HYBRID RENEWABLE ENERGY SYSTEMS

A POSSIBLE PATH TO MOROCCO'S SUSTAINABLE FUTURE

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About this report

RES4Africa Foundation is proud to present its first report on Hybrid Renewable Energy Systems. Driven by a strong commitment to sustainable energy solutions, the Foundation highlights the critical role of hybrid systems in enhancing energy resilience and efficiency. This report serves as a call to action, advocating for the adoption and integration of hybrid renewable energy solutions in Morocco.

The aim of the report is to demonstrate how the deployment of Battery Energy Storage Systems could support Morocco renewable energy integration, optimizing natural gas use, enhance energy system security and support the country efforts to reduce coal dependence.

Data analysis was conducted with reference to official public sources and technical documentation available at the time of writing considering the sources up to 2023, allowing us to analyze the three scenarios from 2024 till 2050. It should be noted that energy-related data, including agreements, strategies, and sectoral decisions from 2024 onwards, were not included in this report.

The data presented in this report is based on solid, verifiable information extracted from reputable reports and trusted sources, ensuring a robust and evidence-based foundation for the analysis and recommendations. Only sources with confirmed accuracy and relevance were considered to ensure the credibility and applicability of the findings.

RES4Africa extends a heartfelt thanks to **Enel Foundation** for their support and to all partners and experts who took the time to read and contribute to this report.

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Disclaimer

This report has been prepared as an independent analysis of RES4Africa Foundation, focusing on energy-related data in Morocco up to 2023 and excluding signatory agreements, strategies, and any other sector-related data from 2024 onwards.

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ABBREVIATIONS

BAU	Business As Usual
BESS	Battery Energy Storage System
BOS	Balance Of System
CAPEX	Capital Expenditure
CCGT	Combined Cycle Gas Turbine
DESNZ	Department for Energy Security and Net Zero (UK)
DF	Dispatch Factor
DNV	Det Norske Veritas
EIA	U.S. Energy Information Administration
FSU	Former Soviet Union
HRES	Hybrid Renewable Energy Systems
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
KWH	Kilowatt Hour
LCOE	Levelized Cost of Energy
LNG	Liquefied Natural Gas
MASEN	Moroccan Agency for Sustainable Energy
MENA	Middle East and North Africa
MW	Megawatt
NDC	Nationally Determined Contributions
NPV	Net Present Value
OCGT	Open-cycle Gas Turbines
O&M	Operation and Maintenance
OECD	Organization for Economic Co-operation and Development
ONEE	Office National de l'Électricité et de l'Eau Potable
PV	Photovoltaic
USE	Unserved Energy
VDMA	Verband Deutscher Maschinen- und Anlagenbau
VRE RATIO	Variable Renewable Energy Ratio
WACC	Weighted Average Cost of Capital

Key Takeaways

Morocco is undergoing a pivotal transformation in its energy sector, with a clear focus on diversifying its energy mix and significantly increasing the share of renewable energy sources, particularly solar and wind. On April 2025, ONEE, the Office National de l'Électricité et de l'Eau Potable in Morocco, launched a call for expression of interest Battery Energy Storage Systems Integrators[1] and in 2023, MASEN, the Moroccan Agency for Sustainable Energy, initiated a tender for the construction of a 400 MW photovoltaic power plant paired with a 400 MWh BESS. This underscores the growing acknowledgment of the critical role that integration of renewables with energy storage plays in the energy transition landscape, as well as ensuring grid stability and reliability. Moreover, Morocco's energy demand is expected to continue rising steadily, highlighting the need for strategic planning and efficient integration of renewable energy sources. Daily and monthly demand profiles, alongside renewable generation patterns, reveal both opportunities and challenges of incorporating a higher share of renewables into the country's energy mix.

This report demonstrates that Hybrid Renewable Energy Systems in Morocco are feasible and highly competitive. By combining various renewable energy sources, hybrid systems can effectively address the intermittency challenges associated with individual renewables, ensuring a more stable and continuous power supply. These systems offer a strategic pathway for Morocco to harness their abundant natural resources, promoting energy independence while contributing to global climate objectives.

The hybrid renewable energy system, which integrates battery energy storage system (BESS) with renewables at both the system and plant levels offers a cost-effective and reliable method for grid stabilization and ensures a consistent energy supply in Morocco. These systems have an LCOE of 95.2 USD/MWh for solar hybrid technologies[2] and 94.6 USD/MWh for the wind hybrid technologies. Through a modelling exercise for the short-term (2024-2030) and medium-term (2031-2050) under three different scenarios – Business As Usual (considers (non)-renewable energy sources), Advanced scenario (replaces gas with HRES), and Strengthened scenario (phases out coal plants with HRES) - this report highlights the crucial role that renewable energy sources and batteries could play in a future Moroccan hybrid renewable power system.

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[1] Further details, the call aim to identify Battery Energy Storage System (BESS) integrators, who may potentially partner with EPC companies, for the design, supply of materials and equipment, construction, testing, commissioning, and long-term maintenance of a Battery Energy Storage System (BESS) with a capacity of 1600 MWh-AC, divided into several lots across multiple sites.

[2] It should be noted with caution that, based on one available source, the lowest bid for the Midelt project was reported to be in the range of 32–34 USD/MWh for hybrid solar technology (Noor Midelt 2 & 3). However, this information could not be independently verified, and no official or solid data has been found to confirm these figures.

To realize Morocco's ambitious energy transition goals, enabling policies must focus on the development of the regulatory framework that will facilitate hybrid renewable energy system integration through streamlined permitting processes, standardization of interconnection protocols, and performance-based incentives for investments in renewable and storage technologies. Flexible energy markets must be promoted, which give value to ancillary services and flexibility offered by BESS: frequency regulation, peak demand management, and energy shifting, in such a way that grid stability is ensured, stimulating the integration of variable renewable sources. There is also a need for well-defined pathways for phasing out fossil fuels gradually, including subsidies on renewables, carbon pricing systems in line with Morocco's Nationally Determined Contributions. In addition to this, support for public-private partnerships would greatly speed up the implementation of modern energy solutions, unleashing private investment and technical expertise at minimal risk. Lastly, research and development and training programs should be financially supported to build better local capacity in renewable technologies, particularly the integration of storage solutions with variable renewable energy sources. These policies will be fundamental in striking a balance for Morocco's surging energy demand, reducing its emissions, and sustaining grid reliability as it advances into a sustainable future.

There are significant opportunities in integrating hybrid renewable energy technologies into other sectors. To fully capitalize on this potential, it will be necessary to address high initial investment costs, technical challenges, and create supportive regulatory frameworks. Enhancing policy integration, modernizing power systems, and building technical expertise will be critical steps toward maximizing the benefits of renewable desalination and achieving Morocco’s long-term sustainability and economic development goals.

Executive Summary and Methodology

Morocco is embarking on a transformative energy transition aimed at enhancing energy sovereignty and sustainability. As outlined in the latest update of its Nationally Determined Contributions (NDC) to the Paris Agreement, the country plans to elevate the share of renewables in its energy mix to at least 52% by 2030, up from the current 40%. This ambitious goal is supported by the development of solar thermal and photovoltaic plants with a combined capacity of 2,500 MW and wind farms totaling 1,200 MW by 2030. These initiatives are integral to Morocco's strategy to diversify energy sources, lessen dependence on imported fuels, and fortify energy security.

Key components of Morocco's energy strategy include expanding solar and wind energy production, fostering a green hydrogen economy, and establishing a robust natural gas infrastructure. The 2021-2050 energy roadmap emphasizes the use of natural gas for industrial and domestic purposes while progressively transitioning towards hydrogen fuel for electricity generation. To achieve its ambitious renewable energy targets, Morocco could explore hybrid power systems that integrate multiple renewable sources - such as solar and wind - with energy storage solutions. These systems offer reliable and continuous power, effectively addressing the intermittency and non-dispatchability challenges commonly associated with standalone renewable technologies. Additionally, Morocco is positioning itself as a future hub for green hydrogen production, as detailed in the Morocco Hydrogen Offer developed by MASEN.[3] This initiative outlines the country's competitive advantages - such as abundant renewable resources, strategic geographic location, and a clear regulatory framework - to attract investment and scale up hydrogen production for domestic use and international export. By leveraging its abundant natural resources and embracing integrated energy solutions, Morocco can significantly enhance the efficiency, reliability, and sustainability of its energy supply while reinforcing its leadership in the regional and global energy transition.

The report presents a roadmap for Morocco's energy transition through Hybrid Renewable Energy Systems (HRES) which will handle rising electricity demands while diversifying energy sources and cutting greenhouse gas emissions. The report evaluates the combination of solar and wind power with battery storage systems analyzing their technical performance as well as economic viability and environmental impacts.

The report examines three energy expansion scenarios: Business As Usual (BAU), Advanced, and Strengthened. Each scenario analyzes methods for incorporating HRES while maintaining cost-efficiency together with system stability and sustainable practices. Under the **BAU Scenario** the (non)-renewable energy sources are utilized while the **Advanced Scenario** replaces gas with hybrid renewable energy plants and battery energy storage systems to boost system optimization, and the

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[3] Launched on March 2024, the Offer is intended to cover the entire value chain of the green hydrogen sector in Morocco.

Strengthened Scenario achieves complete renewable energy transition by phasing out coal plants with HRES.

