systems. From a system technology perspective, the inclusion of natural gas technologies in the IPs is significantly reduces DPP. Nearly all IPs involving natural gas exhibit substantially shorter payback periods compared to equivalent IPs with electrically driven technologies. This is a critical finding, as it directly influences the investment's associated risk over the medium to long term. Moreover, as climatic conditions become more continental – from climatic zone A to zone D – DPP tends to decrease for the same intervention. This trend is primarily attributed to higher energy costs in colder climates, which improves the return on investment.

In Figure 4, LCC vs PEC chart is presented but now showing only if the IPs include a PV system or not. On the right, the respective frequency bar chart shows how many packages with or without PVs fall within the cost optimal region. Figure 5 shows two frequency bar charts showing i) insulation and ii) solar thermal for DHW. From these charts another remark is that PVs inclusion in the IPs has negative effect on both LCC and Payback period. This is mainly attributed to the regulatory framework of Net Billing, which has replaced recently the previous net metering scheme. Residential electricity consumption schedule does not coincide with on-site generation especially in the winter, reducing self-consumption and consequently economic benefits of PVs. This is also evident in respective system frequency bar charts (Figure 5), where no PVs scenarios are dominant, in the cost optimal region. On the other hand, solar thermal systems for DHW seem to have a neutral effect on LCC.

Last but not least, passive measures also contribute significantly when reaching low PEC is the main target. In addition, LCC of IPs with insulation also tend to be fully comparable with similar "only" system related interventions. This is further amplified as the climate becomes more continental, as the heating demand increase significantly.

CP2: 1980 - 2010

Moving to CP2, Figure 6 shows that all IPs achieve better LCC and PEC than CP1 due to the improved envelope insulation and higher efficiency systems of that period.

Same as in CP1, from LCC/PEC perspective, low PEC (<50 kWh/m2) can be achieved by all different technologies but IPs including natural gas appliances perform better in terms of LCC. Better PEC results however are achieved with electrically driven technologies.

Due to the better performing existing state of the building, IPs with a DPP of less than 15 years are reduced significantly compared with CP1 and again, IPs natural gas systems show the lowest payback periods making investment more attractive.

As far as solar energy interventions are concerned, PVs have similar performance as in CP1 as well as DHW solar thermal systems.

Passive interventions in IPs are now having higher LCC than IPs without them, because building envelope of CP2 is considered insulated even with the low requirements of 1979 regulation.

CP3: 2010 – 2018 & CP4: 2018 – 2023

In these CPs insulation levels meet the 2010 and 2017 regulations requirement and further passive measures in order to reach even lower PEC were not considered as the LCC would increase significantly. This is in line with literature review and previous research papers.

Figure 7 shows that in CP3 and CP4 almost no IPs are within cost optimal region and DPP (not presented) is well over 15 years making the investment not viable. This result was expected due sufficient insulation and quite efficient systems. More specifically, in climate zones B and C, the existing system which is a gas boiler (non-condensing for CP3 and condensing for CP4) achieves the lowest LCC. In climate zones A and D where the existing system is an oil boiler, IPs with a new gas boiler get the lowest LCC.

In terms of PEC, natural gas (existing or in IPs) is in the range of 60-120 kWh/m2 while below that electrically driven technologies are necessary. PVs are not cost effective while solar thermal systems for DHW are obligatory for CP3 & CP4 buildings so they are considered as existing.

3.1 SFH building

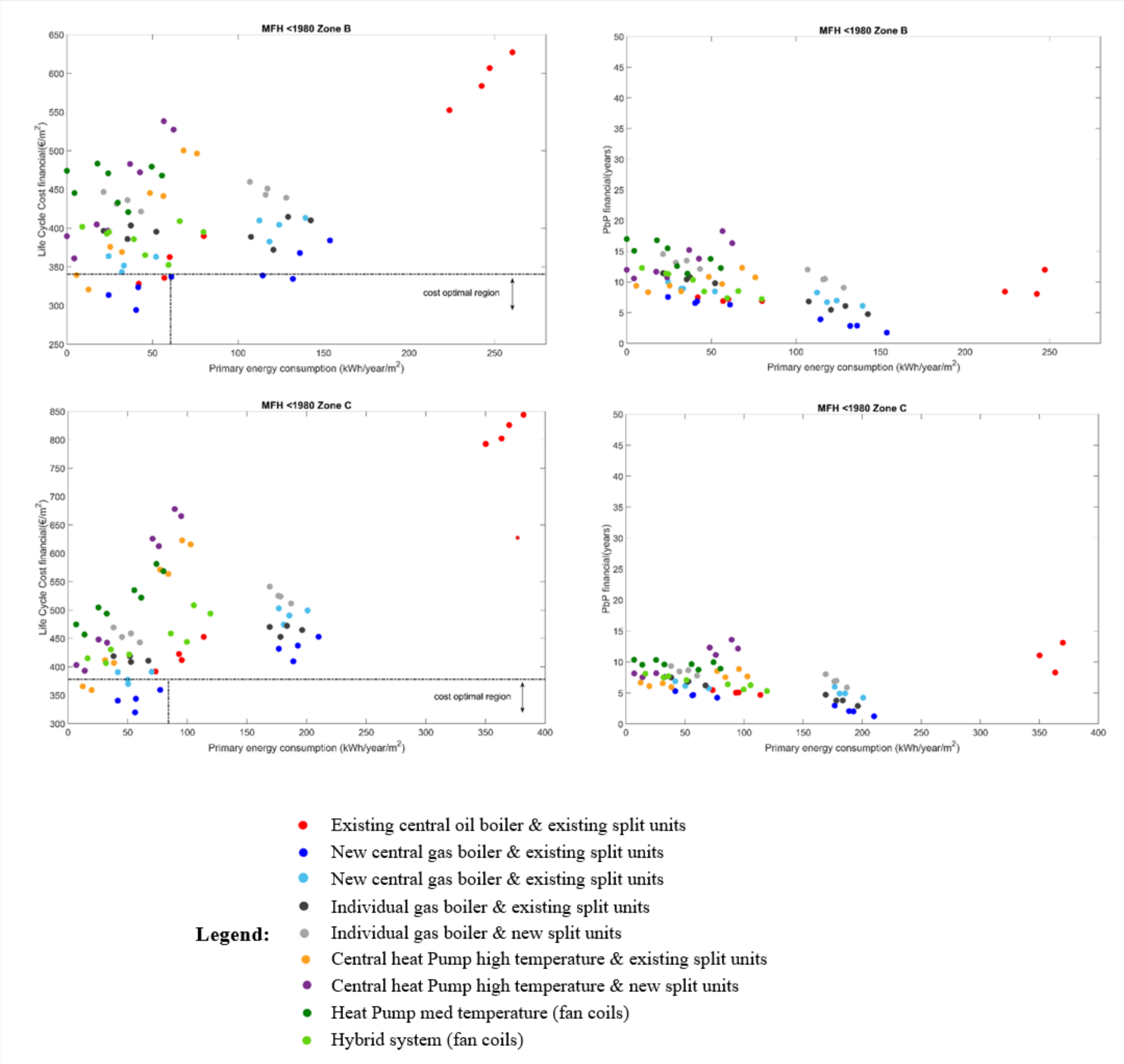


Figure 8: LCC us PEC and DPP us PEC charts for Apartment building in construction period 1(-1980) and climate zone B & C

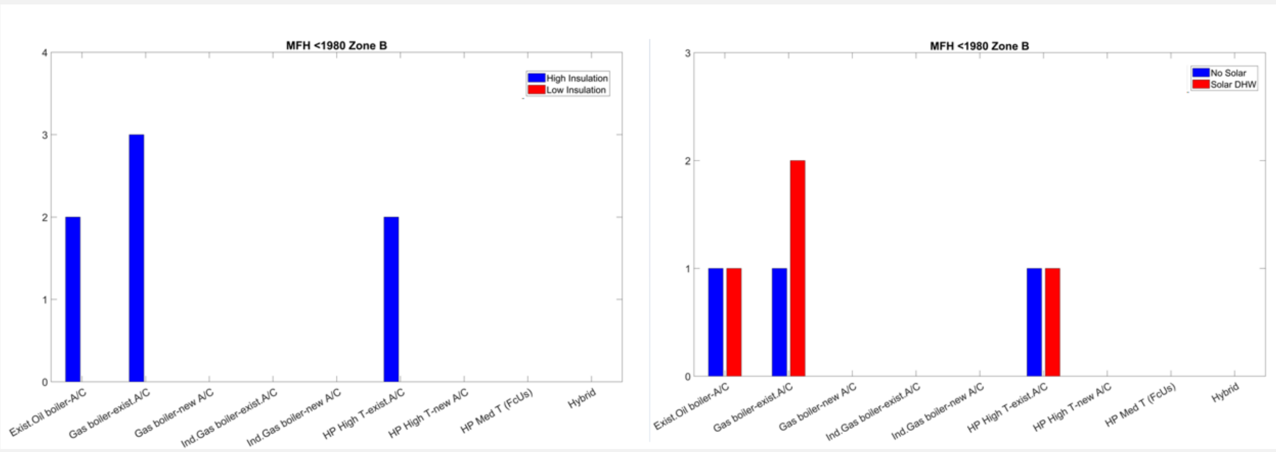


Figure 11: Frequency bar chart for packages including insulation and solar thermal system for DHW for Apartment Building CP 1 (-1980) and climate zone B

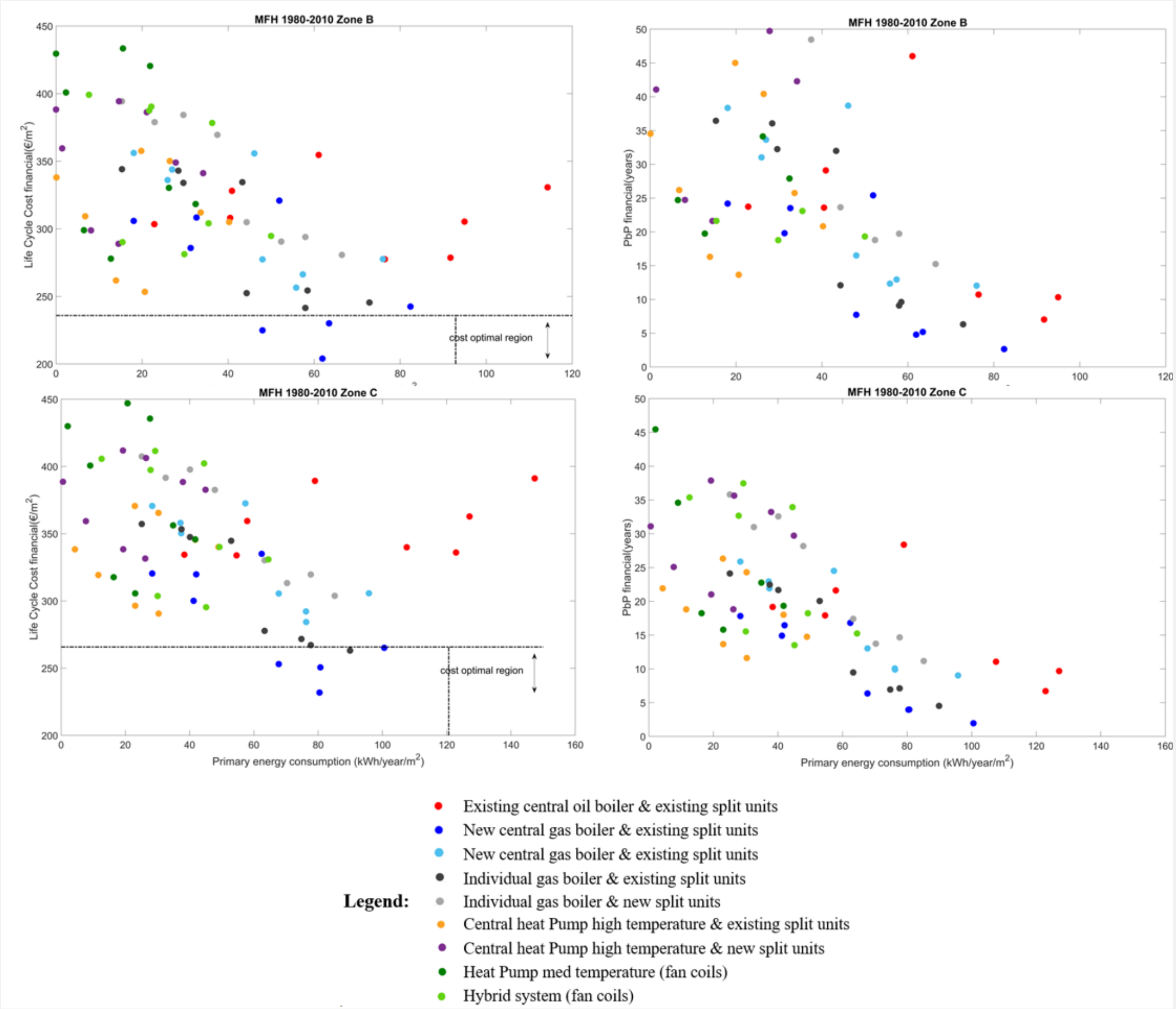


Figure 10: LCC vs PEC and DPP vs PEC charts for Apartment Building in CP 2 (1980-2010) and climate zone B & C

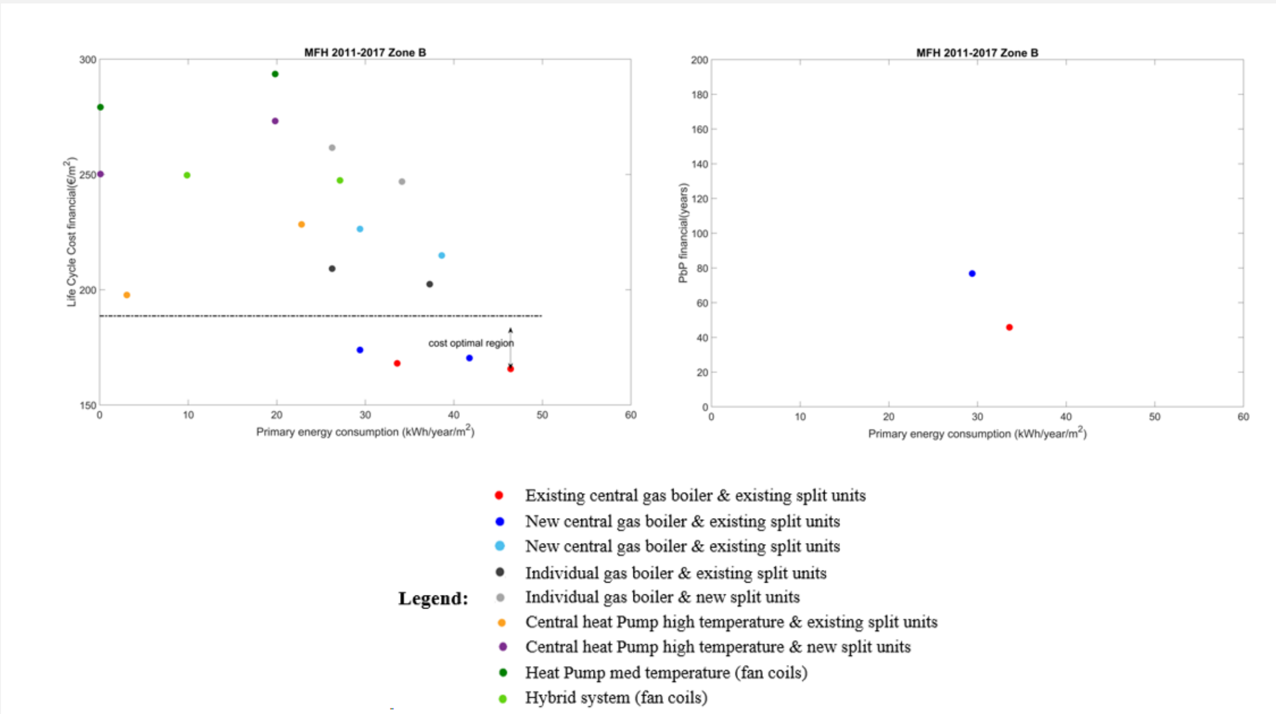


Figure 12: LCC vs PEC and DPP vs PEC charts for Apartment Building in CP3 (2010-2018) and climate zone B

3.2.1 MFH - General remarks
The same general conclusion as in SFH stands also for MFH buildings for all CPs. LCC and PEC increase as CZs goes from coastal to continental, from A to D, due to higher consumption for heating and DHW, caused by higher heating demand. However, due to the size and the shape of the apartment building the specific consumption per area of heating space is lower than that of SFH building. Another general remark is the effect of the economy of scale on LCC results. Central heating systems (electrically driven or not) present reduced Life Cycle Costs, by even more than 25%, compared to individual (per apartment) equivalent systems. Next, conclusions are derived separately for each CP.

CP1: prior to 1980
In Figure 8, LCC and PBB vs PEC charts are presented for CP1 and climate zones B & C which represent the oldest buildings in the climate zones and where the majority of the Greek population lives. Several IPs including all different energy systems technologies enable the typical building to operate within a low to very low range of PEC (<50kWh/m2). This highlights that no single solution is universally optimal and rather all technologies can substantially reduce annual energy costs while achieving the same indoor quality. Across all climate zones (A to D), retrofit packages that include natural gas appliances offer the best performance in terms of LCC (€/m²). However, electrically driven systems achieve the lowest PEC values, meeting nZEB standards.
In terms of DPP, most of the IPs fall under 15 years in zone B and under 10 years in zone C as existing buildings have a really poor performance due to uninsulated building envelopes and low efficiency systems. From a system technology perspective, the inclusion of natural gas technologies in the IPs significantly reduces DPP. Almost all IPs involving natural gas deliver significantly shorter payback periods compared to equivalent IPs with electrically driven technologies. This is a critical finding, as it directly influences the investment's associated risk over the medium to long term. Moreover, as climatic conditions become more continental – from climatic zone A to zone D – DPP tends to decrease for the same intervention due to higher savings potential.
The aforementioned LCC and DPP performance of IPs with natural gas technologies is valid mostly for central heating systems. Installing individual gas boilers is more expensive and the respective IPs have higher LCC and DPP than central HP systems. However, when compared with individual HP systems they tend to be more cost effective depending on the climate zone and the combined cooling system.
In Figure 9, LLC vs PEC chart is presented categorized by the inclusion or not of a PV system. On the right, the respective frequency bar chart shows how many packages with or without PVs fall within the cost optimal region. In contrast to the SFH case, IPs with PVs in MFH improve LCC and DPP even when combined with non-electrically driven heating systems. The main reason for this is lower specific cost due to larger PV system (economy of scale) as the new net-billing regulatory framework allows for one common installation in apartment buildings. In the respective system frequency bar charts (Figure 5), it is also verified that IPs with PVs are dominant in the cost optimal region.
Figure 11 shows the performance of the rest of the measures i) insulation and ii) solar thermal for DHW in the respective frequency bar charts showing. As in SFH, passive measures contribute significantly for reaching low PEC while they achieve LCC comparable with IPs that include only systems upgrade measures. Performance of passive measures improves as the climate becomes more continental and the heating demand increases. On the other hand, solar thermal systems for DHW seem to have a neutral effect on LCC.