HRES demonstrates both feasibility and competitiveness, decreasing unserved energy requirements while optimizing renewable energy utilization. The comprehensive analysis undertaken in this report encompasses several chapters:

- **Definition of key Hybrid Renewable Energy Systems**: Chapter 1 covers the most common three energy configurations: co-located resources, virtual power plants, and full hybrids. Key insights are presented comparing their operational advantages, management needs, and economic considerations, highlighting the essential role of batteries in all configurations.
- **Competitiveness of Technologies**: A detailed economic assessment using Levelized Cost of Energy (LCOE) methodology, presented in Chapter 2, evaluates the viability of various energy technologies, including solar PV, wind, gas plants, and Battery Energy Storage Systems (BESS). This analysis benchmarks Morocco's costs against international standards, reinforcing its competitive position in renewable energy.
- **Demand Analysis**: A thorough analysis of electricity consumption patterns explores how renewable sources can be effectively integrated into the existing energy framework, identifying both challenges and opportunities in Chapter 3.
- **Proposed Technical Solution**: Chapter 4 outlines a technical strategy to meet Morocco's electricity demand, focusing on integrating increased renewable generation. It evaluates different expansion scenarios to ensure operational efficiency and sustainability.
- **Opportunities and Recommendations**: The final chapter identifies additional opportunities for renewable energy integration and provides policy recommendations to support a diversified energy transition.

In conclusion, this report highlights Morocco's strategic initiatives aimed at achieving a sustainable energy future, reinforcing the potential of hybrid systems to play a pivotal role in reaching national renewable energy targets.

THE BENEFITS OF DESIGNING A HYBRID RENEWABLE ENERGY SYSTEM

1. Defining Hybrid Renewable Energy Systems

In 2023, MASEN initiated a tender for the construction of a 400 MW photovoltaic power plant paired with a 400 MWh BESS. The subsequent announcement of pre-qualified bidders, which includes firms from Saudi Arabia, Morocco and France, underscores the growing acknowledgment of the critical role that integration of renewables with energy storage plays in the energy transition landscape.[4]

This chapter explores the rationale behind the design of hybrid renewable power systems, emphasizing their potential to enhance energy reliability, optimize resource utilization, and minimize environmental impact. By combining various energy sources, hybrid systems can effectively address the intermittency challenges associated with individual renewables, ensuring a more stable and continuous power supply. Moreover, these systems could offer a strategic pathway for countries like Morocco to harness their abundant natural resources, promoting energy independence while contributing to global climate objectives.

1.1 Hybrid Renewable Energy Systems

In various disciplines, the term “hybrid” denotes systems composed of multiple distinct parts, each contributing unique characteristics. This concept is gaining traction in the energy sector, particularly in discussions about the evolution of the bulk power system, which includes utility-scale generation and storage technologies connected to the transmission network. Hybrid energy systems, which combine multiple technologies that could also function independently, are at the forefront of this transformation.

Hybrid energy systems are projects that link together utility-scale renewable energy generation sources or combine renewable energy generation with energy storage technologies. The primary goal is to enhance the reliability, affordability, and sustainability of electricity supply by optimizing the contributions of different generation sources.

Additionally, they represent a new level of optimization for both investments and operations. This involves coordinating multiple technologies to maximize overall system performance. In fact, the integration of hybrid systems could have also far-reaching implications for electricity prices, system costs, and market services.

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[4] https://www.pv-magazine.com/2023/12/18/morocco-reveals-bidders-for-400-mw-400-mwh-solar-plus-storage-tender/

However, the shift from a concept of many single technologies to a set of multiple technologies working together presents challenges for the design, operation, and regulation of wholesale electricity markets, state regulation of electric utilities, and the development of energy policies.

In theory, hybrid energy systems aim to achieve economic benefits by leveraging locational and operational synergies. Locational synergies occur when technologies are co-located, while operational synergies involve coordinated operations between the linked technologies, managed either by the grid operator or the plant owner. When the grid operator oversees the operations, the sub-system's activities are optimized in a manner, similar to the broader grid, but with a focus on the specific needs of the linked technologies. If the plant owner manages the operations, it may require advanced control technologies or shared components. This coordination could also involve creating bids or dispatch offers at a level below that of the bulk power system operator, influenced by the synergies of the linked technologies and potential market design flaws.

To better evaluate these systems, a classification differentiating hybrid systems based on their locational and operational synergies is proposed below according to the one identified by the work of C.A. Murphy et al.[5] This classification helps define the configuration, operation, market participation, and settlements associated with the joint system, aiding in policy, regulatory, and modeling evaluations.

Co-located Resources

Co-located resources consist of various energy technologies that are situated together but operate independently. The main advantage of co-location is potential cost savings from shared expenses, although this may come with reduced operational value compared to separate projects. Owners often strategize to maximize the value of these combined systems, but the lack of shared components means they behave similarly to independent systems.

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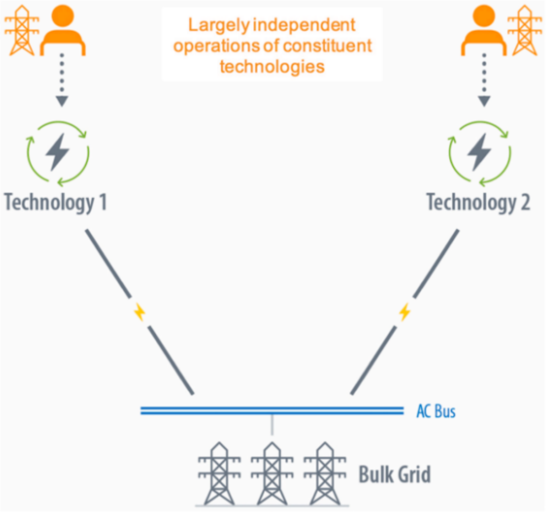
[5] C.A. Murphy, A. Schleifer, K. Eurek, A taxonomy of systems that combine utility-scale renewable energy and energy storage technologies, Renewable and Sustainable Energy Reviews, Volume 139, 2021.

Figure 1: Linkages that define co-located resources category



Source : C.A. Murphy et al. (2021)

Cost savings can arise from shared balance-of-system costs and a common transmission interconnection, enhancing efficiency. However, independent components may allow for easier retrofitting and upgrades. The operational behavior of these technologies is expected to be similar, simplifying management and integration.

The impact of co-location on operational value depends on the complementarity of the systems involved, which can sometimes lead to suboptimal sitting. Any loss in operational value must be balanced with cost savings for co-located resources to be economically viable.

Virtual Power Plants

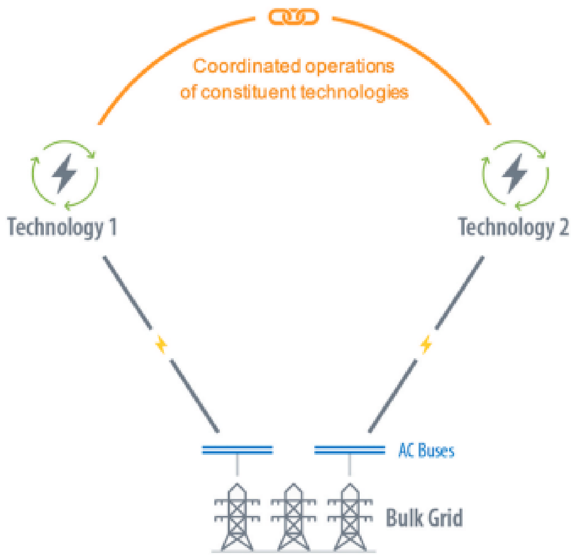
A virtual power plant coordinates the operations of various dispersed energy technologies to harness synergies in their resource characteristics and services. This coordination can enhance value by allowing the virtual power plant to deliver services that independent systems cannot. While potential cost savings may be limited due to the technologies being in different locations, the primary goal is to maximize the overall value in energy markets, especially those with variable pricing and capacity markets.

The effectiveness of a virtual power plant depends on system characteristics (like renewable energy penetration and flexible capacity) and market conditions, which can vary widely across countries. If successfully integrated, the virtual power plant can provide additional grid services more cost-effectively than independent systems.

The key difference between a virtual power plant and broader grid operations is the level of operational coordination. If the virtual power plant merely shifts value from other assets, only its owner benefits. Furthermore, the unique advantage of a virtual power plant is the ability to optimally site each technology, which is particularly beneficial in markets with restrictions on shared interconnections.

Operational linkages can also lead to secondary cost benefits, such as improved financing terms and reduced penalties or integration charges. Additionally, the operational dynamics of a virtual power plant may influence maintenance and operational costs compared to multiple independent projects.

Figure 2: Linkages that define Virtual Power Plant category



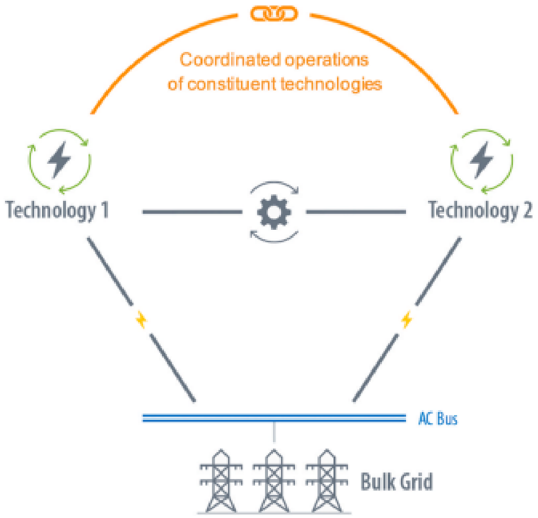
Source : C.A. Murphy et al. (2021)

Full Hybrids

In the full hybrid category, multiple energy technologies are both locationally and operationally interconnected. This category is distinct because the benefits of co-location and coordinated operations are interlinked. To fully realize the advantages of a full hybrid system, co-optimization of the technologies is essential, often involving shared components and control strategies.