CP2: 1980 - 2010
In CP2, as shown in Figure 10 all IPs achieve better LCC and PEC than CP1 due to the improved envelope insulation and higher efficiency systems of that period.
From LCC/PEC perspective, low PEC (<50 kWh/m2) can be achieved by all different technologies but IPs including natural gas appliances perform better in terms of LCC. As a matter of fact, for all climate zones, only IPs with natural gas technologies are within cost optimal region as it is defined in this paper. On the other hand, the best PEC results however are achieved with electrically driven technologies.
Due to the better performing existing state of the building, IPs with a DPP of less than 15 years are reduced significantly compared with CP1 and again, IPs natural gas systems show the lowest payback periods making investment more attractive. Moving from milder to colder zones DPP of most of the IPs reduces significantly. Apart from the higher heating demand, this is also explained by the fact that insulation requirements (Umax) of 1979 regulation were the same for all climate zones
As far as solar energy interventions are concerned, PVs have less positive impact than in CP1 while DHW solar thermal systems effect stays neutral. On the contrary, passive interventions in IPs now induce higher LCC than IPs without them, because building envelopes of CP2 are considered insulated even with the low requirements of 1979 regulation.

CP3: 2010 – 2018 & CP4: 2018 – 2023
In these CPs insulation levels meet the 2010 and 2017 regulations requirement and further passive measures in order to reach even lower PEC were not considered as the LCC would increase significantly. This is in line with literature review and previous research papers.
Figure 7 shows that in CP3 and CP4 almost no IPs are within cost optimal region and DPP (not presented) is well over 15 years making the investment not viable.

This result was expected due sufficient insulation and quite efficient systems. More specifically, in climate zones B and C, the existing system which is a gas boiler (non-condensing for CP3 and condensing for CP4) achieves the lowest LCC. In climate zones A and D where the existing system is an oil boiler, IPs with a new gas boiler get the lowest LCC. However, due to the relatively high efficiencies of existing systems, energy savings are not significant to justify the investment, a fact that is reflected in very high DPP.
In terms of PEC, natural gas (existing or in IPs) are in the range of 30-60 kWh/m2 while below that electrically driven technologies are necessary. PVs are not as cost effective as in CP1 & CP2 while solar thermal systems for DHW are obligatory for CP3 & CP4 buildings so they are considered as existing.

3.2.1 MFH - General remarks

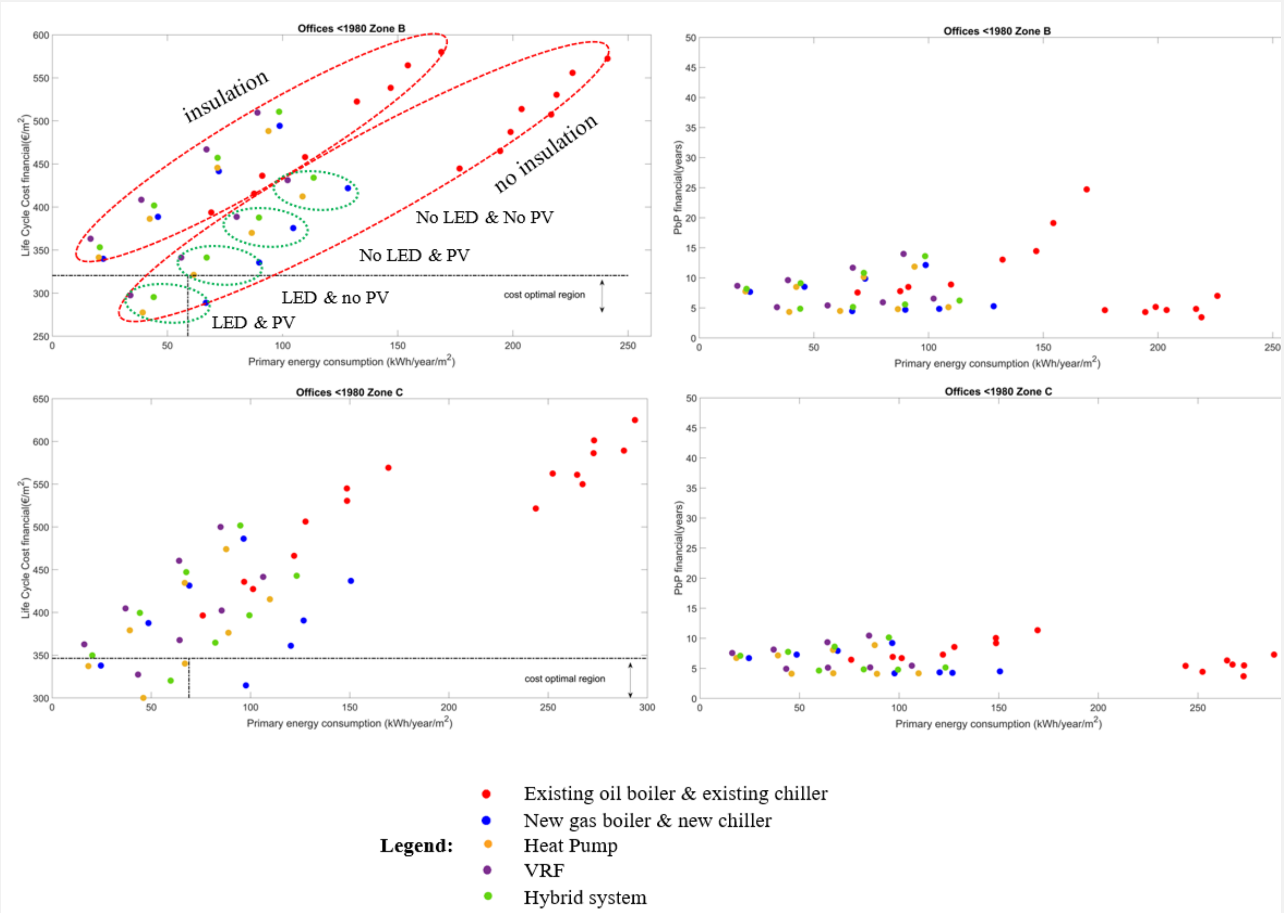


Figure 13: LCC vs PEC and DPP vs PEC charts for Office building in CP1(-1980) and climate zone B & C

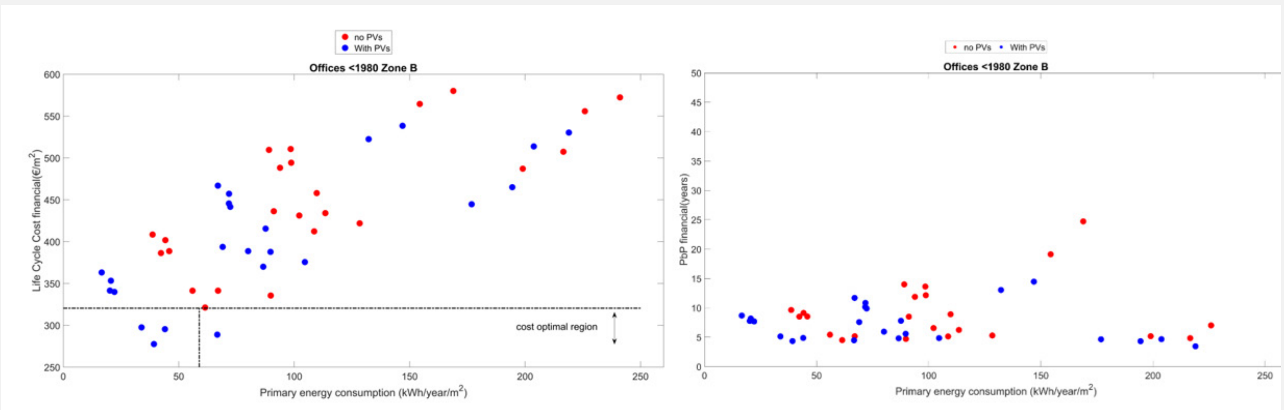


Figure 13: LCC vs PEC and DPP vs PEC charts for Office building in CP1(-1980) and climate zone B & C

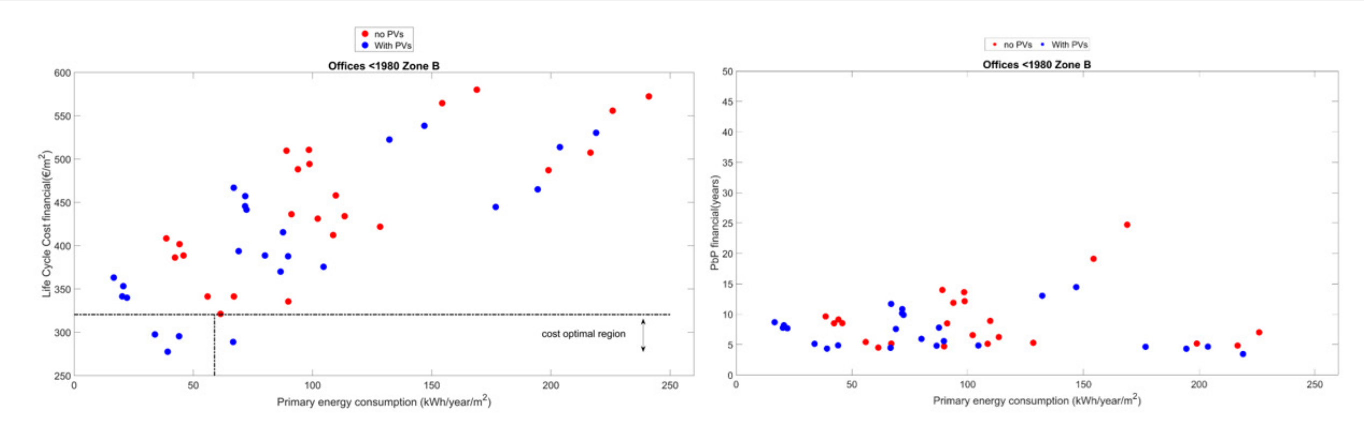


Figure 14: LCC vs PEC & DPP vs PEC chart for Office Building CP1 (-1980) and climate zone B based on PVs or no PVs in the intervention package

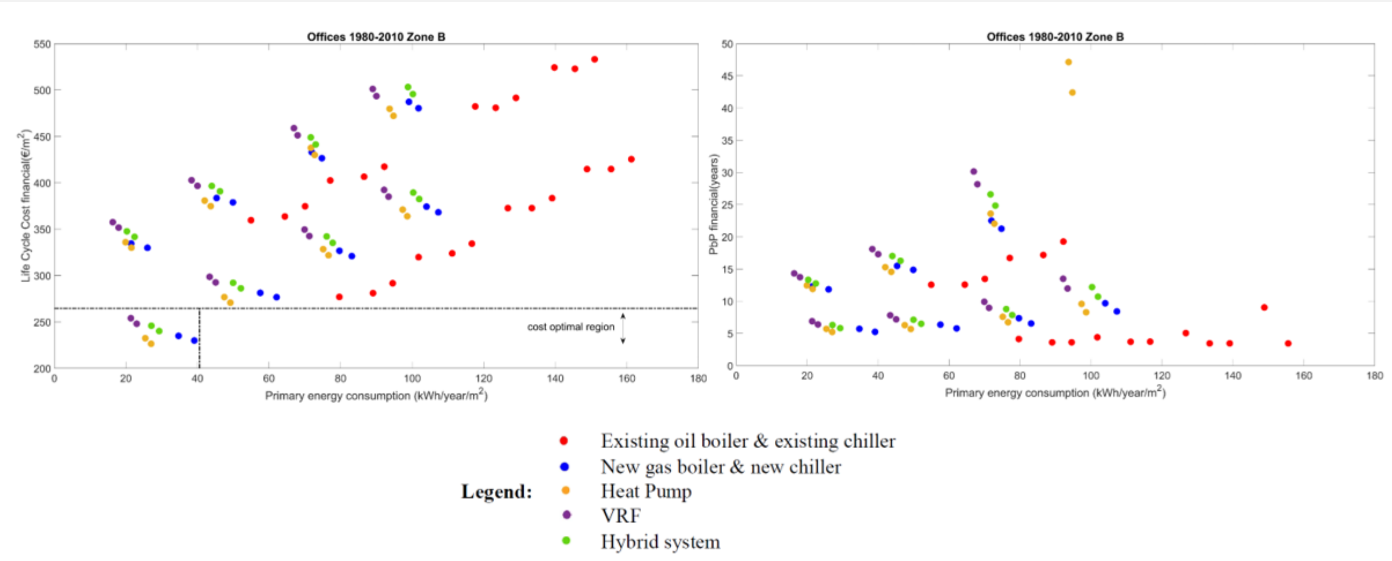


Figure 14: LCC vs PEC & DPP vs PEC chart for Office Building CP1 (-1980) and climate zone B based on PVs or no PVs in the intervention package

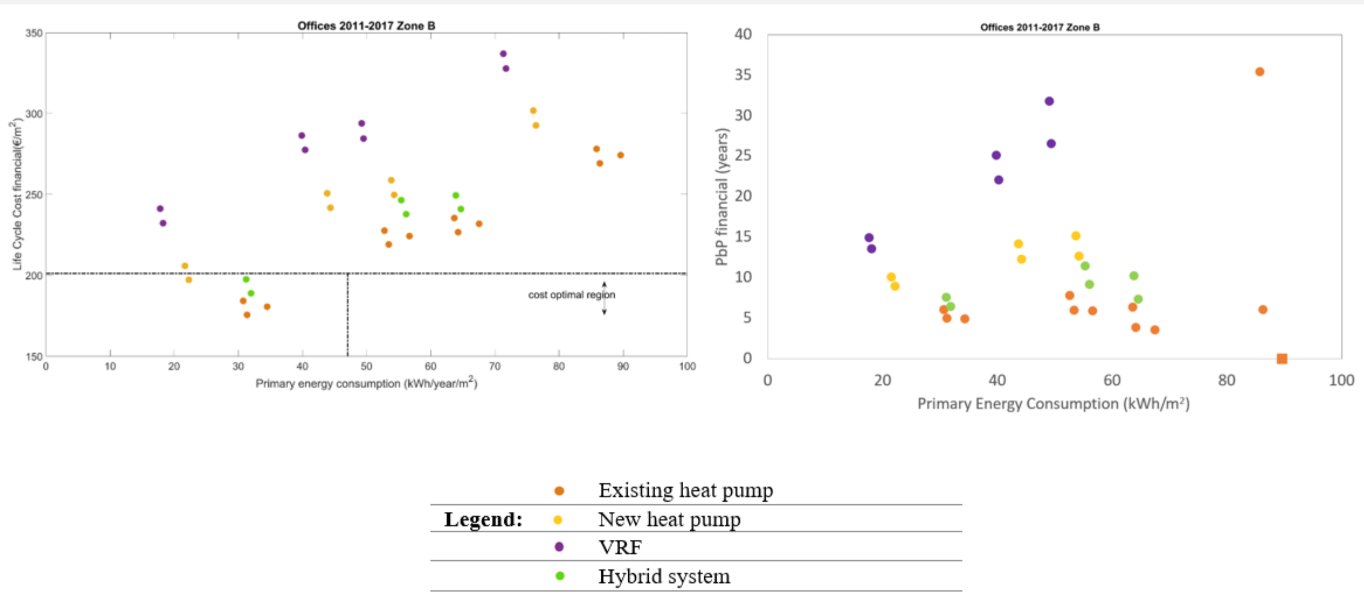


Figure 16: LCC vs PEC and DPP vs PEC charts for Office building in CP3 (2011-2017) and climate zone B

3.3.1 Office buildings - General remarks

Office typical building differentiates greatly from previous two typical residential buildings (SFH & MFH) in terms of type and level of typical annual demands. Office buildings, require significant amounts of energy to cover lighting, ventilation and cooling demands. These demands, as known, are covered by electrically driven systems. Although heating demand also contributes to annual PEC, it is not the dominant one. This particularity dictates that in order to reduce PEC levels and meet nZEB requirements, specific energy measures have to be included in the IPs. Apart from passive ones (insulation and window replacement), the measures are: lighting upgrade, ventilation system upgrade, and PV system for on-site electricity generation.

It is observed in all CPs and all CZs that LCC values of different technologies create clusters of LCC & PEC values close to each other depending mostly on the other measures (LED PV & Insulation) rather than the system technology itself.

Regarding the climate effect, due to the significantly less heating demand and higher cooling demand there is no substantial increase of LCC and PEC as CZ becomes more continental, from A to D.

CP1: prior to 1980

In Figure 13, LCC and PBB vs PEC charts are presented for CP1 and CZs B & C which represent the oldest buildings in the two more populated CZs. Several IPs including all different energy systems technologies enable the typical building to operate within a low to very low range of PEC (<50kWh/m2). This highlights that no single solution is universally optimal and rather all technologies can substantially reduce annual energy costs while achieving the same indoor quality. As explained in the general remarks and is shown at top left chart of Figure 13, several clusters of IPs are formed based on the supplementary measures. In these clusters the lowest LCC is achieved by the HP while the lowest PEC by the VRF system.

In terms of DPP, no definite superior technology can be identified in the IPs. All technologies are included in many IPs with almost similar results of around 5 years. DPP values are generally decreasing when going from climate zone A to D however for some packages this trend is not always clear as heating is not the dominant energy use while lighting and ventilation energy consumptions are constant throughout the zones.

Considering the rest of the measures, the cluster of IPs with PVs and LED present the lowest LCC and the lowest PEC while the cluster with no LED and no PVs the opposite. This proves i) high energy savings from lighting system upgrade and ii) PVs for office use are more cost effective as the on-site generation coincides with electricity consumption due to cooling which boosts net-billing's benefits. Insulation IPs form a group of clusters with a higher LCC than the respective clusters without passive measures. However, in climate zones C and D insulation enters cost optimal region as heating demand rises. Ventilation upgrade is applied in all IPs except the ones with the existing heating and cooling system.