A key benefit of a full hybrid system is the potential for increased revenue from energy, capacity, and ancillary services, which can vary based on regional market rules. The efficiencies gained from shared components—such as inverters—allow for better utilization of generated energy, reducing losses from clipping and other inefficiencies. However, sharing components can also introduce operational constraints that might limit the system's performance during peak demand periods.

Figure 3 Linkages that define Full Hybrid category



Source : C.A. Murphy et al. (2021)

Greater integration of technologies in a full hybrid can lead to additional cost savings through shared infrastructure and balance-of-system costs, enabling project developers to achieve better performance at lower costs. Nonetheless, potential savings must account for the need for advanced control systems and the regulatory challenges of integrating multiple technologies.

Deciding to pursue a full hybrid project requires careful assessment of the interrelated effects of locational and operational linkages. This evaluation demands sophisticated tools and resources, which can involve significant time and cost to develop the necessary data and parameters.

1.2 Similarities and differences in Hybrid Renewable Energy Systems

According to the above-mentioned classification, linking technologies locationally and/or operationally is expected to change the cost or economic value of the joint system compared to independent projects. The economic advantages of hybrid energy systems are realized through strategic siting and coordinated operation of multiple technologies. Several key factors come into play that differentiate their benefits in real-world energy systems as indicated below.

Figure 4 Key advantages and differences of hybrid renewable energy systems

Considerations	Co-located Resources	Virtual Power Plants	Full Hybrids
Operational Advantages	Independent Operation: Flexibility in management and operation.	Coordinated Operations: Ability to provide high-value grid services.	Significant Efficiency Gains: Improved overall system efficiency through shared components.
	Resource Diversity: Enhances grid stability and reliability.	Dynamic Response: Responds to real-time market signals, optimizing operational value.	Optimized Revenue Generation: Monetizes energy generation that would otherwise be lost.
	Battery Role: Provides essential energy storage, ensuring reliability.	Battery Integration: Enhances energy storage capabilities for better load management.	Battery's Critical Role: Improves generation efficiency and load shifting, enabling ancillary services.
Management and Control	Minimal Integration Needs: Simplifies management of independent technologies.	Advanced Coordination Required: Optimizes performance across different technologies.	Sophisticated Control Systems Required: Requires advanced management to integrate operations.
	Operational Independence: Easier to manage individual technologies.	Complementarity Leveraging: Focuses on optimizing technologies with complementary production profiles.	Co-optimization: Maximizes overall performance through simultaneous optimization of multiple technologies.
	Simplified Retrofitting: Easier upgrades with independent systems.	Operational Flexibility: Effectively manages varying outputs from different technologies.	Operational Constraints: Shared components may limit output during peak periods, requiring careful capacity management.
Economic and Logistical Considerations	Shared Balance-of-System (BOS) Costs: Savings from shared engineering, site acquisition, and permitting.	Increased Revenue Potential: Capitalizes on energy, capacity, and ancillary service markets.	Greater Cost Savings: Potential for lower total costs through shared infrastructure and reduced BOS expenses.
	Limited Capital Savings: Lacks additional savings from shared components.	Cost Advantages: Operational efficiencies can lead to higher returns despite dispersed resources.	Initial Investment: Higher upfront costs due to advanced control systems and regulatory compliance challenges.
	Installation and Maintenance Efficiency: Potentially lower costs due to easier independent installations.	Potential for Improved Financing: Better financing terms due to perceived lower risk.	Regulatory Navigation: Must address challenges related to interconnection of diverse technologies.

Source: own elaboration on NREL (2021), Zohuri (2018) and others

2. Measuring Competitiveness of Hybrid Energy Generation Technologies

The economic viability of Hybrid Renewable Energy Systems (HRES) is a crucial factor influencing their adoption and implementation. This chapter delves into the cost analysis of HRES for Morocco, examining the various components that contribute to the overall cost, including capital expenditure, operational and maintenance costs, and the potential for cost savings through technological advancements and economies of scale.

Understanding the cost of energy technologies is essential for comparing the Levelized Cost of Energy (LCOE) of HRES with other energy solutions. The LCOE is a standard metric for measuring the cost-effectiveness of different energy technologies over their lifetimes. By comparing these costs, it is possible to identify which options offer the lowest costs and, consequently, the highest returns.

Investors and policymakers rely on cost analyses to make informed decisions about where to allocate their resources. Knowing the costs associated with HRES helps attract investments and secure funding for projects. Governments also use these comparisons to design subsidies and incentives that support the most efficient and sustainable energy solutions.

Analyzing the costs of different energy technologies highlights areas where improvements can reduce expenses. This drives innovation and helps develop more affordable and efficient energy systems. Additionally, it provides insights into the competitiveness of HRES in the energy market, which is vital for planning and expanding renewable energy projects.

2.1 Key Variables for LCOE Analysis

To evaluate the Levelized Cost of Energy (LCOE) for various energy technologies in Morocco, it is important to consider all variables correlated with the construction and operation of the power plant. These variables provide a comprehensive understanding of the financial and operational aspects that influence the cost-effectiveness and viability of different energy projects. This section will benchmark each variable considering international prices to ensure a thorough and accurate analysis.

Capital Cost (USD/kW): This variable represents the overnight cost of building the plant, excluding cost escalation and interest during construction, normalized by the rated capacity of the plant. Understanding CAPEX is crucial as it directly impacts on the initial investment required for a project and influences financing and budgeting decisions.

Variable O&M (USD/MWh): Operation and maintenance costs that vary with the operating hours, excluding fuel inputs, are considered variable O&M. These costs are significant for ongoing operational efficiency and profitability, affecting the overall LCOE by influencing the cost per unit of electricity produced.

Fixed O&M (USD/kW/y): These are the operation and maintenance costs that are a function of a plant's capacity, such as labor and insurance. Fixed O&M costs are essential for understanding the baseline operational expenses that remain constant regardless of the plant’s output, affecting the long-term financial sustainability of the project.

Fuel Prices (USD/MWh): The cost of the fuel consumed, relative to the primary energy input, not including plant efficiency, is another vital variable. Fuel prices significantly affect the operational costs of thermal power plants, thereby influencing the overall LCOE. Understanding local and international fuel price trends helps in accurately estimating future operational costs.

Energy Production (MWh): electricity production throughout the entire useful lifetime of the power plant, taking into consideration annual degradation and repowering, if any.

Construction Time (Years): This parameter refers to the time required to complete the project from physical installation through to electricity generation, excluding pre-construction stages such as planning and permitting. The construction time affects the project timeline and the period before the plant becomes operational and starts generating revenue.

Lifetime (Years): The expected operational time of a plant, excluding end-of-life extensions, over which the capital cost is amortized, is the plant's lifetime. This variable is critical for financial modeling as it impacts on the depreciation of assets and the period over which returns on investment are calculated.

Cost of Capital (WACC) (%): The weighted average cost of capital, used for discounting in real terms, reflects the split between equity and debt investments. The WACC is crucial for LCOE calculations as it impacts the cost of financing the project. A lower WACC indicates cheaper financing, which can reduce the LCOE.

Each of these variables plays a pivotal role in the calculation of the LCOE. By analyzing these parameters, costs can be benchmarked, identify trends, and determine the most cost-effective and viable energy technologies for deployment in Morocco. The following sections will delve into the specifics of each parameter, providing a detailed assessment based on international and local data.

CAPEX

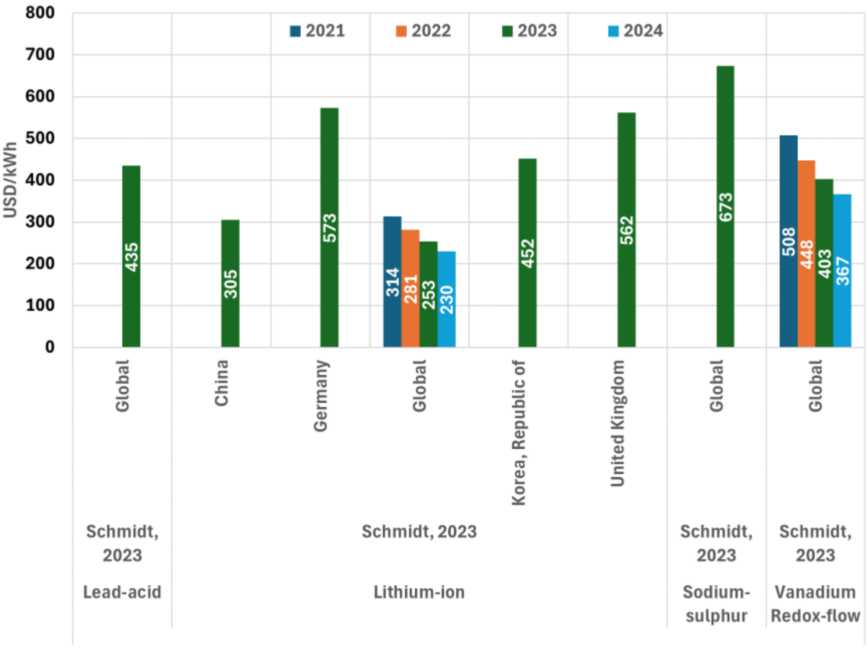
The analysis of capital costs (CAPEX) for various energy technologies is crucial for assessing the economic viability of energy generation projects. This section focuses on evaluating the CAPEX of key technologies such as lithium-ion batteries, sodium-sulfur batteries, vanadium redox-flow batteries, lead-acid batteries, combined cycle gas turbines (CCGT), solar photovoltaic (PV) systems, and onshore wind energy. The reference size for those plants is the utility scale medium size in the range of 50-200 MW.

Batteries Energy Storage

The capital costs for batteries systems vary significantly depending on technology and region. According to Schmidt (2023), the costs for lithium-ion batteries systems globally have decreased from $314/kWh in 2021 to a projected $230/kWh in 2024. In China, the costs for 2023 are $305/kWh, while in Germany they reach $573/kWh in the same year. This reflects a trend of lower costs in markets with higher production and demand, with China having the lowest costs due to its large production capacity and economies of scale.

For lead-acid batteries systems, the global costs in 2023 are $435/kWh. Regarding sodium-sulfur and vanadium redox-flow batteries systems, the global costs in 2023 are $673/kWh and $403/kWh respectively, projected to decrease to $508/kWh and $367/kWh in 2024. These higher costs compared to lithium-ion batteries systems reflect more specialized and less commercialized technologies, resulting in higher prices due to lower economies of scale and greater technological complexity.

Figure 5 CAPEX – Batteries



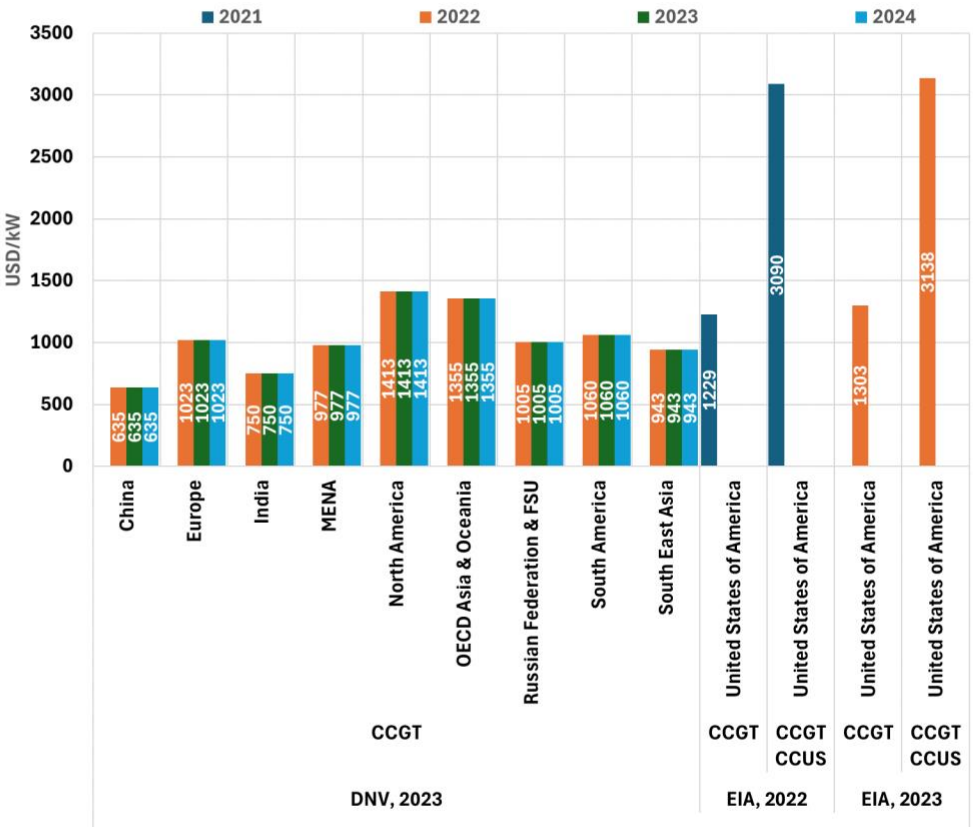
Source: own elaboration

Gas Plants

CAPEX for gas plants fluctuates significantly by region and year. According to DNV (2023), the costs for Combined Cycle Gas Turbine (CCGT) plants in China are $635/kW from 2021 through 2024. In Europe and India, the costs are $1023/kW and $750/kW respectively for the same period. In the Middle East and North Africa (MENA) region, the costs are $977/kW, while in North America, they are the highest at $1413/kW.

For OECD Asia & Oceania, Russian Federation & FSU, and South America, the costs for CCGT plants are $1355/kW, $1005/kW, and $1060/kW respectively from 2021 through 2024. In Southeast Asia, the costs are $943/kW during the same period.

Figure 6 CAPEX – Gas Plants



Source: own elaboration

According to EIA (2022, 2023), the costs for CCGT plants in the United States were $1229/kW in 2021 and increased to $1303/kW in 2023. Lazard (2023) reports the costs for CCGT plants in the United States at $975/kW in 2023 and $925/kW for gas peaking plants in the same year.

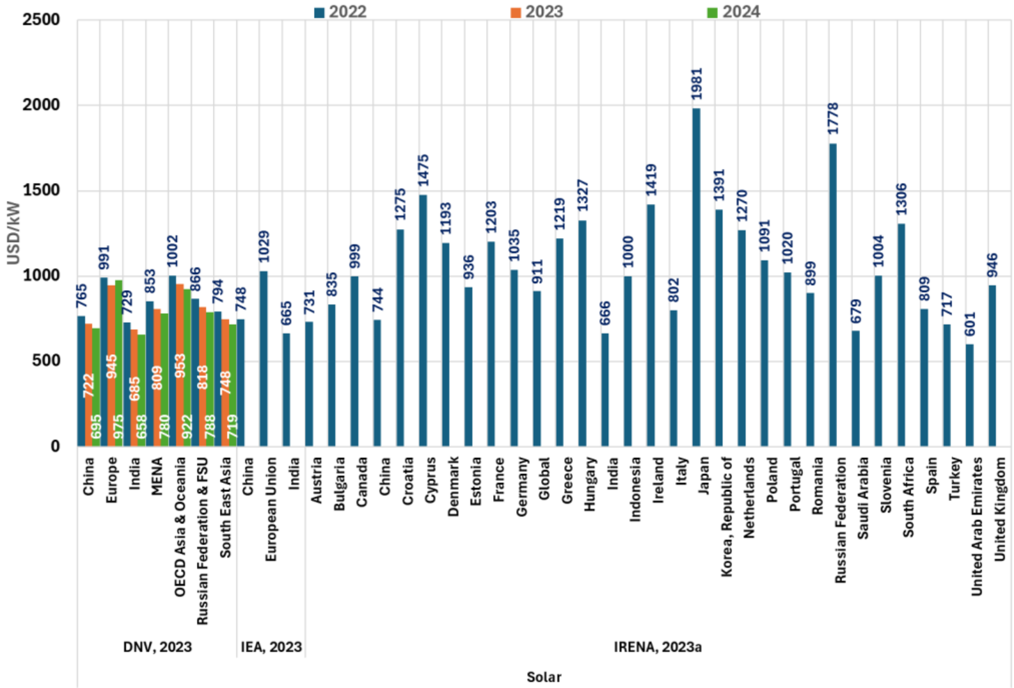
For unspecified gas plants, IEA (2023) reports costs of $582/kW in China, $1040/kW in the European Union, $728/kW in India, and $1040/kW in the United States for the year 2023.

Solar PV Plants

The CAPEX for PV solar ground-mounted plants fluctuates significantly by region and year. According to DNV (2023), the costs in China range from $765/kW in 2022 to $695/kW in 2024. In Europe, the costs are $991/kW in 2022, decreasing to $975/kW in 2024. India sees costs of $729/kW in 2022, dropping to $658/kW in 2024. The Middle East and North Africa (MENA) region shows a decline from $853/kW in 2022 to $780/kW in 2024.[6] In North America, the costs decrease from $1043/kW in 2022 to $937/kW in 2024. IEA (2023) reports costs for China at $748/kW, the European Union at $1029/kW, India at $665/kW. IRENA (2023a) provides extensive data showing costs in various countries, Global costs are $953/kW in 2021, slightly decreasing to $911/kW in 2022.

Overall, CAPEX for solar plants demonstrates diverse trends across different regions and years, reflecting varying market conditions and technological advancements.