CP2: 1980 – 2010

Figure 15 shows the respective results of CP2 of the typical office building. Clustering of IPs is like in the previous CP and all technologies for heating and cooling perform very close to each other. All technologies can achieve a low to very low range of PEC (<40kWh/m2). HPs still have slightly lower LCC and VRF systems the lowest PEC. Again, DPP for half of the IPs is still very low and with minor differences between technologies and very close to the previous CP1 (slightly higher than five years).

Insulation IPs give higher LCCs and DPPs as expected in an already insulated building, while PVs and LED follow the same pattern, creating the optimal cluster with the lowest LCCs and PECs. Ventilation upgrade slightly increases LCC and decreases PEC.

CP3: 2010 – 2018

The following conclusions should be evaluated under the fact that in these periods, the existing heating system is a HP instead of fuel boilers and chillers that were considered as typical technology in the previous two CPs. Therefore, in order to be as realistic as possible, the evaluation of natural gas as alternative energy carrier is performed only through the hybrid system arrangement. In this arrangement, the existing HP is kept and combined with a modern condensing boiler. Thus, the capital investment is acceptable as an alternative to the existing infrastructure.

Furthermore, in those periods where significant insulation levels have already been installed (first and amended KENAK 2010 & 2017), further passive measures to reach even lower PEC would not achieve acceptable LCC levels, so were not considered.

In terms of PEC, IPs with VRF or new HP enable the typical building to operate on an annual basis with even lower PEC (<30kWh/m2) compared to the existing. Of course, LCC values are higher than those of the existing system, deteriorating the economical results of such investments. On the contrary, hybrid system although exhibits similar PEC levels to the existing one, it has only slightly higher LCC values. This difference in terms of LCC becomes almost negligible in continental climate zones C&D.

In terms of DPP, there are some IPs that result with acceptable values (less than 10 years). These are the hybrid systems and the new HP accompanied with PVs and LED. Hybrid systems however, do not achieve lower PEC as they keep the existing HP while new HPs result in lower PEC.

CP4: 2018 – 2023
This period has the same characteristics of the previous one with slightly better system efficiencies and LED lighting. As a result, energy savings potential is very low and the only measure that is improving the LCC is PV installation with the existing heating and cooling system

4. Conclusions

In the present study, a comparative assessment of IPs based on heating system upgrade (and DHW systems where applicable) was performed for three typical buildings built in four different construction periods and for all four climate zones of Greece. The assessment criteria were the LCC and the DPP of the investments while pursuing PEC of nZEB levels. Two residential typical buildings and an office typical building were investigated.

An important conclusion is that all technologies in all typical building cases can reduce PEC at nZEB levels with or without synergies of other measures depending on each case.

In the residential sector where dominant energy use is heating, main findings showed that for older buildings (CP1 & CP2) the lower LCCs and DPPs were achieved mostly with IPs including condensing gas boilers. However, lower PEC is a product of electrically driven technologies (HPs). Passive measures are prerequisite for more cost-effective IPs but only for CP1 and in terms of RES measures. Actually, PVs are not cost effective for SFH building while it has a positive impact for MFH building. Solar thermal systems for DHW have a rather neutral impact on cost effectiveness. For typical residential buildings of CP3 & CP4 there are no IPs with acceptable DPP except for gas boilers in CZs where the existing system is an oil boiler.

Summing up the results in a more structured and compact way helps deriving some conclusions. In the following tables, IPs with the best performance in terms of LCC, PEC & DPP are presented.

<table>
<tr><th rowspan="6">Single-Family House</th><th></th><th colspan="4">Lowest LCC</th><th colspan="4">Lowest PEC</th><th colspan="4">Lowest DPP</th></tr>
<tr><th>CP/Cl.Z</th><th>A</th><th>B</th><th>C</th><th>D</th><th>A</th><th>B</th><th>C</th><th>D</th><th>A</th><th>B</th><th>C</th><th>D</th></tr>
<tr><td>CP1</td><td colspan="4">New Gas Boiler/exist. A/C
Insulation
No PV
No Solar DHW</td><td colspan="4">HP Med
Insulation
PV
Solar DHW</td><td colspan="2">HP Med
No Insulation
No PV
No solar DHW</td><td colspan="2">New Gas Boiler
exist. A/C
Insulation
No PV
No Solar DHW</td></tr>
<tr><td>CP2</td><td colspan="4">New Gas Boiler/exist. A/C
No Insulation
No PV
No Solar DHW</td><td colspan="4">HP Med
Insulation
PV
Solar DHW</td><td colspan="4">New Gas Boiler
exist. A/C
No Insulation
No PV
No Solar DHW</td></tr>
<tr><td>CP3
(exist. Solar
DHW)</td><td>New Gas
Boiler
exist. A/C
No PV</td><td>exist. Gas
Boiler
exist. A/C
No PV</td><td colspan="2">New Gas Boiler
exist. A/C
No PV</td><td colspan="4">HP Med
PV</td><td>New Gas
Boiler
exist. A/C
No PV</td><td colspan="2">exist. Gas Boiler
exist. A/C
No PV</td><td>New Gas
Boiler
exist. A/C
No PV</td></tr>
<tr><td>CP4
(exist. Solar
DHW)</td><td>New Gas
Boiler
exist. A/C
No PV</td><td colspan="2">exist. Gas Boiler
exist. A/C
No PV</td><td>New Gas
Boiler
exist. A/C
No PV</td><td colspan="4">HP Med
PV</td><td colspan="3">exist. Oil/Gas Boiler
exist. A/C
No PV</td><td>New Gas
Boiler
exist. A/C
No PV</td></tr>
</table>

Table 3: SFH lowest LCC, PEC & DPP

<table>
<tr><th rowspan="7">Multi-Family House</th><th></th><th colspan="4">Lowest LCC</th><th colspan="4">Lowest PEC</th><th colspan="4">Lowest DPP</th></tr>
<tr><th>CP/Cl.Z</th><th>A</th><th>B</th><th>C</th><th>D</th><th>A</th><th>B</th><th>C</th><th>D</th><th>A</th><th>B</th><th>C</th><th>D</th></tr>
<tr><td rowspan="3">CP1</td><td colspan="4">New Central Gas Boiler/exist. A/C</td><td colspan="4" rowspan="3">New Central or Ind. HP
Insulation
PV
Solar DHW</td><td colspan="4" rowspan="3">New Central Gas Boiler
exist. A/C
No Insulation
No PV
No Solar DHW</td></tr>
<tr><td>No Insulation</td><td colspan="3">Insulation</td></tr>
<tr><td colspan="4">PV
No Solar DHW</td></tr>
<tr><td>CP2</td><td colspan="4">New Central Gas Boiler/exist. A/C
No Insulation
PV
No Solar DHW</td><td colspan="4">New Central or Ind. HP
Insulation
PV
Solar DHW</td><td colspan="4">New Central Gas Boiler
exist. A/C
No Insulation
No PV
No Solar DHW</td></tr>
<tr><td>CP3
(exist. Solar
DHW)</td><td>New Central Gas
Boiler
exist. A/C
No PV</td><td colspan="2">exist. Central
Gas Boiler /
exist. A/C
No PV</td><td>New Central
Gas Boiler
exist. A/C
No PV</td><td colspan="4">Central or Ind. HP
PV</td><td>New Central
Gas Boiler
exist. A/C
No PV</td><td colspan="2">exist. Gas
Boiler
exist. A/C
No PV</td><td>New Central
Gas Boiler
exist. A/C
No PV</td></tr>
</table>

Table 4: MFH lowest LCC, PEC & DPP

Office Building		Lowest LCC				Lowest PEC				Lowest DPP			
	CP/Cl.Z	A	B	C	D	A	B	C	D	A	B	C	D
	CP1	New HP No Insulation New AHU LED PV				New VRF Insulation New AHU LED PV				All technologies produce similar results			
	CP2	New HP No Insulation Upgrade AHU LED PV				New VRF Insulation New AHU LED PV				All technologies produce similar results			
	CP3	Existing HP LED PV				New VRF LED PV				Existing HP PV			
	CP4	Existing HP PV				New VRF PV				Existing HP PV			

Table 5: Office building lowest LCC, PEC & DPP

Overall, the contribution of the study presented is that it provides robust evidence that there is no single, universally optimal energy technology solution. Instead, choices should be based on rational, context-specific criteria such as the use, location, age, and scale of a building—as these factors significantly affect outcomes in terms of energy efficiency, LCC, and DPP, beyond any ideological considerations.

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In-depth Research

Evaluating the Greek National Energy and Climate Plan: A water-energy-emissions Assessment for the Industry Sector

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Abstract

The global Agenda for energy transition and the imperative for climate adaptation mandate a comprehensive understanding of resource use and emissions in energy systems. Industries play a pivotal role in this transformation, both as major energy consumers and as key contributors to greenhouse gas (GHG) emissions. Building climate resilience requires the inclusion of interconnected natural resources such as water in industrial planning, highlighting the need for joint energy-water assessments to develop adaptive and holistic climate mitigation strategies. This consideration is an overlooked issue in southern European countries, given their lower industrialization levels than northern Europe. However, the analysis of resource use and emissions in industrial energy systems is a particularly critical issue for southern European countries because they face significant challenges due to their drier climate, naturally limited water resources, and their high vulnerability to climate change. At the same time, there are major emitting industries in those countries as well, and the sector's energy transition largely depends on their decarbonization as well. This research addresses this gap by analyzing Greece's industrial energy, water demands, and GHG emissions, from 2022 to 2050.

Keywords

Industrial Decarbonization; LEAP Modeling; Energy Demand Analysis; Greenhouse Gas Emissions; Shared Socioeconomic Pathways (SSPs); Greece.

I. Introduction

The simulated scenarios for Greece are the following: a) the do-nothing scenario (business-as-usual - BAU) which assumes that the current trends will continue applying until 2050; b) the NCNC (National Climate Neutrality Commitments) scenario which assumes that the main sector climate-neutrality policies are jointly implemented, for instance, the combination of cleaner fuels & increased energy efficiency; c) Shared Socioeconomic Pathways (SSPs) scenarios, more specifically: SSP1 (sustainability-focused), SSP2 (moderate progress) and SSP5 (fossil-fueled development), but keeping Energy Intensity reduction rates, as projected from the Greek NCNC's.

The Greek National Energy and Climate Plan (NECP) [1], as defined by the Greek Ministry of Energy and Environment (2024), assumes certain interventions per sector. These refer to improvements of energy use efficiencies and cleaner energy mixes.

Shared Socioeconomic Pathways (SSPs) are climate change scenarios of projected socioeconomic global changes up to 2100 as defined in the IPCC Sixth Assessment Report on climate change in 2021 [2]. They are used to derive greenhouse gas emissions scenarios with different climate policies. The SSPs provide narratives describing alternative socio-economic developments.

This paper exams the Greek industrial system with its 15 sub-sectors, including food and tobacco, textiles and leather, wood products, paper pulp and printing, chemicals and chemical products, rubber and plastic, non-metallic minerals, basic metals, machinery, transport equipment, other manufacturing, mining, cement and steel production.

LEAP is an accounting tool [3], giving the overall cross-sectional energy and Emission Analysis. In our current work, we focus in Industrial Sector, in Demand Side but LEAP performs the absolute balance between energy production (both for Electricity and Fuels) and consumption, per sector, sub-sector, use and per fuel, among the variety of currently used fuels or energy carriers (i.e. electricity). LEAP also gives the chance to estimate and calculate the projected fuel mixture shift, from fossils to renewables, taking on consideration specific key drivers that are leading to energy transition and the energy intensity reduction

II. Methodology

A. Main principles

We adopt the following main principles to implement the calculation method of LEAP Platform [4]. First, we capture the change in energy consumption of the overall industrial sector for the entire transition period (2022-2050), that is given by Greek National Climate & Energy Plan (NCEP). Second, the Activity Level (AL) for the total industrial sector is calculated under two (2) options: i) Either is constant (NCEP scenario) or ii) it is changed due to a greater share of the industrial sector within the overall GDP and Value Added (as a percentage of the overall GDP), according to OECD projections for the European Region. Changes in growth rate of total GDP of Greece, across 2022-2050 period, according to IIASA-OECD sources, are influenced by the SSPs, therefore the different SSPs influence the Activity Level (AL) of the Industrial Sector, in each case.

Therefore, both the overall AL of the industrial sector and the individual ALs of each sub-sector will follow the Growth rate of GDP per each SSP, in any case they will perform an increase but with different rates of increase acoss 2025-2050 period.

As far as the water consumption is concerned, The WaterReqGCH model [5] was used to estimate the water requirements for each one of the 15 subcategories considered, based on typical water consumption values per industrial product.

The LEAP and WaterReqGCH models run for two main scenarios – projections until 2050: i) the baseline (BAU or do-nothing) scenario, ii) the Greek National Energy and Climate Plan (NECP, 2024), which assumes certain interventions relevant to the decarbonization of all sectors of the economy, including the industry.

B. Assumptions

If the overall Activity Level (AL) of the industrial sector is projected to vary across the period 2022-2050, then OECD projections [6] for Europe intuit the different share of the total industrial sector and the downscaled sub-sectors between themselves and across other economic sectors.

Figure 1 describes how the economic activities are estimated to change share in the upcoming decades, according OECD projections per continent, therefore the estimated Growth factor of the Industrial Activity Level can be extracted.

	billion USD 2017/yr	Growth Rate of Greek GDP across time					
Socio-economic scenarios	2022	2025	2030	2035	2040	2045	2050
SSP1	305.6	1.1023	1.1083	1.0909	1.0997	1.0927	1.0793
SSP2	305.6	1.1023	1.1067	1.0796	1.0823	1.0753	1.0676
SSP5	305.6	1.1023	1.1113	1.1135	1.1394	1.1389	1.1237

Figure 2 Changes in growth rate of total GDP of Greece, across 2022-2050 period

As a next step, the Activity Level (AL) of all 15 Industrial sub-sectors, as expressed in 2 ways, Value Added in % and Value Added in m€. Figure 3 shows these ALs

	Food and tobacco	Textiles and leather	Wood and wood products	Paper pulp and printing	Chemicals and chemical Products
Activity Level VA%	31.38	2.67	0.47	4.06	12.26
Activity Level VA (m€)	9481.00	807.50	142.50	1225.50	3705.00
	Rubber and plastic	**Non-metallic minerals**	**Basic metals excluding steel**	**Machinery**	**Transport equipment**
Activity Level VA%	**3.24**	**4.59**	**6.35**	**11.32**	**1.76**
Activity Level VA (m€)	978.50	1387.00	1919.00	3420.00	532.00
	Other manufacturing	**Mining**	**Construction**	**Cement production**	**Steel production**
Activity Level VA%	**1.73**	**2.17**	**16.73**	**0.78**	**0.50**
Activity Level VA (m€)	522.50	655.50	5054.00	237.02	150.00

Figure 3 Activity Levels (AL) of all 15 Industrial Sub-sectors.

The calibration of the Model finishes with the defining of the EI reduction, based on NCEP projections (Figure 4, 5, 6).

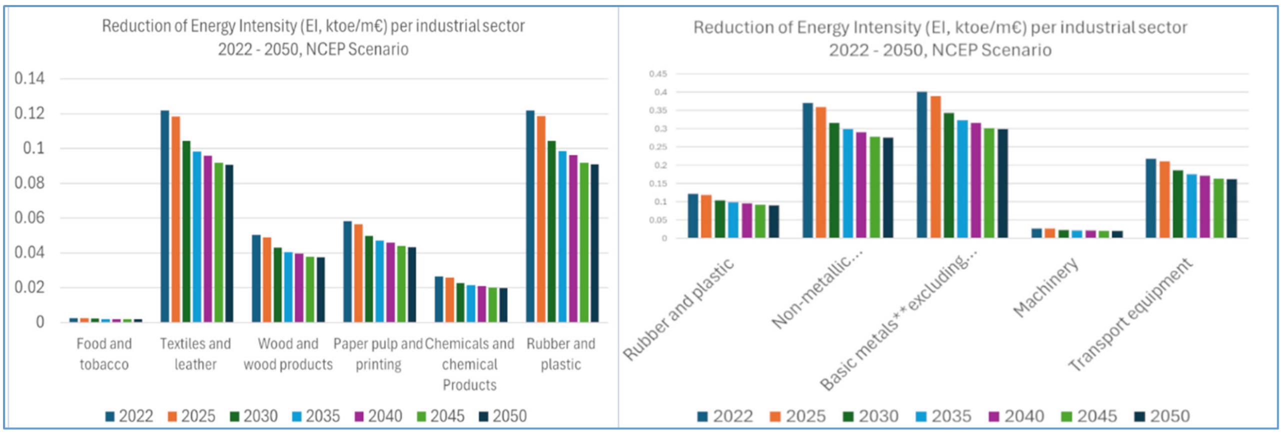

Figure 4. Reduction of Energy Intensity (EI) in ktoe/m€, for 10 industrial sectors: Food & tobacco, Textiles & Leather, Wood & wood Products, Paper pulp & printing, chemicals and Rubber & plastic, Rubber & Plastic, Non-metallic minerals, basic metals (excluding steel), machinery, transport equipment

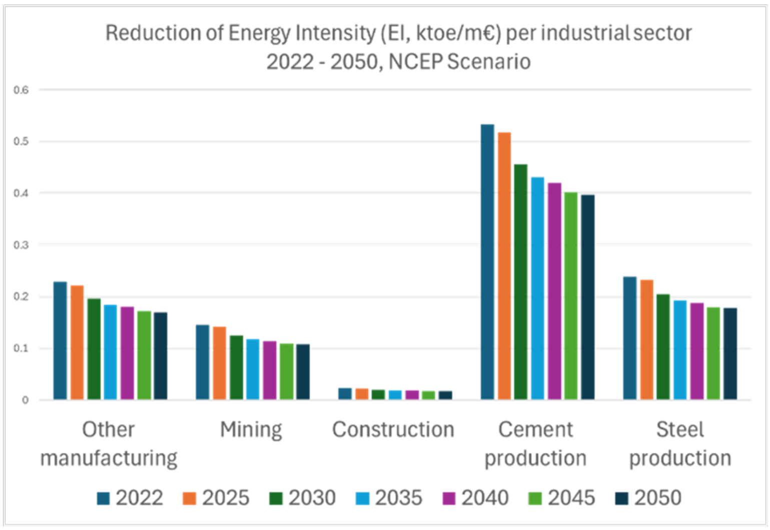

Figure 5. Reduction of Energy Intensity (EI) in (ktoe/m€), for 5 industrial sectors: Other manufacturing, mining, construction, cement industry, steel production

For water stress in industrial sectors, water usage varies largely based on the method of process, the intermediate stages and the peculiarities among raw materials that it might be extracted in each sector.