Figure 7 CAPEX - Solar PV Plants



Source: own elaboration

Wind Onshore Plants

The CAPEX for onshore wind plants shows notable variation by region and year. According to DNV (2023), the costs in China decreased from $804/kW in 2022 to $742/kW in 2023. In Europe, the costs were $1678/kW in 2022, dropping to $1513/kW in 2023. India's costs reduced from $1172/kW in 2022 to $1047/kW in 2023, while in the Middle East and North Africa (MENA) region, the costs fell

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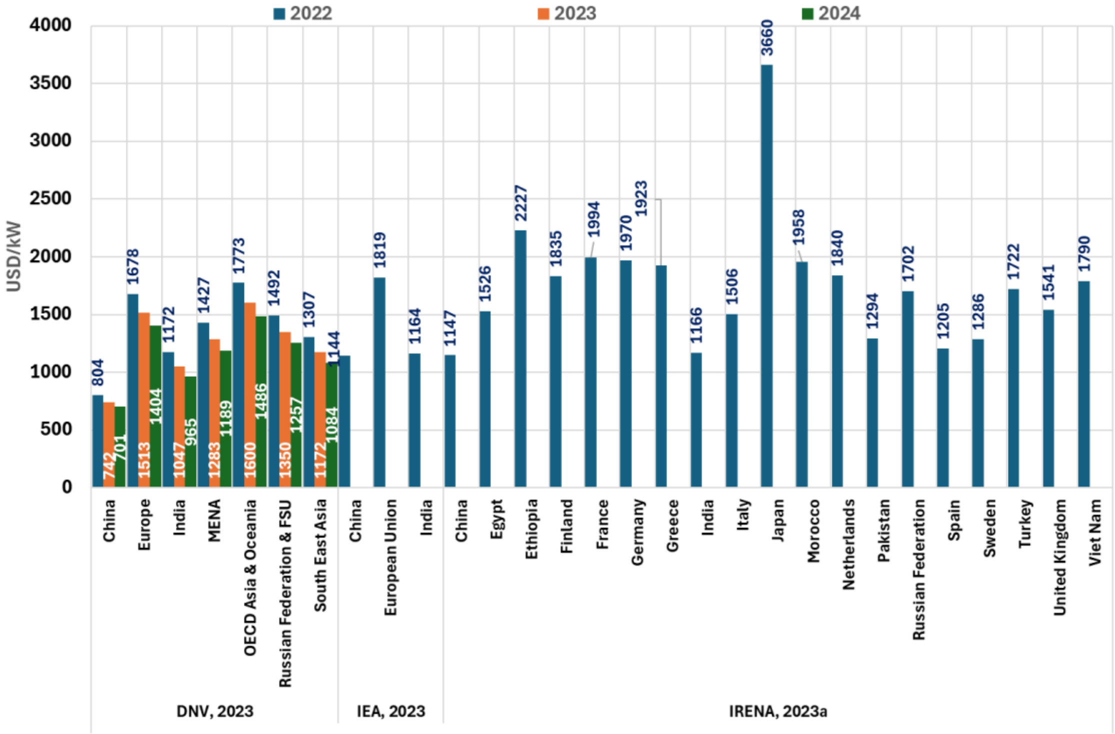
[6] **Hatton, 2024, The Global and National Energy Systems Techno-Economic (GNESTE) Database: Cost and performance data for electricity generation and storage technologies**

from $1427/kW in 2022 to $1283/kW in 2023. North America saw a decrease from $1919/kW in 2022 to $1756/kW in 2023.

The OECD Asia & Oceania region had costs of $1773/kW in 2022, which decreased to $1600/kW in 2023. In the Russian Federation and FSU, the costs were $1492/kW in 2022, dropping to $1350/kW in 2023. In Southeast Asia, the costs went down from $1307/kW in 2022 to $1172/kW in 2023. According to IEA (2023), the costs in China were $1144/kW, in the European Union $1819/kW, in India $1164/kW for 2023.

Figure 8 CAPEX – Onshore Wind PV Plants



Source: own elaboration

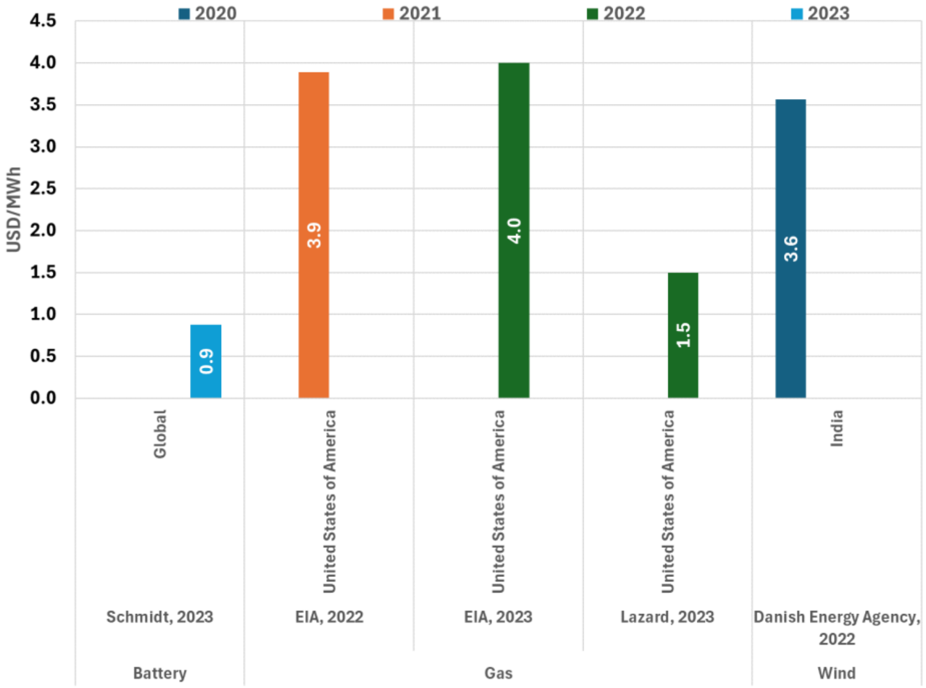
IRENA (2023a) provides detailed data for various countries in 2023. In China, the costs were $1147/kW, and in Egypt, they were $1526/kW. Ethiopia reported costs of $2227/kW, and Finland had costs of $1835/kW. France's costs were $1994/kW, Germany's were $1970/kW, and Greece reported $1923/kW. India had costs of $1166/kW, while Italy's costs were $1506/kW. Japan reported a high cost of $3660/kW. In Morocco, the costs were $1958/kW. The Netherlands reported $1840/kW, and in Pakistan, the costs were $1294/kW. The Russian Federation had costs of $1702/kW, while Spain reported $1205/kW. Sweden had costs of $1286/kW, and Turkey reported $1722/kW. The United Kingdom's costs were $1541/kW, and Vietnam reported costs of $1790/kW. Overall, the CAPEX for onshore wind plants in 2022 and 2023 demonstrates considerable fluctuations across different regions, reflecting the influence of local market conditions, technological advancements, and policy frameworks.

OPEX

Variable O&M

The OPEX for variable operation and maintenance (O&M) costs vary by technology and year. According to Schmidt (2023), the global O&M cost for batteries in 2023 is $0.9/MWh. For gas plants in the United States, the EIA (2022) reports an O&M cost of $3.9/MWh in 2021, which increases to $4.0/MWh in 2023 according to EIA (2023). Lazard (2023) shows a significantly lower O&M cost for gas plants at $1.5/MWh for 2023. The variable O&M costs demonstrate considerable differences across technologies and years, reflecting the specific maintenance and operational requirements associated with each energy source.

Figure 9 Variable O&M – All Technologies



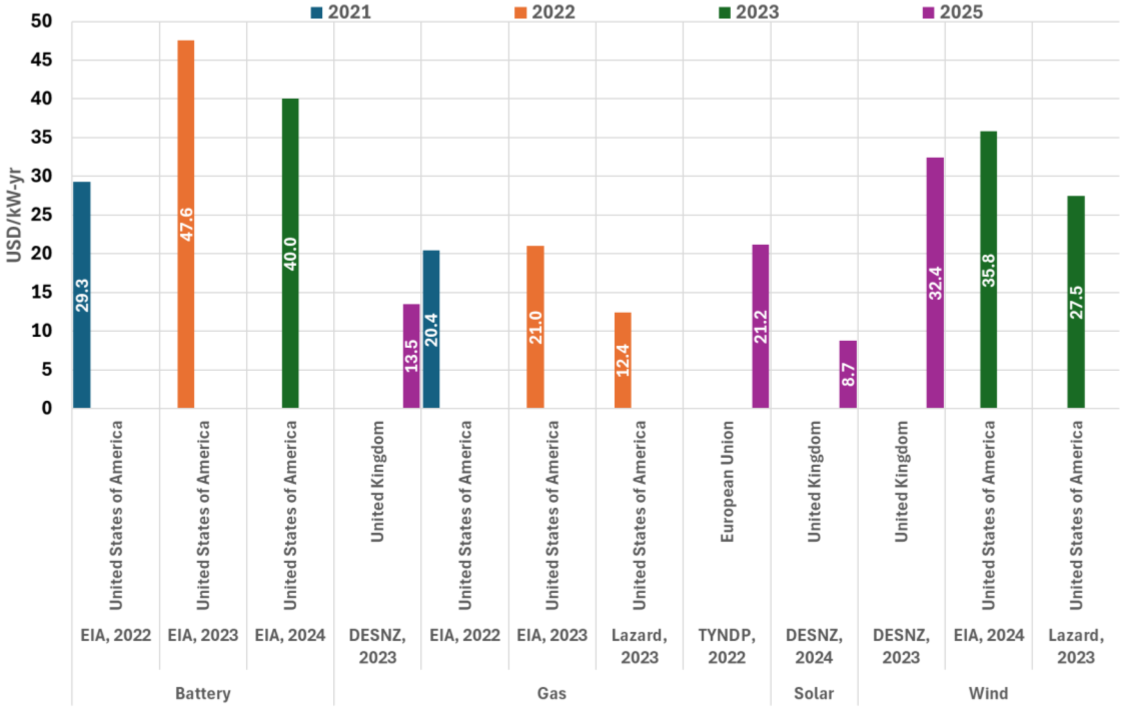
Source: own elaboration

Fixed O&M

The fixed O&M costs for various energy technologies vary by region and year. For batteries in the United States, the EIA (2022) reports a cost of $29.3/kW-year in 2021, which increases to $47.6/kW-year in 2022, before dropping to $40.0/kW-year in 2024 according to EIA (2024). For gas plants, DESNZ (2023) reports a cost of $13.5/kW-year in the United Kingdom. In the United States, the EIA (2022) reports a cost of $20.4/kW-year in 2021, which increases slightly to $21.0/kW-year in 2023 according to EIA (2023). Lazard (2023) shows a lower fixed O&M cost for gas plants in the United States at $12.4/kW-year for 2023. Additionally, TYNDP (2022) reports a cost of $21.2/kW-year for the European Union.