C. Analysis

The Low Emissions Analysis Platform (LEAP) was used to simulate the energy consumption and the associated GHG emissions of multiple pollutants, of the Greek industrial sectors. Therefore, LEAP Platform includes:

a) Detailed representation of all sectors' energy uses. The energy demand (D) has been calculated as the product of an activity level (AL) and an annual energy intensity (EI, energy use per unit of activity), according to LEAP's Final Energy Demand Analysis method:
*D"sector,scenario"=ALsector,scenario*EIsector,scenario (1)*

b) Detailed representation of all primary feedstock fuels, secondary fuels & their transformation processes to feed the demand.

The primary resources of the Greek Supply energy system are mainly solar power, crude oil, coal lignite, hydropower, wind, coal, municipal solid waste and biofuels.

The secondary resources which are essentially the main energy vectors satisfying the demand of transportation sector are 1) the dominant fossil fuels, such as: Diesel, kerosene, CNG, LPG, gasoline, and 2) the fuels of the energy transition like electricity which already becomes an emerging source for urban mobility and the fuels of the upcoming development of green fueling, such as: Hydrogen, biogas, electricity, synthetic fuels.

c) The GHG emissions which are then estimated automatically and based on the emission coefficients of the IPCC's Fifth Assessment Report (IPCC, 2014) per sector, per use and per fuel type for the demand side, and per process for the supply side. The main types of pollutants are CO2, CH4, N2O, PM2.5, Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Sulfur Hexafluoride (SF_6), Black Carbon (BC), Organic Carbon (OC).

The aggregated estimation of final energy consumption for the Industrial Sector is described by Figure 7.

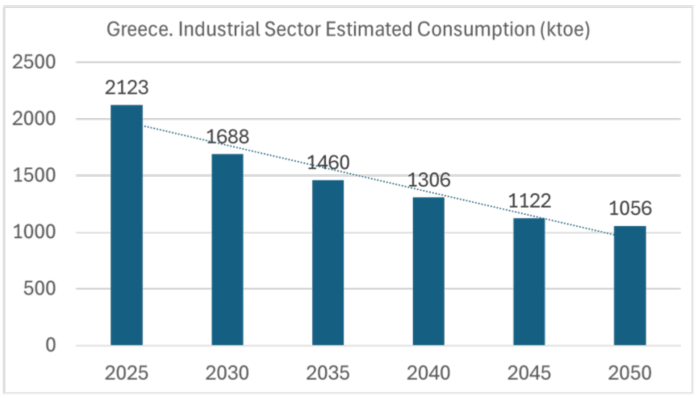

Fig. 6. Greece. Industrial Sector Estimated Consumption (ktoe), Source: Greek Ministry of Energy & Environment (2024): National Energy & Climate Plan (NECP)

The estimated fuel mix, based on the projections of NECP, are shown in Figure 8. Fuels are represented in an aggregated level (for instance, "oil products" is an aggregated category for gasoline, diesel, residual fuel oil etc.)

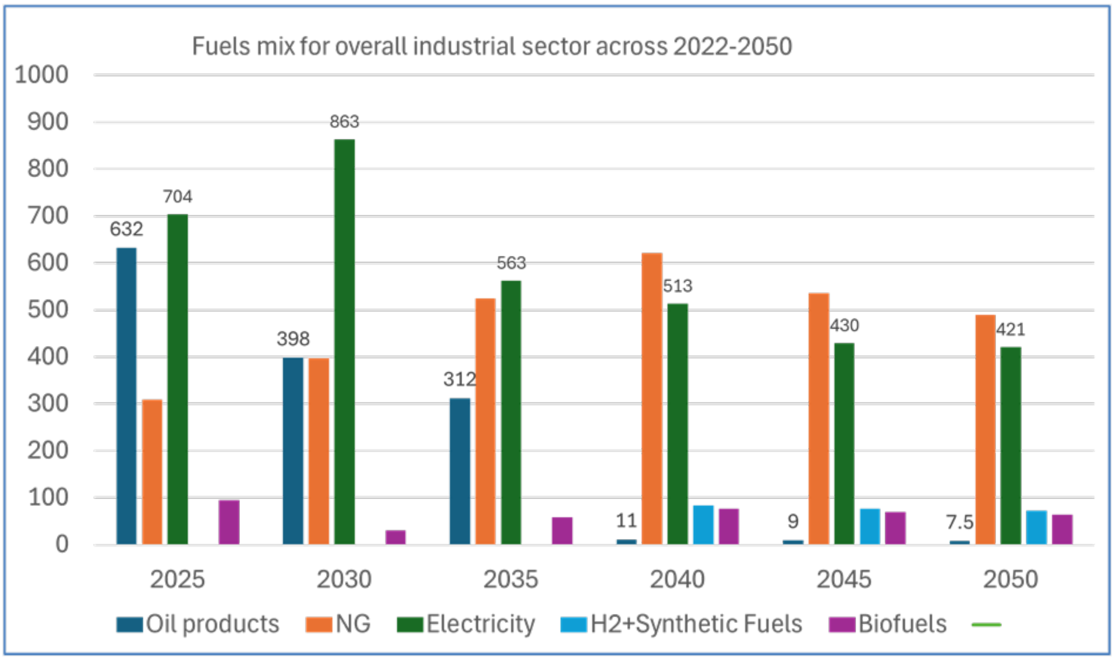

Fig.7 Fuels mix for overall industrial sector across 2022-2050 Source: Greek Ministry of Energy & Environment (2024): National Energy & Climate Plan (NECP)

Furthermore, for water stress in industry, water usage varies significantly among different industries, each with its unique set of challenges and opportunities for sustainable management.

Industries of heavy manufacturing, such as steel, automotive, and machinery manufacturing are among the highest water consumers. They use water primarily for cooling processes, dust control, and metal finishing. Water recycling and reuse are critical in these industries for reducing water intake and minimizing wastewater discharge.

Moreover, the chemical industry uses large amounts of water in the production of chemicals, pharmaceuticals, and petrochemical products. The focus here is on managing process water quality and implementing advanced treatment technologies to allow reuse within the plant and safe discharge into the environment.

Water is a critical component in pulp dilution and paper formation processes, textile and food & beverage industry.

Then, the energy generation facilities use large quantities of cooling water. The challenge is in managing the thermal impacts on water bodies and maximizing cooling water recirculation.

RESULTS

In the BAU scenario, the industrial energy consumption is at a standard level of 2.123 thousand tonnes of oil equivalent (ktoe) and emits 4.724 thousand metric tonnes of CO2 equivalent. These figures have been compared to the NECP scenario, which represents in essence the national commitments to the European Union's Green Deal. In the NECP scenario the overall industrial energy consumption is 50.2% reduced (compared to the BAU), estimated at 1.056 ktoe, in 2050 (Figure 8). This is going to happen through a rate of a continuous consumption reduction from 2025 to 2050.

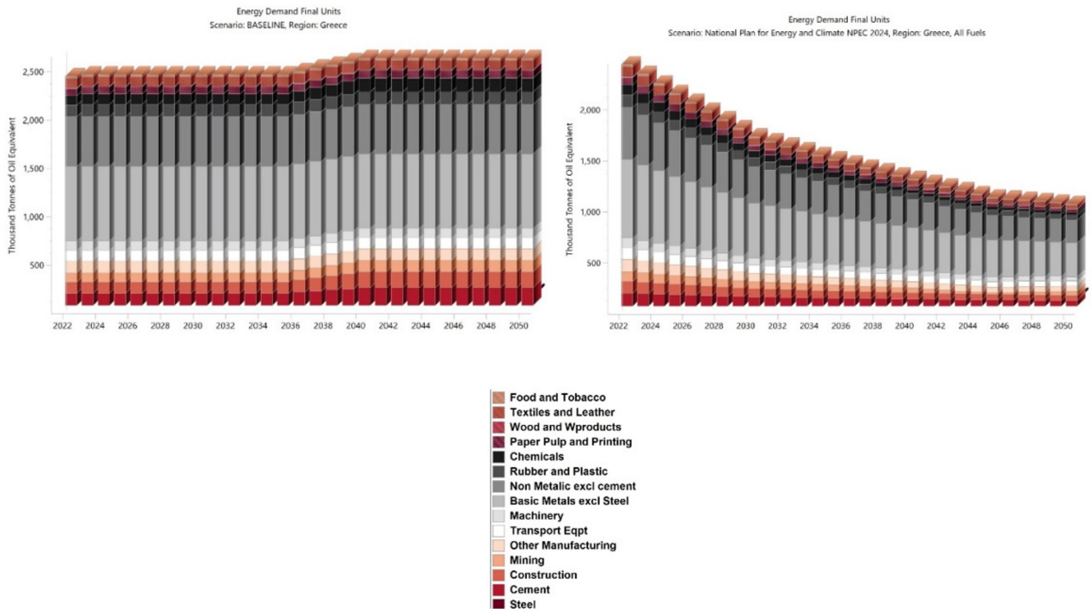

Fig. 8. Comparison of energy demand under NECP and BAU scenarios for all uses and fuels/resources of industry over the 2022 -2050 period

The GHG emissions of the NECP scenario are 1.177 thousand metric tonnes of CO2 equivalent in 2050, a reduction of about 75%, compared to the BAU.

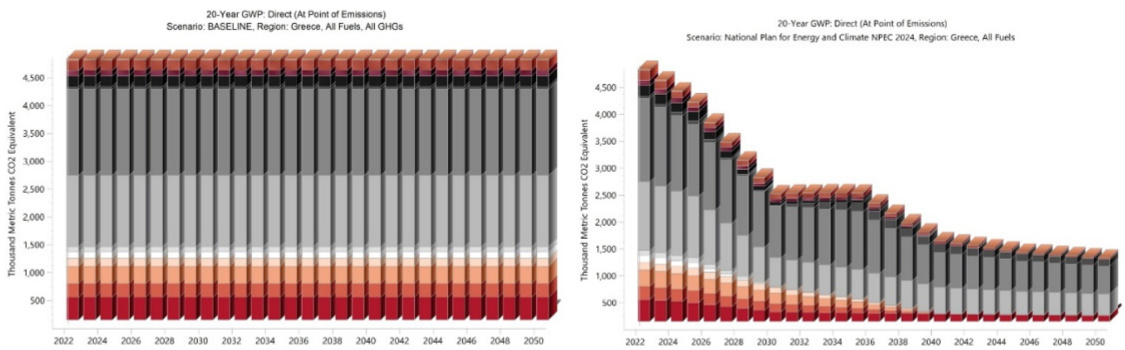

Fig. 9. Comparison of GHG emissions under NECP and BAU scenarios for all uses and fuels/resources of industry over the 2022 -2050 period

With regards to the energy demand for each energy technology or resource, Figure 10 shows the estimated fuel mix as projected by NCEP, over the 2022-2050 period. A great share of Electricity over time, and at the same time drastic reduction of demand are demonstrated: for electricity after 2030 and for Natural Gas after 2040. Coal and fossils are going to be diminished after 2035. Hydrogen and biogas with increased deployment after 2040.

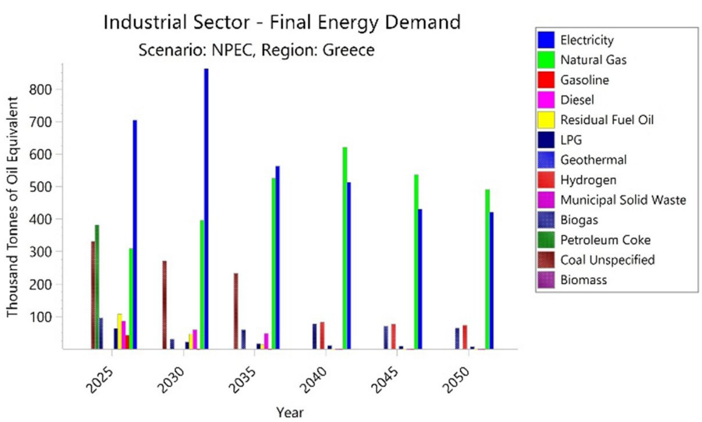

Fig. 10. Estimated energy demand per fuel, as projected by NCEP, over the period 2022-2050

As far as the energy demand projected per industrial sub-sector is concerned, the Non-metallic industries (i.e. ceramics and glass) are going to perform the more drastic reduction. The same for the basic metals excluding steel (non-ferrous metals and aluminum). Steel and cement are going to perform a moderate reduction in energy consumption. These are presented in Fig. 11.

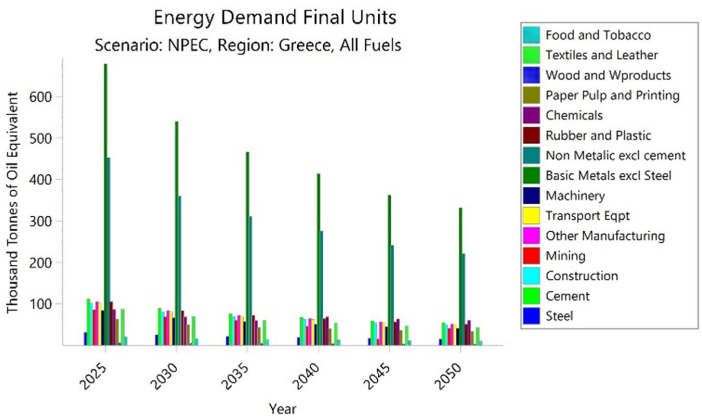

Fig. 11 Estimated energy demand per industrial sub-sector, as projected by NCEP, over the period 2022-2050

The projections of GHG Emissions per fuel and per industrial sub-sector, according to NECP are presented in Fig 12 and 13 respectively. Fig 12 shows that after 2040, emissions by Natural Gas are going to be reduced. Next to 2025-2030 period, emissions by fossils are going to be reduced drastically.

Fig. 13 indicates that Emissions are going to be reduced drastically in 1) non –ferrous metals, (aluminum etc.), 2) non-metallic materials (glasses, ceramics etc.) 3) in maintenance of transportation equipment, 4) textiles and leather. Also, there is a drastic reduction in emissions of steel and cement. In these sectors, the fuel mix shift will play an important influence in emission reductions.

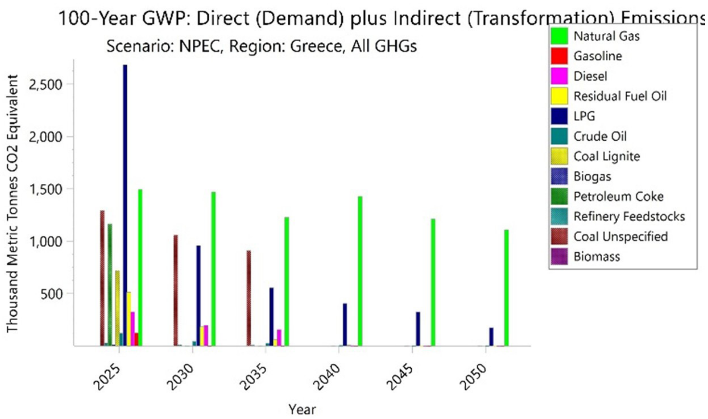

Fig. 12. GHG Emissions projections, according to NECP Scenario by fuel, over the 2022 -2050 period

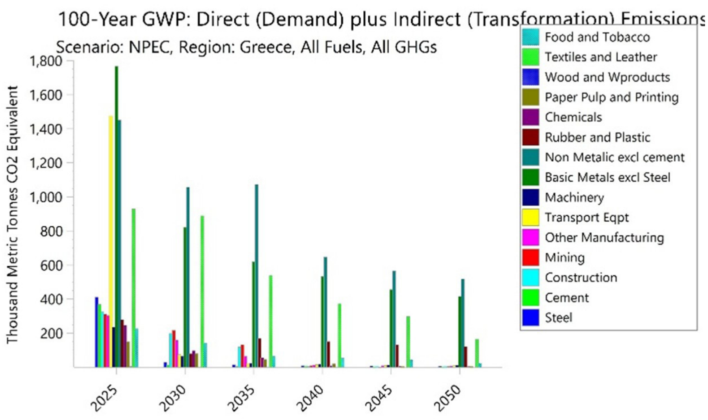

Fig. 13. GHG Emissions projections, according to NECP Scenario by industrial sub-sector, over the 2022 -2050 period

Hypothetically, if any of SSP scenario is adopted instead of NECP, it is to be reminded from Paragraph B (Figure 2), that SSPs influence the Activity Level (AL) of the Industrial Sector, through their influence to growth of GDP. Therefore, since the main driver is the growth of GDP, the Demand increases (with a different rate) in comparison with NCEP. SSP1, SSP2, SSP5 results are similar, but they present lower consumption over time, thanks to Energy Intensity reduction hypothesis. Figures 14, 15, 16 show the above mentioned trend.

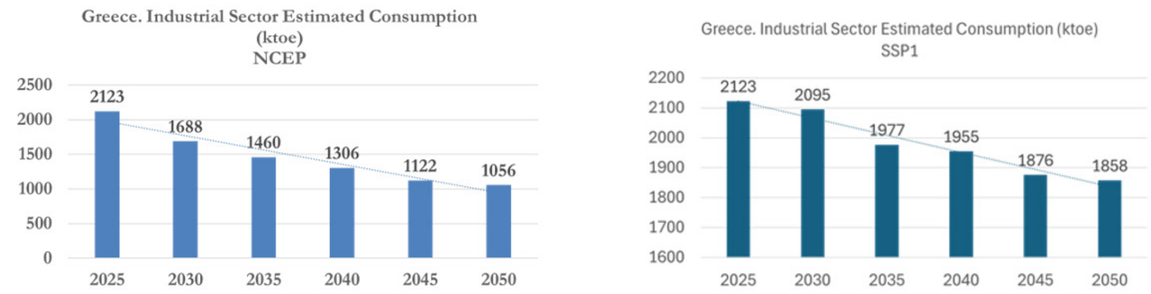

Fig. 14. SSP1 Scenario for Industrial Demand

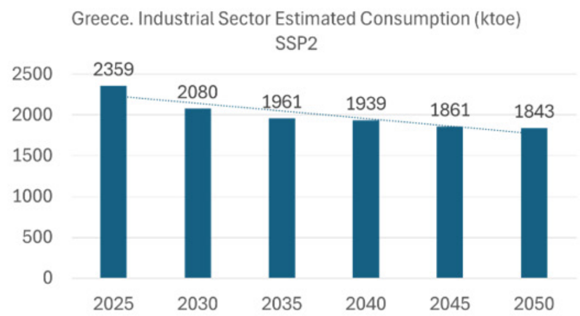

Fig. 15. SSP2 Scenario for Industrial Demand

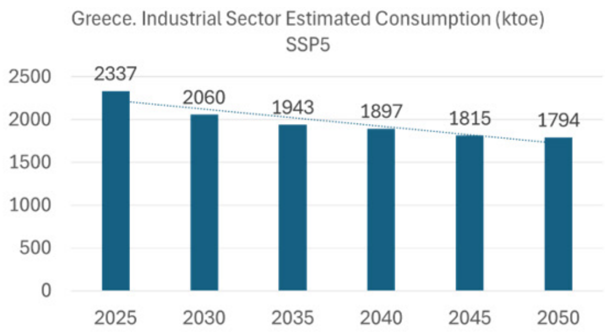

Fig. 16. SSP5 Scenario for Industrial Demand

As far as the GHG Emissions are concerned with regards to SSPs, again the Activity Levels of SSPs are increased, compared to ESEK scenario, but the Energy Intensity reduction affects the emissions which are also reduced. Up to 2035, the emission reductions are similar to NCEP, in case of SSP1 and SSP2. After 2035 the reduction is more drastic in ESEK than in SSP1 and SSP2. But in SSP5 emissions are much higher than all the other scenarios, because in this case, there is no fuel shift, from fossil to renewables. Of course, again in SSP5 there are emissions reductions, thanks to Energy Intensity reduction. Figures 17, 18, 19 show the above mentioned trend.

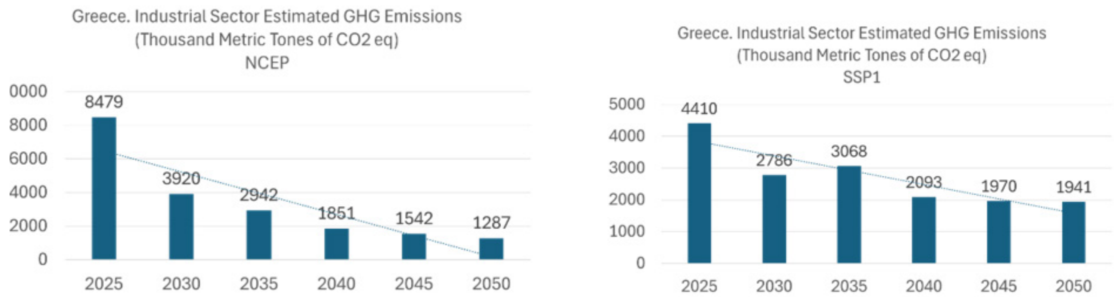

Fig. 14. SSP1 Scenario for Industrial Demand

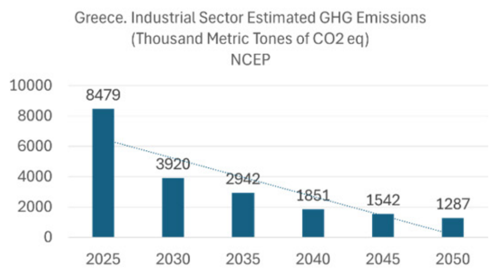

Fig. 18. SSP2 Scenario for Industrial Emissions

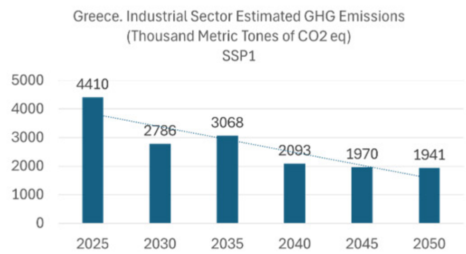

Fig. 19. SSP5 Scenario for Industrial Emissions

Next, based on the analysis presented in Paragraph C (Analysis), Figure 20 presents the water requirements per industrial sub-sector.

- Industries such as steel, automotive, and machinery manufacturing are among the highest water consumers. They use water primarily for cooling processes, dust control, and metal finishing. Water recycling and reuse are critical in these industries for reducing water intake and minimizing wastewater discharge.
- large amounts of water are consumed in the production of chemicals, pharmaceuticals, and petrochemical products.
- In Food and beverages sector, water consumption is typically significant due to requirements in processing, cleaning, and sanitation.
- Paper and Pulp industry is particularly water-intensive also.
- energy generation facilities (like thermal plants or Green Hydrogen production) use large quantities of cooling water.

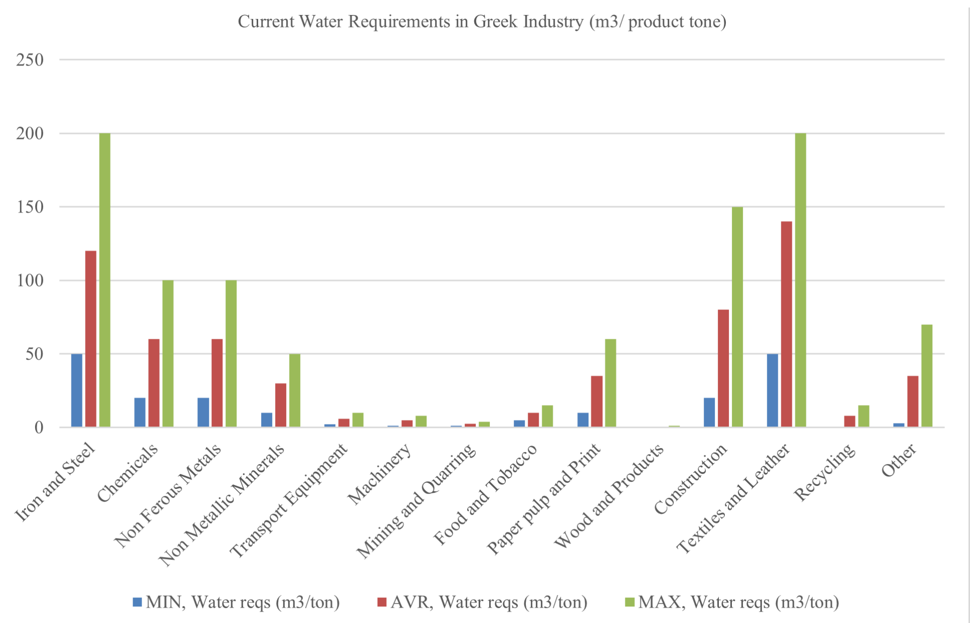

Fig. 20. Water requirements per Industrial Sector

Iii. Conclusions

The combinative application of the LEAP with the sustainability and National Commitments scenarios provides significant results considering the interplay among these different scenarios. NCEP can reduce significantly the industrial energy consumption and emissions levels to 2050.

NECP performs projections for a significant Energy Intensity reduction, therefore Energy Demand reduction and at the same time a drastic reduction in GHG emission, thanks to the generous fuel mix shift, it assumes. So, if compared with the –Do Nothing – Scenario, a remarkable sustainability progress is going to happen in Greek Industrial sector.

In the NECP scenario the overall industrial energy consumption is 50% reduced (compared to the BAU)

The GHG emissions of the NECP scenario in 2050, are performing a reduction of about 75%, compared to the BAU.

It is interesting to compare NECP, with hypothetical scenarios, based on Shared Socio-Economic Pathways, the SSPs.

These scenarios assume an increased GDP growth, therefore they seem to give an increased Activity Level (AL), so if we apply the same measures, similarly to ESEK, then the Energy Consumption will be a little bit higher than ESEK, but it keeps the same rule of gradual reduction during the upcoming period, 2025-2050, thanks to the Energy Intensity interventions in all cases.

But with regards to GHG emissions, SSP5 will perform much more emissions, compared to the other scenarios, because not important fuel mix shift (from fossil to renewables) is going to happen.

It is essential to define, estimate and calculate which are the main drivers of the future transition, the drivers of change in fuel future preference per use, or the drivers of reduction of Energy Intensity (energy savings interventions).

Sub-sectors, such as metals, steel, minerals, cement or construction, have the potential to further lower their energy use and emissions, especially if green fuels or renewable energy are mainstreamed. The water requirements are not considered in the NECP, however, they should be part of the ongoing efforts to improve the overall efficiency of the industrial activities.

Whenever Processes emissions cannot be reduced by fuel mix changes, then these emissions should be implemented throughout LCA and Circularity Principles, to improve material efficiency.

For water efficiency improvements, there are some technology innovations, that might support the efficient water use practices [7]. These innovations can apply to:

1) Advanced Membrane Technologies (e.g., reverse osmosis, nano-filtration) for treating and recycling process waters.

2) Internet of Things (IoT) and AI-driven systems for real-time water quality and quantity monitoring, allowing for predictive maintenance and better water management.

3) Adopting the appropriate LCA and Circularity principles

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In-depth Research

A possible step forward to green hydrogen use expansion

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Abstract

In order to limit average Earth temperature change in 2050 to 1.5°C with respect to pre-industrial times, as per Paris Agreement 2015, electrification by renewable energy of carbon emitting activities plays a major role.

However, electrification is difficult in some processes of the so-called "Hard-to-Abate" (HTA) sectors and hydrogen is a suitable energy carrier for many applications and is expected to provide 12% contribution to the decarbonization needed, which seems today very hard to achieve. Although various initiatives have been taken and many projects have been announced, their execution is in doubt, mainly because of high costs.

This paper evaluates various tools, mainly technical (eg. fossil fuel replacement rates), economic (eg. diffusion and learning curve), environmental (eg. GHG impact), some alternatives and analyze in detail the one(s) likely to start before 2030.

The analysis shows that green hydrogen production near HTA industries is an opportunity to do something which has to be done in any case, it allows some synergies, with affordable incentives, as for other sectors in the early stages of development and generates a large enough market to initiate a positive learning curve.

Replacement of fossil fuels in HTA industrial plants, particularly EAF steel plants, with locally produced hydrogen is a possible next step to extend the use of hydrogen, to facilitate technical improvements and economies of scale to make hydrogen less expensive and, therefore, to extend its use to other sectors.

1. Introduction

To combat climate change, IEA roadmap [63] calls for an increase of renewable energy (32% of total GreenHouse Gases, GHG, emissions reduction needed in 2050), electrification (20%), efficiency (12%) and other levers, emphasizing the use of renewable electricity, which is developing fast [64].
However, electrification is challenging in some processes.
In these cases GHG emissions can be reduced, further to efficiency and other measures, either by capturing and using/storing carbon dioxide or by replacing fossil fuels with hydrogen.
Direct use of electricity is generally more efficient than burning hydrogen, which retains only about 50% of the electricity spent producing it.
According to Ref. [63], hydrogen is expected to provide a global 12% contribution to the decarbonization effort.
Achieving this level of diffusion is challenging, as shown in Ref. [1] [2] [3] [4] [5] [60] . Despite various initiatives and announced projects, execution remains uncertain, also because there are several alternatives and current studies and policies tend to address more the global evolution of hydrogen technology and markets, rather than immediate initiatives to make hydrogen more viable.

Hydrogen can be produced by different methods, associated with different specific atmospheric emissions:

- Gray, produced by Steam Methane Reforming, without Carbon Capture,
- Blue, produced by Steam Methane Reforming, with Carbon Capture, Utilization and Storage (CCUS)
- Turquoise, produced by Methane Pyrolysis,
- Green, produced by Water Electrolysis, using wind or solar electricity,
- Pink, produced by Water Electrolysis, using nuclear electricity

In 2024, Green Hydrogen was about 5 times more expensive than Gray Hydrogen, whose kWh has already been substantially more expensive than the kWh from natural gas. Blue hydrogen is also advocated [66] but involves CCUS which requires high investment and storage availability.
Figure 1 below, from Ref. [6], reports current hydrogen production of 117 Mt/y, with less than 0.3 Mt/y being "Green". This low share is likely due to high costs, making investors hesitant to proceed with announced projects.
As detailed below, [10] reports over 700 projects for over 200 GW from Concept-stage to Final Investment Decision/ Construction-stage, but only 10% have reached the final stage.
To achieve 95% carbon neutrality by 2050, Ref. [6] consider that green hydrogen production must grow to 27,6 Mt/y (117,4 GW) in 2030 and to 164 Mt/y (373 GW) in 2050, covering all uses, industrial (mainly steel, petrochemicals, glass), transportation (airplanes, ships, trucks, cars), buildings etc.

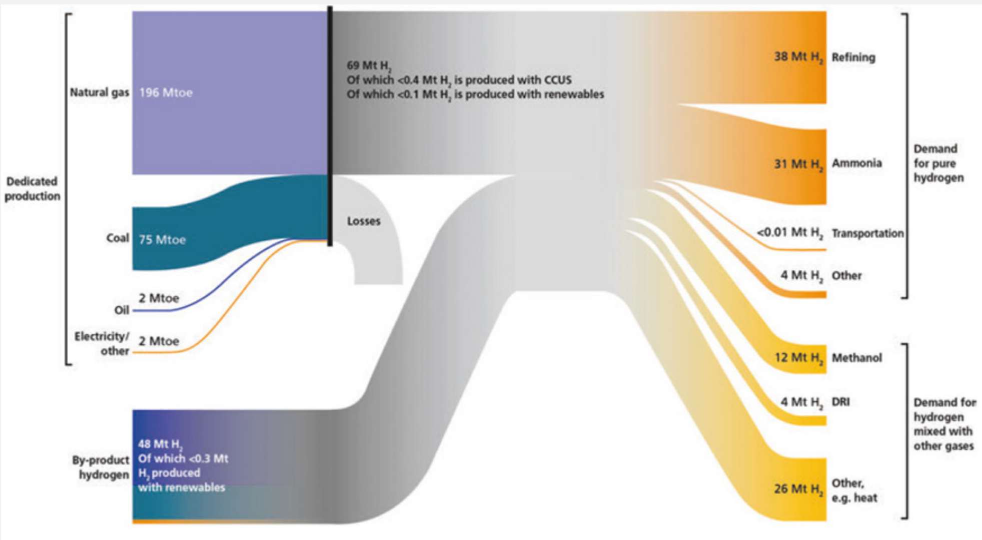

Figure 1 Hydrogen production 2023, Source [6]

2. Previous experiences

To effectively fight climate change by reducing the cost of green hydrogen, it is beneficial to learn from previous experiences. These experiences have shown that increasing cumulative capacity leads to substantial cost savings, particularly with photovoltaic (PV) plants and Lithium Ferrum Phosphates (LFP) batteries.
In 2009, when PV power production was almost a pioneering technology, our company built a 33 kW rooftop-integrated PV in central Italy for € 150.000, which equates to 4.5 €/W.
The owner received a feed-in tariff of 0.45 €/kWh for a production of 40 MWh/y, resulting in a payback of 8.3 years.
By 2024 a similar PV plant was installed for € 35.000, or 1,1 €/W, without a feed-in tariff.
At the average 2024 grid rate of 0.1 €/kWh the payback time was 8.8 years.

This direct experience aligns with U.S. National Renewable Energy Laboratory [7] reporting:
- for residential 7-8 kW PV systems, costs were 7.53 $/W in 2010 and 2,51 in 2020,
- for commercial 200 kW systems, costs were 5,57 $/W in 2010 and 1,72 in 2020.

By the end of 2024 global PV capacity is estimated to be around 2000 GW, up from 1 GW end of 2000, 60 GW end of 2010, 300 GW end of 2015, as shown in Figure 2.

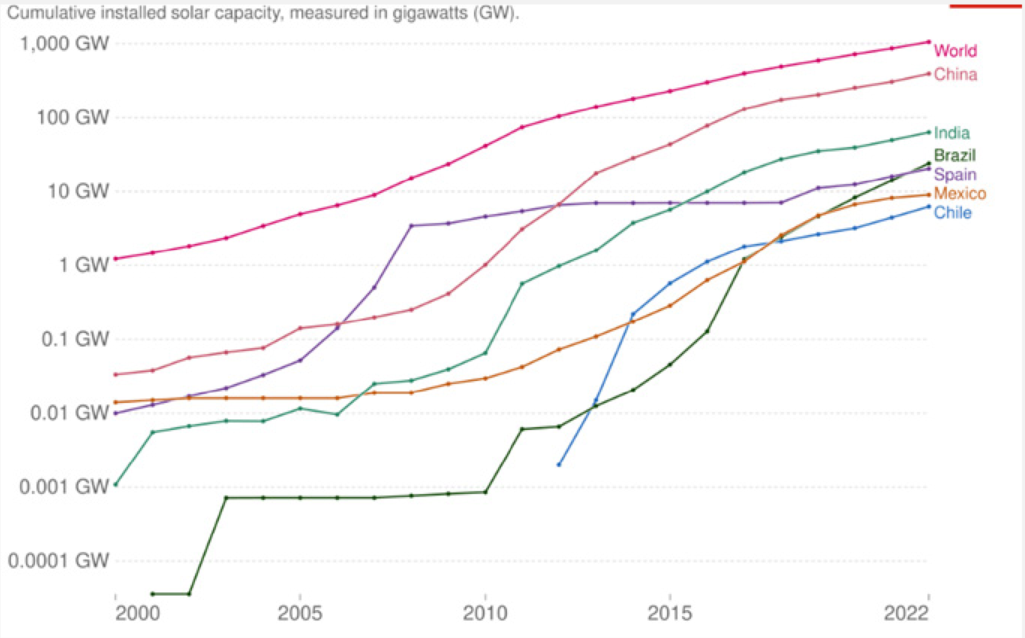

Figure 1 Hydrogen production 2023, Source [6]

Similarly, for LFP-Battery Energy Storage Systems (BESS), in 2015, we designed a 15 MWh LFP-BESS, inside a CCGT plant, which was built for 12 M€, with 800 €/kWh, with expected remuneration of 0.1 €/kWh for 10 GWh/y, resulting in a payout time of 10 years.

A similar design in 2024 estimated costs of 6 M€, or 400 €/kWh, with expected remuneration of € 8.000/MWh/y, resulting in a payout time of 10 years.

This direct experience aligns with Bloomberg New Energy Finance [8] reporting, for LFP packs only, costs declining from 345 $/kWh in 2015 to 115 $/kWh in 2024, with the worldwide market growing from 50 GWh to 1200 GWh in the same time frame.