For solar power, DESNZ (2024) reports a fixed O&M cost of $8.7/kW-year in the United Kingdom for 2024. For wind power, DESNZ (2023) reports a fixed O&M cost of $32.4/kW-year in the United Kingdom for 2023. In the United States, the EIA (2024) projects a fixed O&M cost of $35.8/kW-year for wind power, while Lazard (2023) reports a lower cost of $27.5/kW-year for 2023.

Figure 10 Fixed O&M – All Technologies



Source: own elaboration

Fuel Prices

The main fuels used for electricity generation in Morocco are Coal, Natural Gas or LNG, Fuel Oil (bunker) and Diesel Oil. These fuels are highly correlated with international energy commodities. This is because the marginal power plant (last power plant in the merit order called upon dispatch to supply the demand) is usually a thermal power plant or a hydroelectric power plant with a "water value" equivalent to the opportunity cost of dispatching a thermal power plant in the future. For this scenario, full availability of fuels is assumed. For the commodity projection, IMF's latest release of April 2024 for the short and long-term are assumed. Table 1 shows this projection.

Table 1. Projected prices according to IMF in real 2024 USD

Commodity	Unit	2024	2025	2026	2027	2028	2029	2030
Coal, Australia	USD/ton	135.8	132.5	125.7	123.5	119.8	117.7	117.7
Crude oil, avg, spot	USD/bbl	77.67	71.41	67.23	64.28	62.26	60.82	60.82
Natural gas, US	USD/MMbtu	2.3	3.3	3.6	3.5	3.4	3.3	3.3
WTI	USD/bbl	74.0	68.1	64.1	61.3	59.3	58.0	58.0
BRENT	USD/bbl	80.6	74.1	69.8	66.7	64.6	63.1	63.1

* Note: Price Projections from 2029 onward are assumed to remain constant.

Liquefied Natural Gas (LNG): The estimation is based on an empirical market formula applied in the region, which adds approximately 5 USD/MMBTU to the Henry Hub (HH) price of gas. This value considers 15% of HH price representing the losses in the liquefaction process; 3.15 USD/MMBTU as liquefaction fee, transportation, and port services and 1.3 USD/MMBTU related to the regasification infrastructure costs.

Coal: Coal price in Puerto Bolivar (Colombia) as 89% of the Coal Australia. This value along with the regional logistic costs to power plants results in the prices considered at plant site. The coal internalization cost was 25 USD/ton for Atlantic. Morocco's reliance on specific sources, such as Puerto Bolívar in Colombia, would depend on market prices and logistical factors, including transportation costs across the Atlantic. As for internalization costs, it is reasonable to assume $25 USD/ton for logistical expenses. We have included the assumption of coal supply from Puerto Bolívar, as well as these internalization costs. However, since coal provides baseload generation, fluctuations in its price would not significantly impact the marginal cost or system dispatch in the model developed.

Liquid fuels: They represent commodities traded in international markets and keep a direct correlation with crude oil prices. The forecasts for bunker and diesel oil prices have been estimated with a linear regression model as a function of crude oil price (explanatory variable). The parameters of the regression model are empirically adjusted to account for freight and internalization costs.

Based on the calculated internalization costs, the resulting CIF fuel prices are shown in the following table.

Table 2. Fuel Price assumptions - Morocco

Fuel	Unit	2024	2025	2026	2027	2028	2029	2030
LNG	USD/MMbtu	7.1	8.2	8.6	8.5	8.4	8.3	8.3
Coal Atlantic	USD/MMbtu	6.1	6.0	5.7	5.7	5.5	5.4	5.4
Bunker 3%S	USD/MMbtu	11.6	11.3	10.8	10.3	9.9	9.6	9.6
Diesel	USD/MMbtu	16.6	16.2	15.6	15.0	14.5	14.2	14.2

Source: Own elaboration

Construction Time

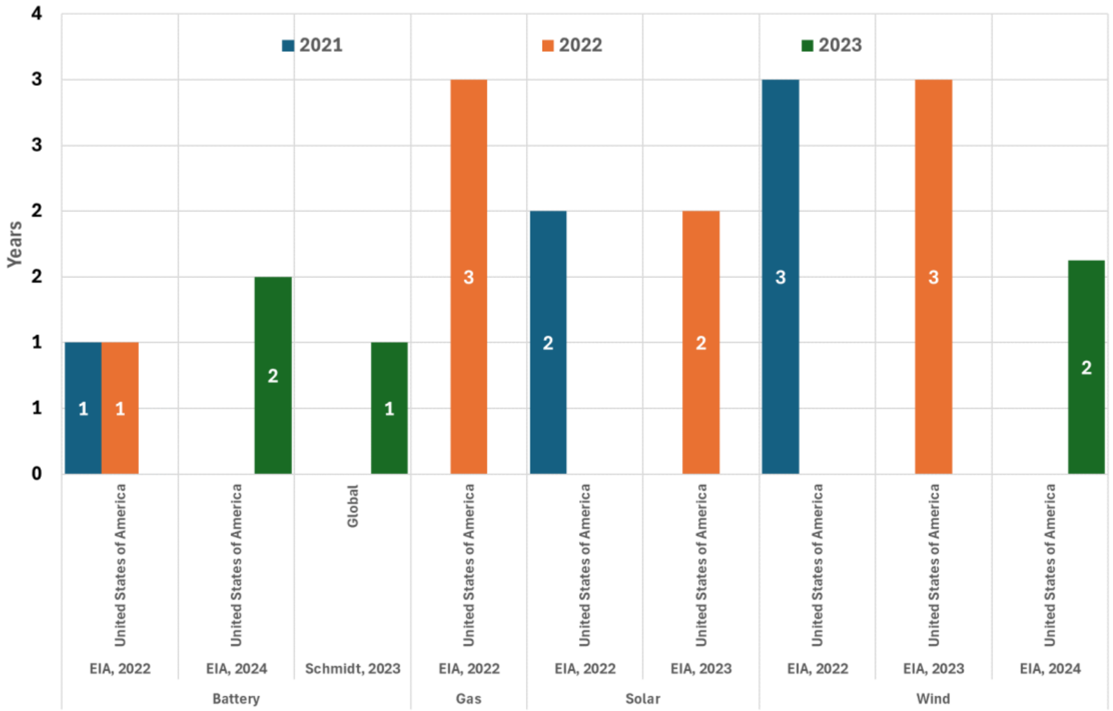
The construction time for various energy technologies, measured in years, varies by region and year. According to EIA (2022), the construction time for battery projects in the United States is 1 year in both 2021 and 2022. EIA (2024) projects an increase to 2 years by 2024. Schmidt (2023) reports a global average construction time for battery projects of 1 year in 2023.

For OCGT gas projects, DESNZ (2023) reports a construction time of 3 years in the United Kingdom. In the United States, EIA (2022) reports a construction time of 3 years, while Lazard (2023) reports a shorter time of 2 years for 2023.

For solar projects, DESNZ (2024) reports a construction time of 1 year in the United Kingdom. EIA (2022) and EIA (2023) report a consistent construction time of 2 years for solar projects in the United States.

Wind projects also show variability. DESNZ (2023) reports a construction time of 2 years in the United Kingdom. In the United States, EIA (2022) and EIA (2023) report a construction time of 3 years, with a projected decrease to 2 years by EIA (2024).

Figure 11 Construction time – All Technologies



Source: own elaboration

Lifetime

The projected lifetime of energy projects, measured in years, varies by technology, region, and year.

For battery projects, the Danish Energy Agency (2024) reports a 20-year lifetime for projects in Denmark. In the United States, EIA (2024) and Lazard (2023) both project a 20-year lifetime. Kebede (2021) reports a shorter global average lifetime of 11 years. Some projects also foresee the replacement or partial retrofit of battery banks to extend the facility's lifespan.

Gas projects show regional variations. According to the Danish Energy Agency (2024), the lifetime for gas projects in Denmark is unspecified. DESNZ (2023) reports a 25-year lifetime in the United

Kingdom, while Lazard (2023) indicates a 20-year lifetime in the United States. TYNDP (2022) reports a 25-year lifetime for the European Union.

Solar projects also show variations. The Danish Energy Agency (2022) does not specify a lifetime for projects in India. DESNZ (2024) reports a 35-year lifetime in the United Kingdom. TYNDP (2022) indicates a 40-year lifetime for the European Union. VDMA (2024) reports a 25-year lifetime in 2023, increasing to 30 years by 2025 for the European Union.

For wind projects, the Danish Energy Agency (2022) does not specify a lifetime for projects in India. DESNZ (2023) reports a 25-year lifetime in the United Kingdom. In the United States, EIA (2024) projects a 23-year lifetime, while Lazard (2023) indicates a 20-year lifetime. TYNDP (2022) reports a 30-year lifetime for the European Union.

Figure 12 Lifetime – All Technologies

Source: own elaboration

Cost of Capital

The Weighted Average Cost of Capital (WACC) is a crucial metric for evaluating the cost of financing a project. It represents the average rate of return required by all a company's investors, including equity holders and debt providers. The WACC is essential for assessing the feasibility and attractiveness of energy projects, as it directly impacts the overall cost of capital.