These examples show how cost reductions are achievable with increasing market size, although in these cases helped by market conditions and technical advances, such as increasing efficiency in PV and better energy density in LFP batteries.

This can be translated into a learning curve, as in Figure 3, which shows that, as cumulative production increases, the time or cost per unit decreases, due to increased efficiency and experience. Learning curves for PV plants and LFP batteries suggest that by doubling installed capacity the cost is reduced by around 60% of the last year's considered slope.

This may also be achievable for electrolyzers to produce green hydrogen and facilitate their diffusion: should this not be as immediate as for PV and LFP batteries, a stepwise approach may be a wise choice.

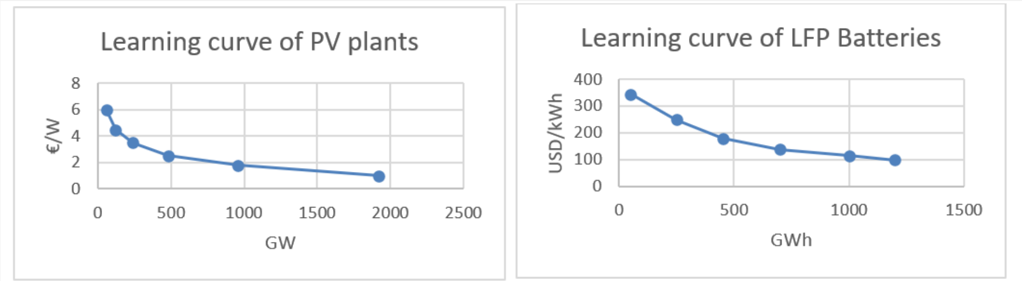

Figure 3 Learning curves experienced for photovoltaic plants and LFP batteries
Source: own elaboration from BNEF data

3. Green hydrogen facilities

It is well known [9] [14] that green hydrogen can be obtained by water electrolysis, using two main commercial systems:

- AEL (Alkaline Electrolysis), with alkaline electrolytes (typically potassium hydroxide or sodium hydroxide) cells, where hydrogen is produced at the cathode (negative electrode) through the reduction of water molecules.
- PEMEL (Proton Exchange Membrane Electrolysis), using a solid polymer electrolyte membrane to facilitate proton movement between the anode and cathode, generating hydrogen at the cathode and oxygen at the anode

Both systems arrange sequences of cells in stacks.

AEL has been the most established and cheapest method but requires longer times than PEMEL to adapt to fluctuating electricity supply, as obtained from renewable sources, and therefore requires larger energy storage.

As shown in Figure 4 below, in recent years PEMEL has approached the cost of AEL, to the point that major suppliers offer it at around 1 €/W, including electrolysis stack and most Balance of Plant, ie. water and gas purification, power supply (PSU), instrument air, cooling and chilling facilities: including installation and indirect costs, the total installed cost is likely to be 1,1-1,2 €/W.

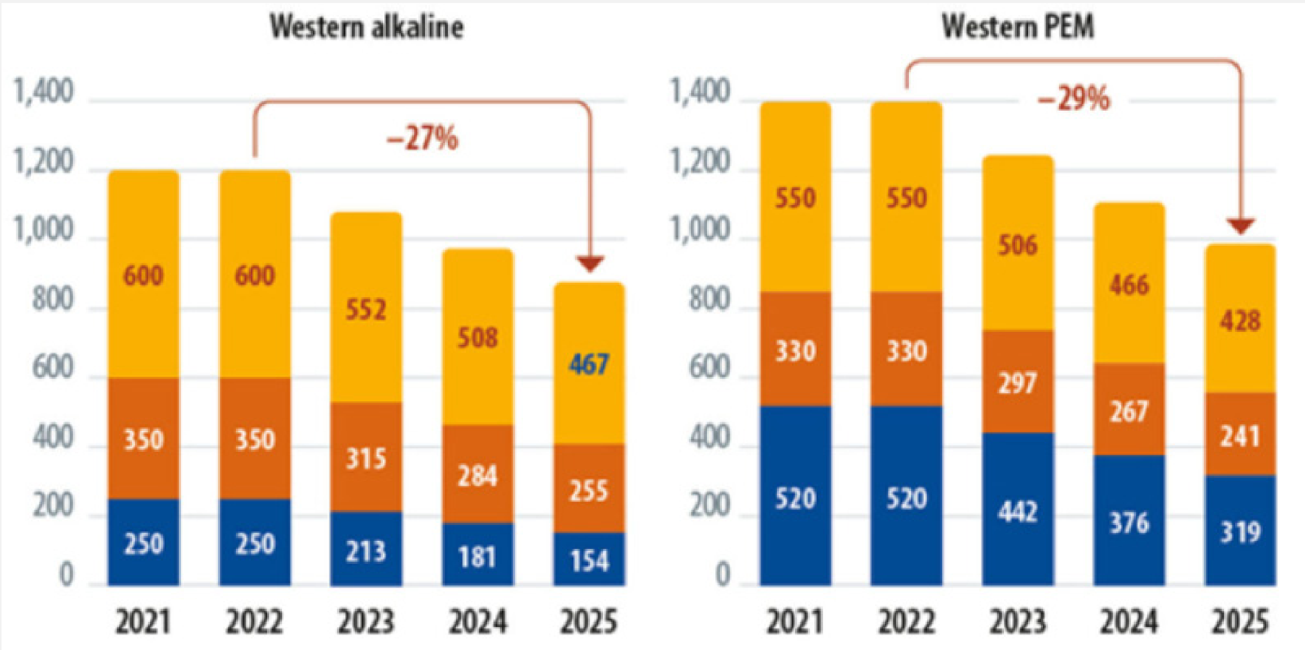

Figure 4 USD/kW evolution in Europe/USA (stack in blue, then BOP, EPC) of AEL and PEMEL, Source [12]

Assuming an economy-of-scale profile like PV and LFP-BESS for a 5 MW PEMEL, with 2024 installed capacity of 120 MW at unit cost of 1 €/W, it can be estimated that, with a few thousands MW installed capacity, as shown in the figure below, electrolyzer cost could be reduced to close to 0.3 €/W. Meanwhile, PV cost is estimated to be reduced to 0.2 €/Wp.

IEA estimates updated to Mar.5, 2025 [10] shows green hydrogen projects with Final Investment Decision globally at 20,000 MW, of which 9,700 MW are in China, 4,500 MW in Europe, 2,200 MW in South Africa, 1,300 MW in India and 1,100 MW in the USA.

Even the lower estimate of Figure 5 will allow the cost of green hydrogen to be more aligned with the current cost of gray hydrogen and obtain a cost of hydrogen-kWh close to current natural gas-kWh cost.

However, there have been many estimates of the future costs of green hydrogen, all linked to its diffusion in several sectors, according to policies and projects that have been announced. [12], [13], [14],[15], [16], [17], which have been subsequently reviewed according to perceived market trends [4].

Many sources estimate annual hydrogen requirements between 20 and 100 Mt in 2030 and between 90 and 1,200 Mt in 2050; such ranges are very high, showing how hard it is to predict the demand.

The purpose of this paper is to try to figure out means by which electrolyzers can be applied sooner in a context where they are likely to be needed in the long term and can be used with not too difficult changes in the application.

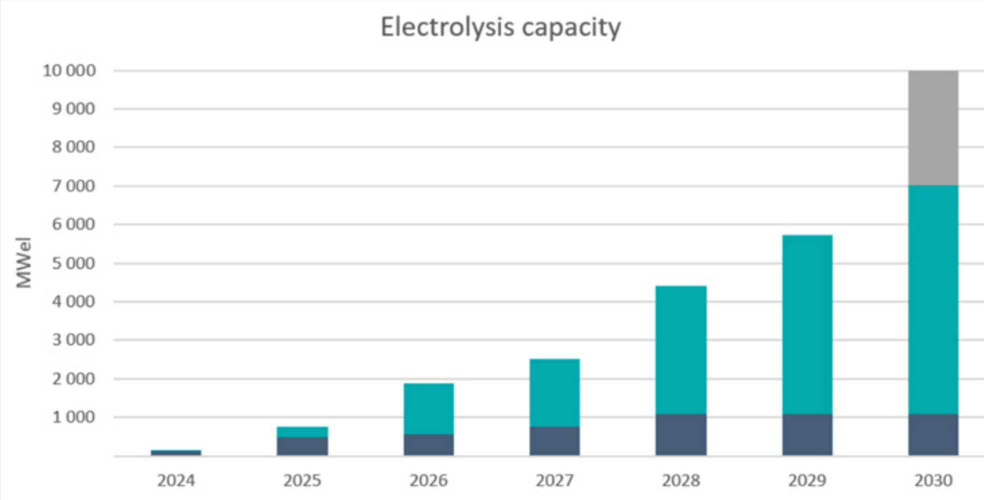

Figure 5 Global evolution of electrolysis capacity expected Jan.2025, Source: [11]

4. Sectors for Green Hydrogen application

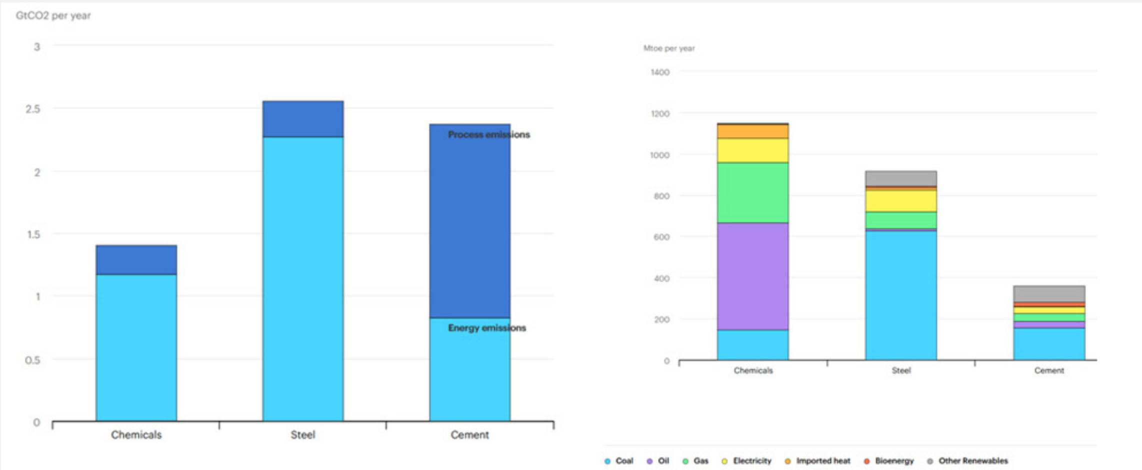

Figure 6 2022 direct CO2 emissions and final energy demand for some industry sectors, Source: [31}

Generally, it is considered that demand for hydrogen will come from the following sectors:

- Heavy industry, such as steel, cement, chemicals, oil refining, glass, paper, mostly to replace fossil fuels or feedstocks,
- Passenger cars, Trucks, Buses and Rail, equipped with Fuel Cells, to replace gasoline end gasoil,
- Ships, to replace bunker oil,
- Airplanes, to replace jet fuel,
- Buildings, to replace fossil fuels for heating/cooling

Heavy industry is a significant focus because it accounts for over a third of global energy use and a quarter of greenhouse gas emissions [18], as indicated in Figure 6. Other sectors, such as passenger cars and buildings, can be decarbonized through direct electrification, considering that in 2024 renewable electricity accounted for more than 40% of world power consumption [19] and this share is expected to continue growing. Aviation and shipping decarbonization, although important, is quantitatively less effective than heavy industry decarbonization.

Heavy Industries are particulalry challenging to decarbonize, due to technical and economic factors, such as product heterogeneity, equipment longevity, cost sensitivity and trade exposure [20]. They are often described as Hard-To-Abate (HTA) due to their energy- and carbon-intensive nature. In these industries, process heating is a significant contributor to industrial energy consumption and a major part of it is supplied at temperatures above 100°C, making it difficult to find market-ready alternatives to fossil fuels.

5. Decarbonize Hard-To-Abate Manufacturing Sectors

The literature on decarbonization options in HTA manufacturing industry focuses on specific technologies, such as hydrogen production [21], electrification [22], demand-side management [23], carbon capture, utilizazion and storage (CCUS) [24], or on specific sectors, like chemical and petrochemical [25], iron and steel [26], paper [27], cement [28], and glass [29], or on specific measures to improve energy efficiency [30].

Ref. [20] proposes a methodology to evaluate different decarbonization alternatives, Ref. [33] analyses decarbonization measures for HTA sectors according to their Technology Readiness Level and their potential for GHG reduction, Ref. [32] proposes a roadmap for heavy industry decarbonization.

The following is a brief analysis of main decarbonization routes, better illustrated in the references.
As is known, Scope 1 emissions refer to the industry direct emissions, Scope 2 to emissions from energy supply, Scope 3 to emissions in the value chain (purchased materials, use and disposal of sold products); data are taken from [35], [36], [37], [38].
In the steel sector (year 2023: 2,8 Gt/y GHG Scope 1+Scope 2 emissions, 8,1% of global CO_2), the main source of emission is the blast furnace. Decarbonization options, further to efficiency, include replacing it with low-emissions Electric Arc Furnace, which can only take place if scrap feed, whose availability is limited, is integrated with Direct Reduced Iron, from the treatment of iron ore with hydrogen (or natural gas). Emissions also come from product reheat, often with natural gas (replaceable by hydrogen), before secondary treatment. [39] [40]
In the cement sector (2,4 Gt/y, 7,7%), CO_2 emissions come from raw material calcination and fossil fuel heat supply. These cannot be easily changed with electricity or hydrogen supply, making CCUS probably the most viable alternative for decarbonization. [47] [48]
In the chemical sector (1,4 Gt/y, 4,5%), the main emissions source is process heat. Decarbonization options include, further to efficiency, electrification (for low temperatures) and green hydrogen, for combustion and as feedstock for ammonia and methanol synthesis.
Production of these may increase to obtain suitable hydrogen carriers to be transported overseas and split before hydrogen end-uses.[41] [42] [43]
In the refining sector (1.3 Gt/y, 4%), fossil fuels result from the operations and cannot be easily replaced with zero GHG heating. Therefore, together with efficiency improvements, CCUS is likely to be the most viable alternative for decarbonization. Hydrogen is widely used in refining, eg. in hydrotreating for sulfur removal and in hydrocracking, to improve value of heavy fractions; most refineries requirements of hydrogen are provided by naphtha catalytic reforming to make motor gasoline.[49] [50]
In the paper sector (0.4 Gt/y, 2%), emissions are mainly generated by steam production and can be reduced by cogeneration and/or electrification, with limited scope for using hydrogen or CCUS.[51] [52]
In the glass sector (0.1 Gt/y, 0,3%), emissions are mainly generated to melt the solid feed and can be reduced, further to better recycling and process changes, by use of oxygen instead of combusting air or by electrification (as in a few plants in Europe), with limited scope for use of hydrogen or CCUS. [37] [38] [42] [43] [44]
As it turns out from the above brief analysis, the steel industry is probably an interesting sector where, together with other measures [62], electrolyzers for hydrogen production are likely to be needed in the long term and can be used with not too difficult changes in the application, leading to the economies of scale which can make them more affordable also for other sectors.
This analysis offers suggestions for green hydrogen adoption in the steel industry, considering economic, political and environmental implications.

6. Steel industry

Steel is produced by two main classes of plants, shown in the figure below for Europe: the integrated blast furnace-basic oxygen furnace (BF-BOF) (red) and the electric arc furnace (EAF) (blue).

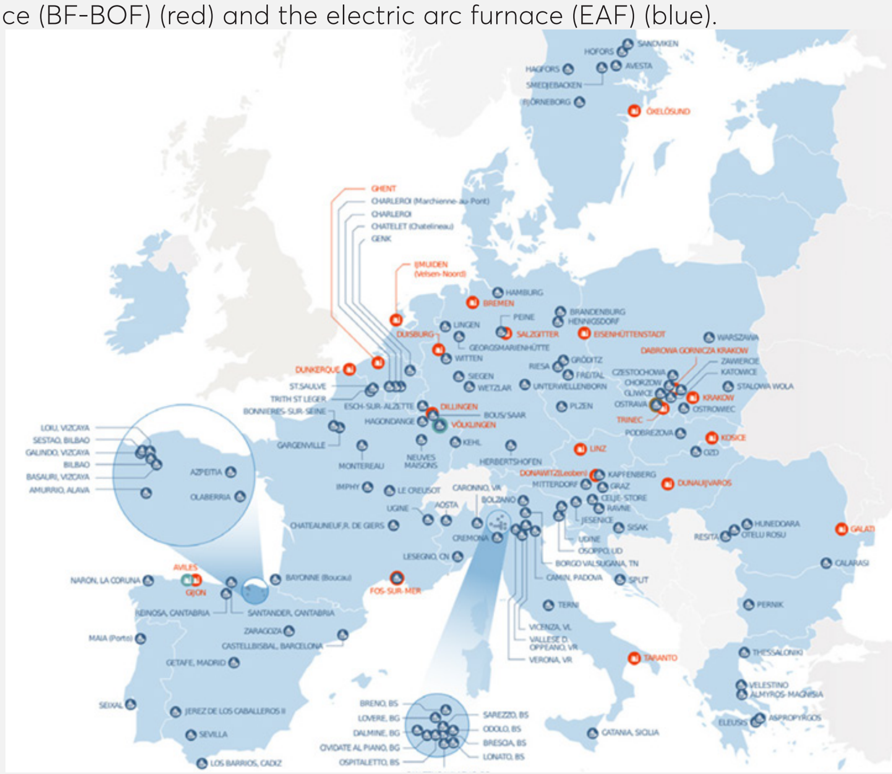

Figure 7 – Map of steel plants in Europe. Source [40}

BF-BOF Route: Also known as the "integrated route," it is the most common method for producing new or "virgin" steel. It involves the use of a blast furnace to extract iron from iron ore using coke, followed by a basic oxygen furnace to refine the resulting molten iron into steel. The raw materials include iron ore, coal, limestone, and recycled steel. This route accounts for approximately 70% of global steel production.
EAF Route: It primarily recycle steel scrap. It involves melting steel scrap in an EAF and can also use Direct Reduced Iron (DRI) or hot metal, to supplement scrap availability. The raw materials mainly include recycled steel and electricity. This route accounts for about 30% of global steel production.
Both routes produce billets or slabs, which are finished either by cold rolling or through a reheat furnace, into plates, pipes or coils.
Steel production through EAF plays an increasingly important role in modern steelworks concepts [61].
In some countries, such as Italy and Spain, EAF steel production is significantly higher than BF-BOF steel production. In the modern EAF, chemical energy contributes 25-45% of the total energy required for scrap smelting and refining. Natural Gas (NG) burners provide 40-80 kWh/t of steel [39], meaning that producing 100 tons of steel requires the combustion of 370-750 Nm3 of NG with CO2 emission of 0.75-1.5 tons.
Due to limited availability of suitable scrap, expanding EAF requires reducing iron mineral to feed it to an EAF, similarly to the initial stages of the BF-BOF route.
This can be accomplished by Direct Reduction of Iron, which involves subtracting oxygen from minerals by burning it with natural gas or hydrogen. As of the end of 2024, there were over 100 such plants operating worldwide.

Current actions to decarbonize the industry include the following:
- Designing and realizing burners that can work with NG/H2 mixture, up to 100% hydrogen, tracking the performance of hydrogen burner in replacement of methane and evaluating H2 effect on steel quality, as ongoing by CELSA (Spain) and FERRIERE NORD (Italy).
- Designing facilities for safe storage, transport and injection of hydrogen, enriched by Life Cycle Assessment (LCA) analysis.
- Evaluating DRI+EAF and other decarbonization routes for further diffusion [62]

7. Case study

7.1 Application case
To appreciate the implications of green hydrogen introduction in an EAF-steelmaking plant, the rather common case of a facility with annual production capacity of 450.000 tons can be evaluated. This plant operates with a 90 tons net steel batch size, 1 hour cycle time (tap-to-tap) and works 48 weeks/y from Monday 6:00 to Friday 22:00 with 0.94 service factor.
There are about 100 such facilities in the EU (and over 150 in North America), with 60 located in France, Germany, Italy and Spain. These plants consume on average 2.8 GJ of thermal energy per ton of steel, ie 28,3 Mm3/year of natural gas.

7.2 Green Hydrogen for the case
It is known that EAF burners can accommodate a 20% replacement of natural gas with green hydrogen, without significant modifications.
For this case, hydrogen annual requirement will be 1,600 tons, which can be produced by three 5 MW PEMEL, fed by 80 GWh electricity annually.
PEMEL is chosen for its adaptability to renewable power fluctuations, although improvements are needed (and are ongoing) to ensure the assumed lifetime of 10 years.
Figure 7 shows in yellow the facilities included in a typical 5 MW electrolyzer package.
The Balance Of Plant (BOP) for this case includes hydrogen compression and storage, power station with electrical and control facilities and civil works.

7.3 Economics
In this case study, it is suggested that steelmakers plan, justify and get authorizations for green hydrogen production, as shown in Figure 8 below, within their assets.
Incentives should be provided by the relevant authority to ensure a sufficient return on investment, assumed to be 6%.
If the Renewable Energy (RE) feed is solely photovoltaic, with an average capacity factor of 0.14 at 45°N latitude, a capacity of 66 MW on about 60-hectare surface is required. Alternatively, other RE sources may be used or bilateral Power Purchase Agreements (PPA) with RE producer(s) may be used, following the additionality principle. defined by EU Renewable Energy Directive II (RED II).
To expand PEMEL opportunities and achieve economies of scale, it may be beneficial to consider the cancellation, limitation or deferral of this requirement as part of the authorization process.

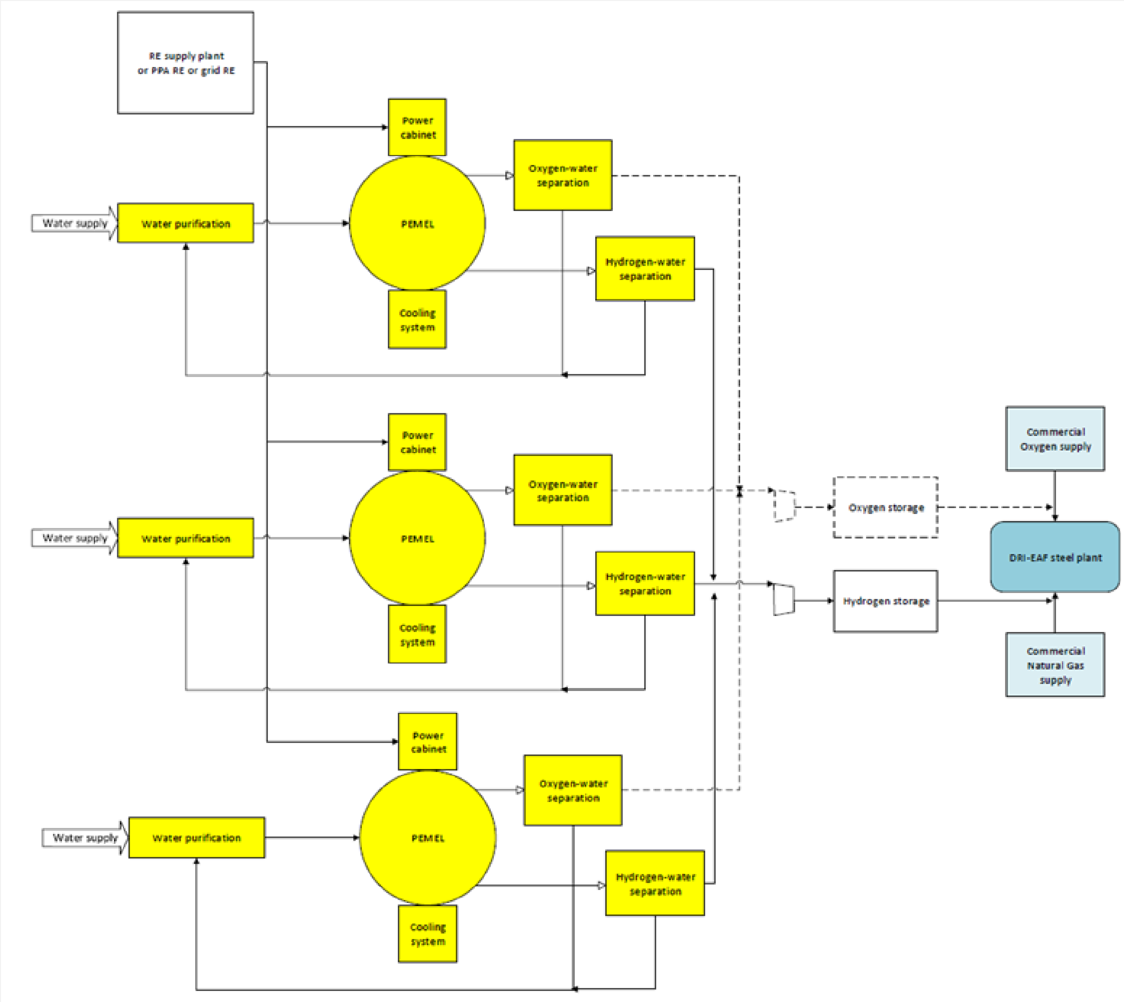

Figure 8 – 500 kt/y DRI-EAF with 3x5 MW PEMEL flow diagram and specification

Table 1 shows economics for two scenarios, with the same BOP:
- Own RE supply, where RE generation constitutes two-thirds of the investment.
- External RE supply at 1Q2025 prices, where RE supply accounts for two-thirds of the running cost.

Both scenarios achieve hydrogen costs around 6 €/kg.

For the first scenario, if grid connection is insufficient, additional investment in batteries may be evaluated, considering that:
- PEMEL is rather flexible for fluctuating power supply,
- RE generation is sized to supply 20% of steel plant's heat requirements annually,
- in emergencies hydrogen supply can be reduced or power can be sourced from the grid.

7.4 System effects

To ensure a 6% return on investment, as shown in the table below, steelmakers require an incentive of 10,4 M€/y for 10 Mt/y CO2 saving, ie. about 1 €/t CO2 saved.
Thanks to economies of scale assumed in par.3 above, incentives will diminish, as the green hydrogen price drops to around 2-3 €/kg, aligning with the cost of natural gas.
It must be noted that the 3 electrolyzers require about 14.000 m3 of water to replace with hydrogen 20% of natural gas consumption by the steel plants. This quantity will be recycled by the combustion of hydrogen and can be sourced from salt water, if necessary, as discussed later in this paper.
Since scrap volumes are not sufficient to feed all EAF's, some mineral ore must be used and chemically reduced by removing oxygen via Direct Reduction of Iron (DRI), using natural gas or hydrogen, which will increase the required incentive.
However, for the purpose of this work, comparing the cost of scrap-fed EAF incentives with learning rate results and life cycle effects is sufficient.
Assuming one-third of EAF plants adopt in 10 years the 20/80 hydrogen/natural gas blend, this will require around 1200 MW of new PEMEL capacity. If a 20% learning rate occurs, similar to PV, hydrogen cost will drop below 2€/kg, potentially eliminating the need for incentives. Initial incentives will be similar to the budget allocated for EU Fuel Cells and Hydrogen (FCH) and Fuel Cells and Hydrogen 2 (FCH 2) Joint Undertakings (JUs), with no immediate result in emissions reduction.

Hydrogen production, kt/y	1.6											
Power requirements, GWh	80											
	2025						**2035**					
PEMEL investment, Eur/W	1						0.3					
PV investment, Eur/Wp	0.7						0.2					
RE PPA power price, Eur/kWh	0.06						0.02					
	Own RE supply			***External RE supply***			***Own RE supply***			***External RE supply***		
Green Hydrogen Investment	units	Meur/un	Meur	units	Meur/un	Meur	units	Meur/un	Meur	units	Meur/un	Meur
Electrolyzers	3	5	15	3	5	15	3	1.5	4.4	3	1.5	4.4
PV plant, MW	66	0.7	46				66	0.2	13			
BOP+H_2 compression & storage			10			10			6			6
Total investment			71			25			24			10
Green Hydrogen Production Cost												
Oxygen credit, t O_2/t H_2	8	-0.04	-0.3	8	-0.04	-0.3	8	0.0	-0.3	8	-0.04	-0.3
Power supply+transport&overhead, GWh				80	0.08	6.4				80	0.04	3.2
Water supply + O&M, 2% investment			1.4			0.5			0.5			0.2
Depreciation 10y PEMEL, 20y BOP			4.3			2.0			1.4			0.7
ROI 6%			4.3			1.5			1.4			0.6
Hydrogen cost, eur/kg			6.1			6.3			1.9			2.8
Eur/kWh from Hydrogen			0.18			0.19			0.06			0.08

Note: The 3 electrolyzers of this case produce 1,6 kt H_2/y (and 13 kt/O_2, about 50% of EAF requirements) leading to a unit cost of 6 €/kg, ie. 0,18 €/kWh vs. 0,05 from natural gas; incentive for a 6% ROI is therefore (0,18-0,05) €/kWh x 80.000.000 kWh = 10.400.000 €. In 10 years, with economies of scale assumed in par.3, H_2-kWh cost will be close to natural-gas-kWh.

7.5 Assumptions and sensitivities
EAF and PEMEL standards have been used in the simulation, as outlined above.
Lifetime is assumed 10 years for PEMEL and 20 years for BOP.
Required ROI is assumed 6%.
2035 RE PPA price is assumed 0.02 €/kWh (+0,02 transport & overhead)
The following sensitivities can be calculated:

- Sensitivity to a 3 years shorter lifetime for both leads to 2035 external RE supply H_2 cost of € 2,9/kg
- Sensitivity to 10% leads to 2035 external RE supply H_2 cost of € 3,1/kg
- Sensitivity to 0,03 €/kWh leads to 2035 external RE supply H_2 cost of € 3,3/kg

Although these H_2 costs are not competitive with 2024 natural gas prices, they represent a significant improvement and would have been competitive in other timeframes, such as year 2022.

7.6 Risks mitigation
The proposed approach considers some risks, and their mitigation, as follows:
- Power price volatility: Incentives should compensate for the extra cost of H_2-kWh vs. fossil-kWh
- Technical reliability and performance shall be included in EPC contracts guarantees
- Social acceptance shall be seeked as required by local standards and habits, trading off extra cost with lower pollution and higher security

8. Life Cycle Assessment of PEMEL for EAF steel plants

A Life Cycle Assessment (LCA) must provide the main environmental indicators for the use of green hydrogen in current EAF steelmaking worldwide.
A comprehensive review of hydrogen production LCA for mobility in Germany under different energy scenarios [53] cites previous studies mostly addressing the GHG component:

- Electrolysis with wind power supply emits 0,97 kg CO_2 per kg H_2
- Electrolysis with PV power supply emits 2,4 kg CO_2 per kg H_2
- Steam Methane Reforming emits 11,9 kg CO_2 per kg H_2, or 3,3 with Carbon Capture and Sequestration

and states that electrolysis GHG impact is due to over 90% to electricity supply.
It analyzes the years 2017 (34% RE) and 2050 (60% RE), with an option to limit electrolysis to 3000 h to benefit of 100% RE). On top of GHG emissions (defined as Climate Change or CC), it considers six other impact categories: Ozone depletion (OD), Terrestrial acidification (TA), Human toxicity (HT), Particulate oxidant formation (POF), Particulate matter formation (PM) and Metal depletion (MD).
The Life Cycle Inventory (LCI) considers stack technology evolution with substantial reduction and recycling of expensive components and BOP including 0,1 TWh pump storage and 0.5 TWh hydrogen storage.
The results show that:

- PEMEL is a viable alternative to conventional steam methane reforming production and is flexible enough to fit into hours with volatile electricity production having very high shares of renewables, contributing to a significant reduction of greenhouse gas,
- The composition of the electricity mix mainly determines the impacts on Climate Change,
- Influence of system components plays a minor role, but critical materials are relevant,
- Results are subject to the restriction of using existing databases, not including increases of efficiency in energy production technologies (e.g. solar panels materials, emission factors etc.)

Another study [54}, although relevant to all green powerfuels (ie. hydrocarbon-based renewable energy carriers and feedstocks) and not following ISO 14044 standard, is worth considering, for the analysis of other components, such as biodiversity loss, land-system change, freshwater use and hydrogen leakage.
Also relevant is Ref. [59], which, through a Multi Criteria Decision Making technique, compares AEL and PEMEL, showing an economic advantage for AEL, offset by the better flexibility of PEMEL.

For the purpose of this paper, it is interesting to evaluate different components to understand whether the selection of EAF steelmaking to achieve economies of scale is appropriate from an economic and environmental perspective.
Compared to other HTA sectors, as previously discussed, steelmaking is the highest contributor to GHG and therefore initiatives to decarbonize it are probably a priority.
The LCA made using LCA Calculator (https://pro.lcacalculator.com/) shows that the suggestion of this paper has few drawbacks:

- PEMEL requires critical materials: use minimization is a major R&D effort by all manufacturers, recycling has yet to be started but will represent a major effort too.
- PV power supply, although in a less LCA impacting agrivoltaics form, requires too much land and may lead to a phasing of PEMEL modules investment according to the power availability, or be complemented with other sources of power, through PPA or, if additionality criteria can be waived, through other existing renewable sources.
- Safety standards must be imported and adapted to new uses from what has been learnt in current uses, such as petrochemical.

Water sourcing, also according to other literature [55], is unlikely to be a big problem.
As water is obtained from hydrogen combustion in the end-uses, its use for hydrogen production is unlikely to waste much of this precious resource.
However, seawater can also be considered, either with appropriate membranes [56] or by purification systems (eg. Reverse Osmosis) with integrated dehydration of brine to produce salt in replacement of current marine or mining facilities; but in this case, saltwater feed must be transported to the PEMEL-EAF facilities, which is difficult for many cases.
Each case can be studied by Proposers and submitted to environmental impact assessments, provided that a support policy as outlined above is planned, including particularly the possibility of waiving Renewable Energy (RE) additionality of RED II, if enough power cannot be supplied through own investment or PPA, eventually phased.
This is not different from what has been done in the last 20 years for other RE projects.

9. Conclusions

a. To fight climate change, electrification with use of Renewable Energy (RE), who has reached 40% of global power generation in 2024, is not applicable to some sectors requiring high temperature heat, difficult to provide by electrification, known as Hard-To-Abate (HTA).
b. For these sectors, emissions must either be captured or avoided by burning hydrogen generated from water electrolysis with RE, resulting in non-carbon emissions (so-called "green"), but with current kWh cost much higher than kWh from fossil fuels.
c. To reduce green hydrogen kWh cost, economies of scale are desirable, as experienced in the photovoltaic (PV) and LFP battery industries in recent decades. Therefore, it may be useful to find an HTA sector in which to concentrate available resources, along with ongoing long-range planning and R&D efforts.
d. The steel industry appears a priority, due to its economic and environmental importance, and to the numerous Electric Arc Furnace (EAF) plants, which allow hydrogen application, also for the integration of Direct Iron Reduction to supplement limited scrap steel availability. Other HTA sectors are probably more interested in other forms of decarbonization. For the steel case:
- To limit technical complications in the end-use, hydrogen may be used in 20% blend with natural gas.
- A project proposal can be made by each steelmaker, including Proton Exchange Membrane ELectrolyzers (PEMEL), RE supply, water sourcing and hydrogen storage. If it is authorized after examination by competent Authorities, it obtains subsidies allowing the steelmaker a satisfactory return on investment.
- It is challenging to provide for the whole RE needs of the projects, so waiver to EU RED II additionality or phasing of investments (and subsidy) to Power Purchase Agreement availability to the Proposer must be considered.
e. Life Cycle Assessment (LCA) of the suggested prioritization suggests also the need to continue working on PEMEL improvements, particularly in increasing current density (which decreases weights and cost) and reducing/recycling critical materials, which represent the major LCA impact after power production.

As closure, it has to be noted that low impact hydrogen diffusion is difficult and there have been some false starts in the past; many studies and pilot projects have been financed, from industrial to transport uses, piping networks and international trade have been explored, giving rise to a multitude of options which make decisions on investments more complex.
This paper tries to show some of the difficulties related to a specific application, the steel industry.
Perhaps, as it is suggested by some [56] [57] [58], they may be better tackled if, instead of waiting for the harmonization of plans for the whole picture of green hydrogen diffusion, it is left to interested industrialists to make their own business plan, including assets design, power supply decisions, etc., to be submitted for authorization, as for other RE facilities.

After authorization, Public Authorities may accord financial support and adaptation of RE supply. This will allow the electrolyzers market to expand, which, together with PV cost reduction, should reduce the need for public support to green hydrogen end uses to the cases where specific investments are required, such as process modifications, e.g. for using 100% hydrogen.