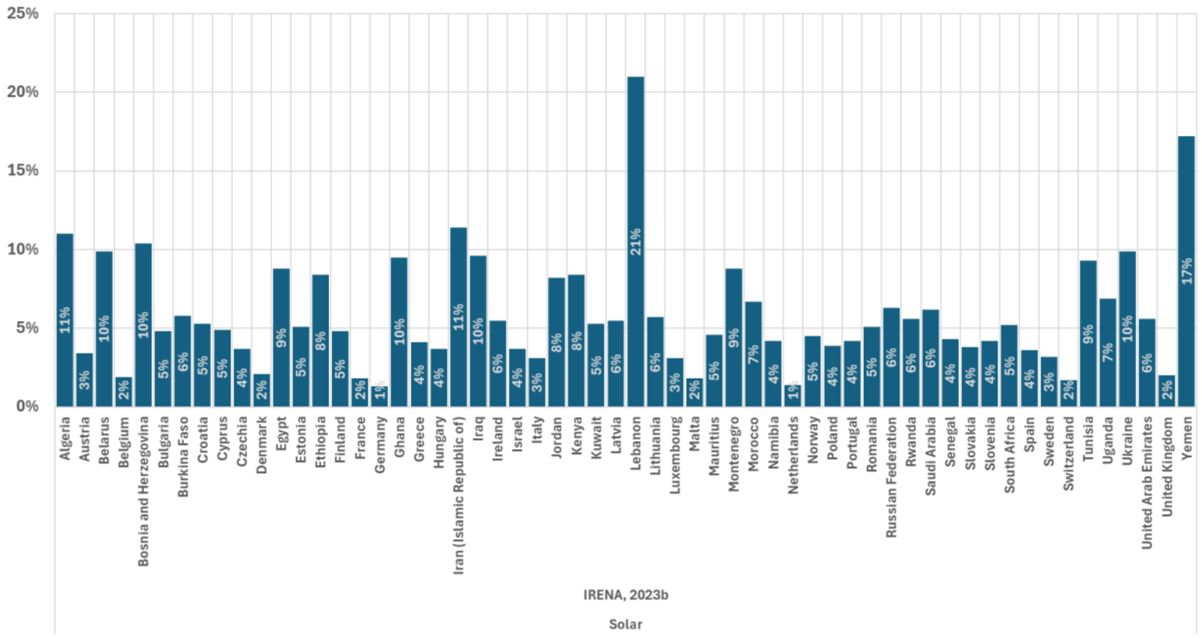
In the context of the Middle East and North African (MENA) region, the WACC can vary significantly due to differing risk perceptions and economic conditions. The WACC for energy projects in the MENA region typically ranges between 6% and 9% (Komendantova, 2019). Specifically, for North African countries like Morocco, Tunisia, Egypt, and Algeria, the WACC tends to be on the higher side due to increased risk factors and investment challenges. The WACC for Algeria and Egypt is around 8.3%, while for Morocco and Tunisia, it is slightly higher at approximately 9.2%. These elevated WACC values reflect the perceived risks and the need for higher returns to attract investment in these regions. Below is a benchmark of WACC for solar and wind technologies to compare Morocco's position relative to other countries.

Solar Plants

Next Figure presents a benchmark of WACC for solar projects across various countries in 2021, according to data from IRENA (2023b). The WACC values vary significantly, reflecting the diverse economic conditions and investment climates of each country.

For Morocco, the WACC for solar projects is 7%. This places Morocco in a competitive position compared to many other countries in the region. For instance, Algeria has a WACC of 11%, and Egypt has a WACC of 9%, indicating higher investment risks in these countries compared to Morocco. Tunisia also has a WACC of 9%, further highlighting Morocco's relative attractiveness for solar investments.

Figure 13 WACC – Solar Plants



Source: own elaboration

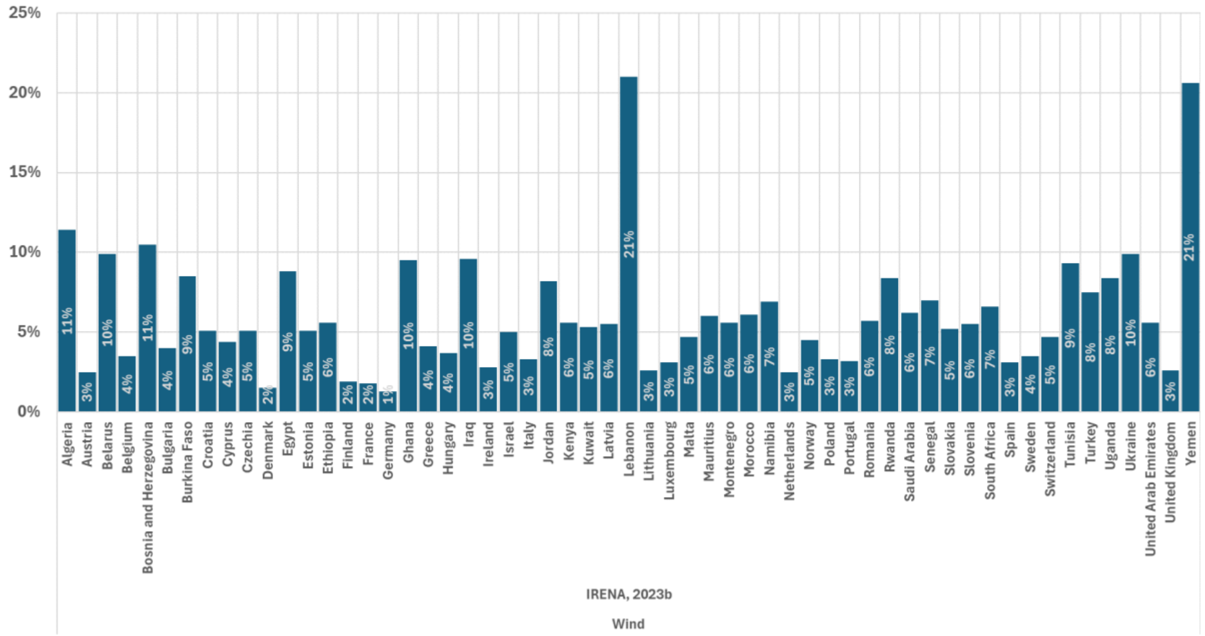
Several countries have significantly higher WACC values, indicating greater investment challenges. Argentina, for example, has a WACC of 14%, and Lebanon shows the highest WACC at 21%. These figures suggest high-risk environments that demand higher returns for investors to compensate for the perceived risks.

Wind Plants

Next Figure presents a benchmark of the WACC for wind projects in various countries for 2021, based on data from IRENA (2023b). The WACC values differ significantly across countries, reflecting diverse economic environments and investment conditions.

For Morocco, the WACC for wind projects is 6%. This indicates a moderate investment risk compared to other countries. Algeria has a higher WACC at 11%, and Egypt has a WACC of 9%, suggesting higher investment risks in these countries relative to Morocco. Tunisia also has a WACC of 9%, highlighting Morocco's favorable position for wind energy investments.

Figure 14 WACC – Wind Plants



Source: own elaboration

Comparatively, some countries exhibit much lower WACC values, indicating more stable investment climates. For example, Germany and the United States both have a WACC of 3%, and the United Kingdom also has a WACC of 3%. These lower values typically reflect lower perceived investment risks.

2.2 LCOE Estimation for Energy Technologies in Morocco

In the following section, the Levelized Cost of Energy (LCOE) for Morocco is estimated. The estimation process will use benchmark variables from the previous sections.

Assumptions

The assumptions for this calculation are specifically tailored to the context of Morocco, using data pertinent to the country, the MENA region, and relevant market benchmarks. The goal is to determine realistic and accurate values for the Levelized Cost of Energy (LCOE) of various technologies in Morocco. The figure below outlines the key parameters.

Figure 15 Main assumptions for LCOE - Morocco

Tech	Characteristic	Capacity MW	Capital Cost USD/kW	Variable O&M USD/MWh	Fixed O&M USD/kW/yr
Gas Turbine	Peaking	70	1124	4	21
Gas CC	Intermediate	200	977	4	21
Solar	PV	100	780	0	9
Wind	Onshore	100	1958	0	15
BESS	Standalone	100	1012	0	48
Solar+BESS	100 PV + 100MW/4MWh	100	1792	0	13
Wind+BESS	100 PV + 100MW/400MWh	100	2970	0	30

	Construction Time Years	Lifetime Years	WACC %	Fuel Cost USD/MMBTU	Dispatch Factor %	
Gas Turbine	3	25	9%	8.3	20%	-
Gas CC	3	25	9%	8.3	50%	-
Solar	2	25	6%	0	25%	-
Wind	3	25	6%	0	35%	-
BESS	2	20	6%	0	17%	-
Solar+BESS	2	20	6%	0	25%	17%
Wind+BESS	3	20	6%	0	35%	17%

Source: own elaboration

These values will be used to calculate the typical LCOE for Morocco, providing insights into the economic viability of various energy technologies in the country. The calculation will consider the specific costs and operational characteristics to reflect the unique conditions in Morocco's energy market. The focus of this report is on co-located HRES systems, where energy storage and renewable generation sources, such as solar and wind, are integrated at the same site. This approach offers several substantial advantages that have been previously discussed.

Firstly, CAPEX and OPEX synergies are significant in co-located systems. By sharing infrastructure like inverters, control systems, and connection points, co-located HRES systems reduce overall project costs. Moreover, operational efficiencies are achieved because maintenance and control processes are unified, minimizing the complexity of managing separate assets. The result is lower ongoing operational costs, which enhances the financial viability of these projects.