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In-depth Research

Better safe than sorry! Fire and flood hazards to pv parks

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Overview

The ongoing climate change has undeniably influenced several sectors of the global economy, including Renewable Energy Sources (RES) projects (e.g. Gallina et al., 2016; Xu et al., 2024). In Greece, in particular, significant catastrophic events have occurred in recent years that should alert us. Natural disasters in Greece. Notable examples include the major flooding caused by Storm Daniel in September 2023 (e.g. Dimitriou et al., 2024; Falaras et al., 2025), the devastating wildfires, in the North Evia Island areas (August 2021), the devastating wildfires in the Dadia National Park and Rhodes (summer 2023).

Mitigation measures should be implemented at the design phase, as prevention is the most cost-effective and safest method for the infrastructures. In this context, two natural disasters—wildfires and floods—are assessed in a hypothetical photovoltaic (PV) park located in Greece (Figure 1). Using the ArcGIS Pro software toolbox, the potential impact of these hazards can be visualized, and specific mitigation measures can be proposed to reduce the risk of natural disasters.

Figure 1 The location of the study area in Peloponnese

Methods

For the purpose of this research, a hypothetical PV park located in northern Peloponnese has been assessed under the scope of flooding and wildfire events as presented in Figure 1. Using ArcGIS Pro software tools, these two natural disasters have been analysed in detail.

Regarding wildfire risk, Pallikarakis & Konstantopoulou (2024) utilized the multicriteria analysis capabilities of ArcGIS Pro to estimate the potential risk of wildfires in another region of Greece. In their research, ten factors were considered for the assessment of fire risk, including geomorphological, social, environmental, and climatic factors Through Multi-Criteria Decision Analysis (MCDA) and the Analytic Hierarchy Process (AHP), fire risk was assessed for both current and future conditions. The Wildfire Hazard Risk has been categorised into five classes, ranging from Negligible (lower scale-1) to High (highest scale-5).

For the purposes of this research, the same methodological framework was applied, focusing specifically on the geographical area where the photovoltaic (PV) park is situated. Initially, all relevant factors were analyzed using ArcGIS software to spatially represent and assess their influence. The relative importance of each factor was subsequently evaluated through the Analytic Hierarchy Process (AHP), as illustrated in Figure 2.

Key factors such as slope, Fire Weather Index (FWI), and land cover were identified as having greater significance in determining fire risk, thereby exerting a more substantial influence on the overall assessment. Finally, fire risk under current conditions was assessed using a combination of Multi-Criteria Decision Analysis (MCDA) and presented in the next chapter.

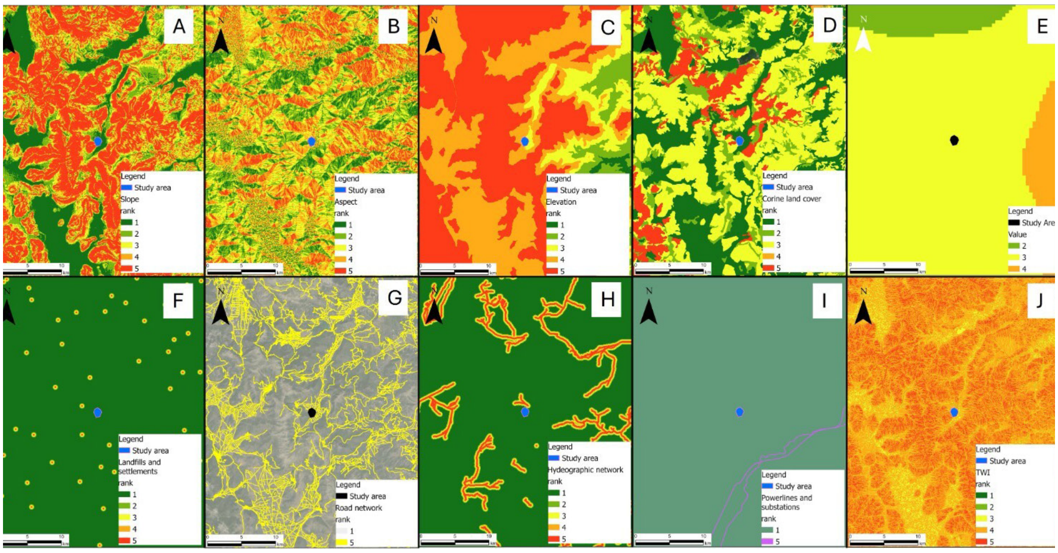

Figure 2 Presentation of the considered factors. A) Slopes, B) Aspect, C) Elevation, D) Land Cover, E) Fire Weather Index (FWI), F) Distance from settlements and landfills, G) Distance from road network, H) Distance from hydrographic network, I) Distance from high voltage OHL/substations, J) Topographic wetness index (TWI)

Based on data provided by the Adaptive Greece Hub, the Fire Weather Index (FWI) has been obtained for both the current period and for the near-future period, as it shown in (Figure 3). Notably, projections indicate that climatic conditions are expected to become increasingly conducive to fire occurrence in the future. As a result, fire risk can be systematically assessed under both present and projected future conditions, covering the time horizon of 2031–2060.

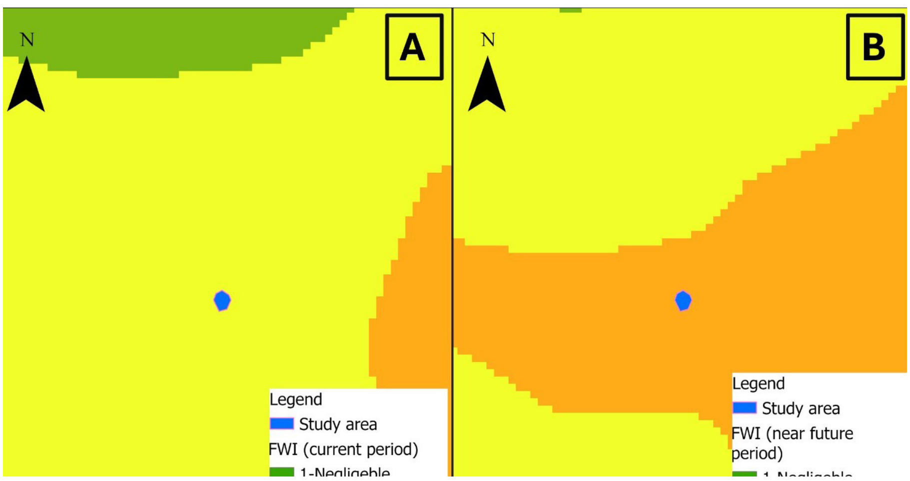

Figure 2 Presentation of the considered factors. A) Slopes, B) Aspect, C) Elevation, D) Land Cover, E) Fire Weather Index (FWI),

Regarding the flooding risk, the impact of heavy rainfall on the area of the hypothetical PV park has been analysed using ArcGIS Pro software tools (Flood Simulation). This tool provides an efficient means to visualize potential flood scenarios for a study area. It also enables accurate flood risk assessment. For this analysis, data such as soil permeability, lithological formations, and rainfall height in the area have been utilized, based on international literature from sources like the Hellenic Survey of Geology and Mineral Exploration (HSGME) and Meteo.gr. For the precipitation height used in the model, two scenarios were considered: the first was based on the actual daily rainfall measured in 2024 at the nearby Ziria station (~85 mm, Meteo.gr) and the other one on an extreme event scenario, where the daily rainfall is equal to the estimated annual precipitation (~720 mm, EMY.gr). For comparison purposes, it is assumed that the rainfall duration in both scenarios is 12 hours.

Results

Based on the multicriteria analysis mentioned earlier, the study area is experiencing low to significant wildfire risk for the current period, as illustrated in Figure 4 below. The majority of the plot falls within an area characterized as Low risk (class 2) and Moderate risk (class 3), while a very small portion is classified as Significant risk (class 4).

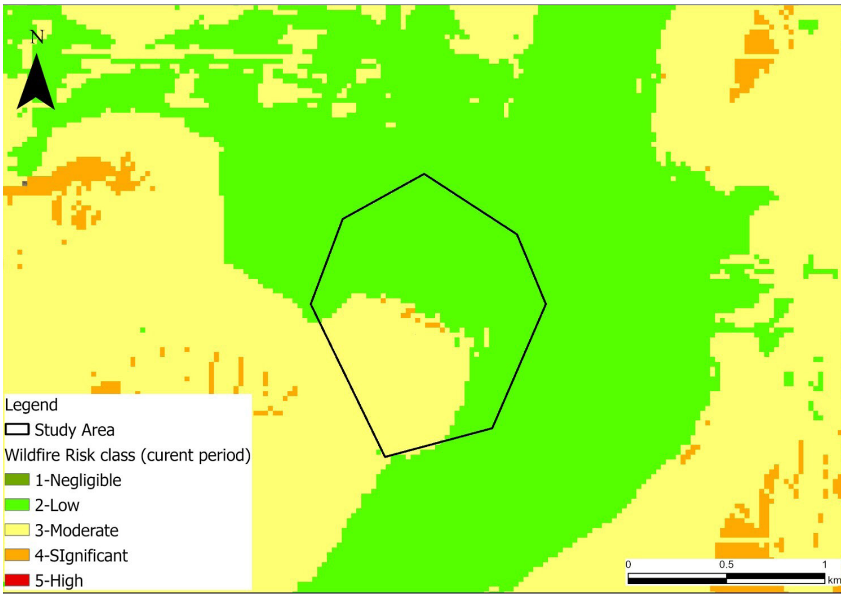

Figure 4 Wildfire risk assessment for the current period

According to the methodology outlined by Pallikarakis & Konstantopoulou (2024), future risk can be predicted using online data provided by Adaptive Greece Hub (Figure 3). Consequently, the estimated wildfire risk for the near future period (2031-2060) has been analysed and presented in Figure 5 below. Notably, the majority of the studied plot is now classified as Significant and Moderate risk, while half part of the plot is still characterized as Low risk.

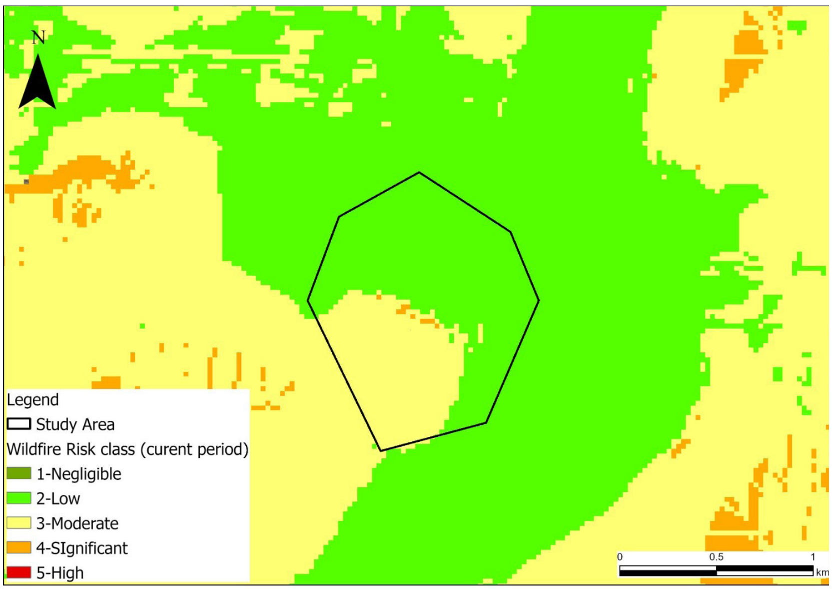

Figure 5 Wildfire risk assessment for the near future period (2031-2060)

As mentioned before, the flood risk for the studied plot was evaluated under two distinct rainfall scenarios: a typical precipitation event and an extreme meteorological phenomenon. As illustrated in Figure 6, following the scenario of the more "common" rainfall event with a total precipitation of 85 mm the influenced area is mainly adjacent to the local hydrological network. Within the boundaries of the studied plot, the maximum floodwater depth is estimated to be less than 0.6 meters, indicating relatively low inundation levels.
Conversely, under an extreme rainfall scenario—such as the one associated with Medicane Daniel in September 2020—the extent and severity of flooding increase substantially. As shown in Figure 7 floodwater depths in the vicinity of the plot are projected to exceed 5 meters, while within the plot itself, water depths may reach up to 1.6 meters. This scenario reflects a significant hydrological response, likely driven by high-intensity precipitation and saturated soil conditions, resulting in extensive surface runoff and elevated flood risk.

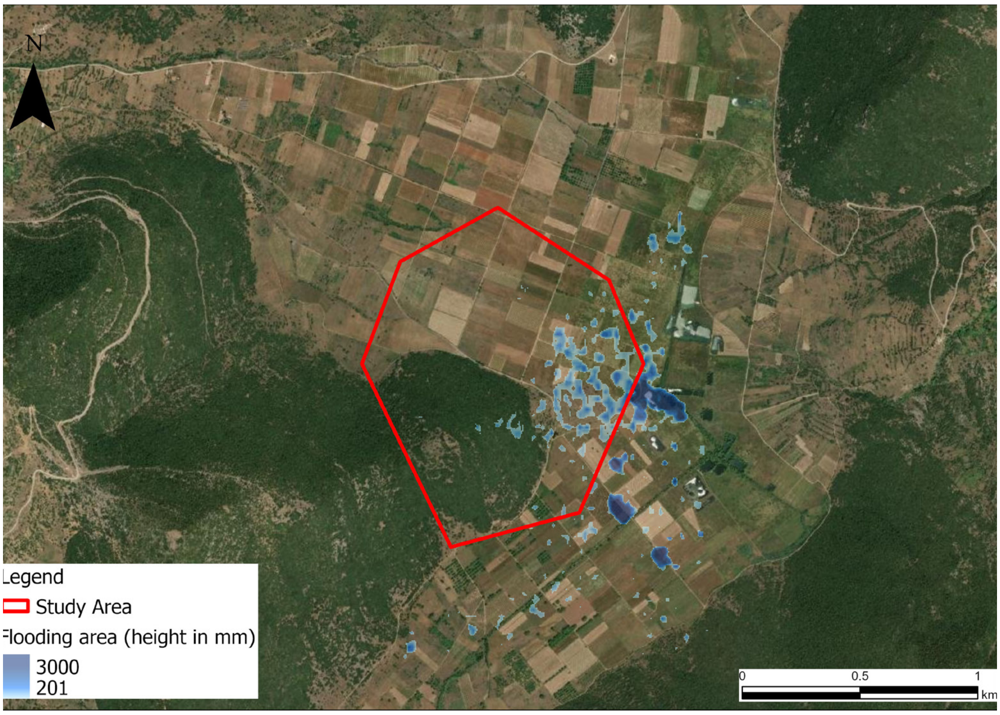

Figure 6 A simulation of the flooded area, under the "common" rainfall scenario

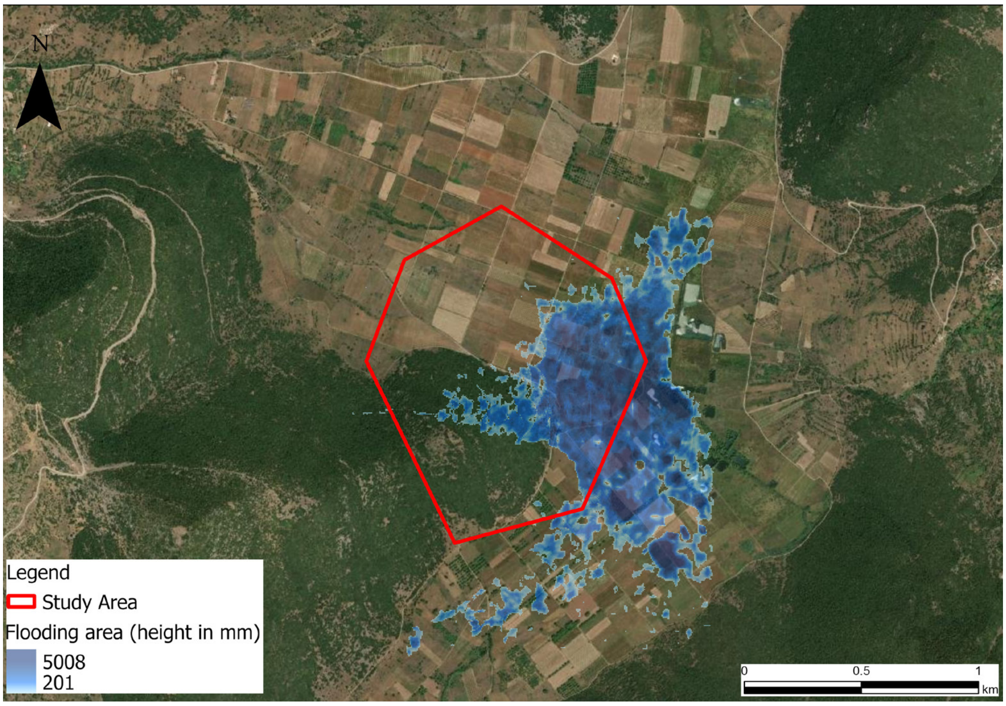

Figure 7 A simulation of the flooded area, under the "extrema" rainfall scenario

Discussion and Conclusions

The comparative analysis of the two hydrometeorological scenarios clearly demonstrates that extreme weather events pose substantial risks to the operational integrity and long-term viability of the proposed photovoltaic park. The findings underscore the vulnerability of RES infrastructure to climate-induced hazards, highlighting the necessity for climate-resilient design strategies.

Based on the methodologies employed, it is evident that climate change is expected to intensify the frequency and severity of such events, thereby amplifying the exposure of RES installations to environmental stressors. This necessitates the integration of adaptive and preventive measures during the design and planning phases of PV infrastructure.

For instance, wildfire resilience can be enhanced through the application of Best Available Techniques (BAT), which include straightforward yet effective interventions such as maintaining adequate spacing between PV modules to reduce fire propagation risk (e.g., Namikawa et al., 2017), and incorporating fire-resistant materials and fire suppression systems into the installation. Furthermore, innovation in PV panel design should prioritize the use of inherently fire-retardant materials to further mitigate fire-related risks.

Similarly, the technical design must account for hydrological hazards. The flood risk assessment indicates that the site is significantly susceptible to inundation during extreme rainfall events. To address this, engineering solutions such as elevating the mounting structures of PV panels above projected flood levels, or strategically relocating vulnerable components to adjacent, less flood-prone plots, should be considered as part of a comprehensive risk mitigation strategy.

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SEPTEMBER 2025

Special Edition

A PUBLICATION OF:

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