Furthermore, network losses are reduced when energy storage is physically co-located with renewable generation. Since energy is stored on-site and dispatched locally, the energy losses associated with long-distance transmission are minimized. This is particularly beneficial for remote renewable energy facilities, such as wind farms located far from load centers, where transmission losses could otherwise be significant. The ability to store and use energy locally ensures that more of the generated power reaches end-users, increasing the system's overall efficiency.

Another important benefit is the potential to defer investments in grid infrastructure upgrades. Co-locating HRES with renewable energy generation helps alleviate pressure on the transmission network by managing peak loads locally. This reduces the immediate need for costly grid upgrades, as energy storage can effectively balance demand and supply at the generation site.

Additionally, regulatory processes are simplified in co-located physical systems. Since both the storage and generation assets are part of the same infrastructure, there is no need to establish new market structures or complex operational frameworks to manage them separately. This makes it easier for project developers to navigate regulatory requirements, speeding up project approvals and reducing administrative burdens. The simplicity of this model facilitates faster deployment, making it a more attractive option for regions looking to scale renewable energy quickly.

In this analysis, we are using virtual HRES systems based on the definitions outlined earlier. Due to the lack of information about Morocco's grid, the battery systems and renewable power plants are modeled on the same bus.[7] In this modeling approach, these plants are operated together, much like a physically co-located system, or a pure HRES. Therefore, it can be assured that the resulting system price and plant dispatch are not affected by this simulated configuration. Furthermore, all characteristics that apply to real HRES systems remain valid for the virtual ones, as the optimization program does not factor in these variables in its calculations.

LCOE formulation

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[7] On the same bus refers to the electrical grid modelling where multiple power systems (such as battery systems and renewable power plants) are treated as if they are connected to the same electrical node or "bus" in the grid. In the case of this report, it means that the renewable power plants (wind and/or solar) and the battery storage systems are assumed to be operating together at the same point in the grid. This simplifies the modelling, especially when there isn't detailed data about how Morocco's grid is structured, by assuming that these power sources and storage systems are interacting as if they were physically located together, like in a hybrid renewable energy system (HRES).

Thermal Technologies

Thermal technologies include power plants that use fossil fuels such as natural gas, or oil to generate electricity. The formula to calculate the LCOE for these technologies is[8]:

$$LCOE_{\text{term}} = \frac{\sum_{i=0}^{n}\left(\frac{CCap+CO\&M_i+CFuel_i}{(1+d)^i}\right)}{\sum_{i=0}^{n}\left(\frac{Egen_i}{(1+d)^i}\right)}$$

Where:
CCap : Initial capital cost.
CO&M_i : Operation and maintenance costs in year i
CFuel_i : Fuel costs in year i
d: Discount rate.
Egen_i : Energy generated in year i
n: Project lifespan in years, for this study is 20 years.

Renewable Technologies

Renewable technologies include energy sources such as solar and wind, which use natural resources to generate electricity without consuming fossil fuels. The formula to calculate the LCOE for these technologies is[9]:

$$LCOE_{\text{renov}} = \frac{\sum_{i=0}^{n}\left(\frac{CCap+CO\&M_i}{(1+d)^i}\right)}{\sum_{i=0}^{n}\left(\frac{Egen_i\cdot(1-\sigma)^i}{(1+d)^i}\right)}$$

Where:
CCap : Initial capital cost.
CO&M$_i$: Operation and maintenance costs in year i
d: Discount rate.
Egen$_i$: Energy generated in year i
σ: Annual degradation rate.
n: Project lifespan in years, for this study is 20 years.

Hybrid Renewable Energy Systems

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[8] (Lai, et al., 2017)

[9] (Lai, et al., 2017)

Hybrid technologies combine different energy sources, such as solar/wind and battery storage. For the purposes of this study, we use the definition of Virtual Power Plant outlined in Section 1, which refers to the coordinated operation of renewable energy technologies and Battery to maximize their collective value. The formula for calculating the LCOE for these technologies is[10]:

$$LCOE_{\text{hyb}} = \frac{\sum_{i=0}^{n}\left(\frac{CCap+CO\&M_i+CDeg_i+CRep_i}{(1+d)^i}\right)}{\sum_{i=0}^{n}\left(\frac{Egen_i+(Estore_i\cdot\eta)}{(1+d)^i}\right)}$$

Where:
CCap: Initial capital cost.
CO&M$_i$: Operation and maintenance costs in year i
CDeg$_i$: Degradation costs in year i.
CRep$_i$: Replacement costs in year i.
d: Discount rate.
Egen$_i$: Energy generated in year i
Estore$_i$: Energy stored in year i.
η: Storage efficiency.
n: Project lifespan in years, for this study is 20 years.

The above formulas were used to obtain the results shown in the figure below. The operating cashflow was calculated for a 20-year period. The obtained LCOE results do not incorporate taxes or subsidies that could penalize or incentivize their value.

LCOE Calculation

The figure below provides an estimation of the LCOE for various technologies in Morocco, compared with the minimum and maximum values reported by Lazard in 2024, published in June of this year. For comparative purposes, these results are presented alongside the Lazard 2024 report.

Figure 16 LCOE Estimation – Morocco

Technology	Unit	Morocco LCOE Estimation
CCGT	USD/MWh	103.5
GT	USD/MWh	162.6
Solar	USD/MWh	37.5 (DF: 25%)
Wind	USD/MWh	56.0 (DF: 40%)
BESS StandAlone	USD/MWh	154.0 (DF: 17%)
Solar+BESS	USD/MWh	95.2 (DF: 30%)
Wind+BESS	USD/MWh	94.6 (DF: 48%)

Source: own elaboration

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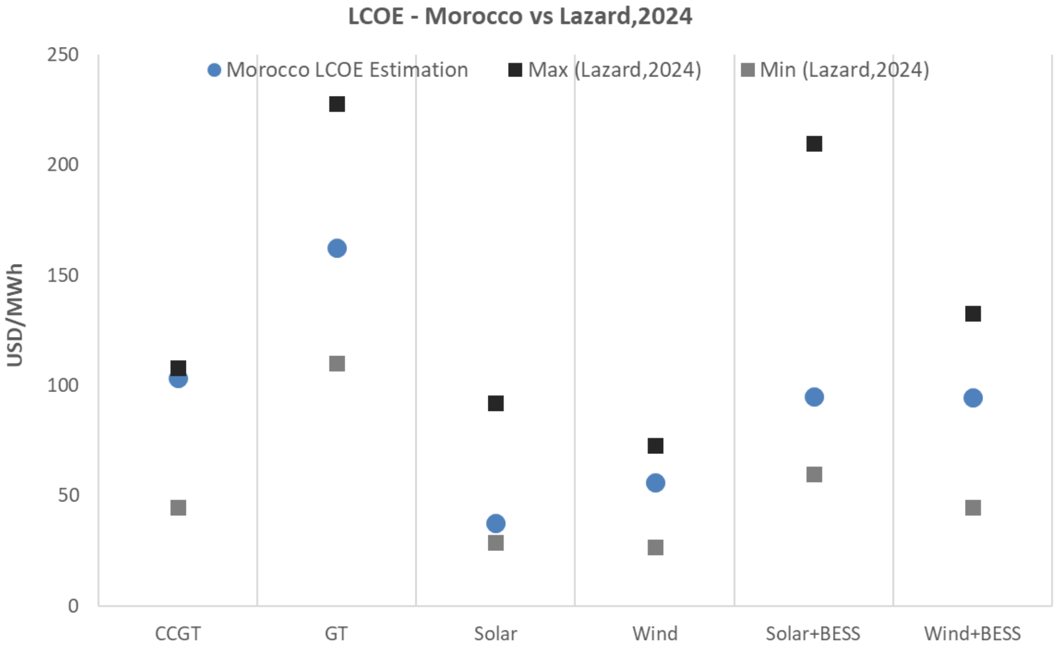
[10] (Lai, et al., 2017)

Figure 17 LCOE Estimation - Morocco vs Lazard (2024)



Source: own elaboration

The LCOE analysis for various energy technologies in Morocco provides valuable insights into their economic viability and competitiveness. By benchmarking the LCOE results against the Lazard 2024 report, a comprehensive comparison with international standards can be ensured.

The analysis demonstrates that all other technologies—CCGT, GT, Solar, Wind, Solar+BESS, and Wind+BESS—fall within an acceptable range of LCOE. This indicates that Morocco's investments in renewable energy and hybrid systems are economically sound and competitive.

The LCOE for Solar is particularly favorable, highlighting the country’s significant solar potential and the effectiveness of its solar projects. Wind also shows competitive LCOE values, reflecting Morocco's strategic placement of wind farms in high-potential regions.
The integration of storage with Solar and Wind (Solar+BESS and Wind+BESS) presents a more balanced and cost-effective solution,[11] enhancing the reliability and stability of the energy supply.

These findings underscore the importance of continuing to develop and integrate renewable and hybrid energy systems in Morocco. The favorable LCOE values support the country's ambitious goals to increase the share of renewables in its energy mix to 52% by 2030, promoting energy sovereignty and sustainability.

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[11] The hybrid solution offers a cost-effective alternative to Combined Cycle Gas Turbines (CCGT) for providing "baseload" power. Currently, the cost of hybrid systems is comparable to that of CCGT, and they are expected to become even more competitive in the future as battery costs continue to decline.

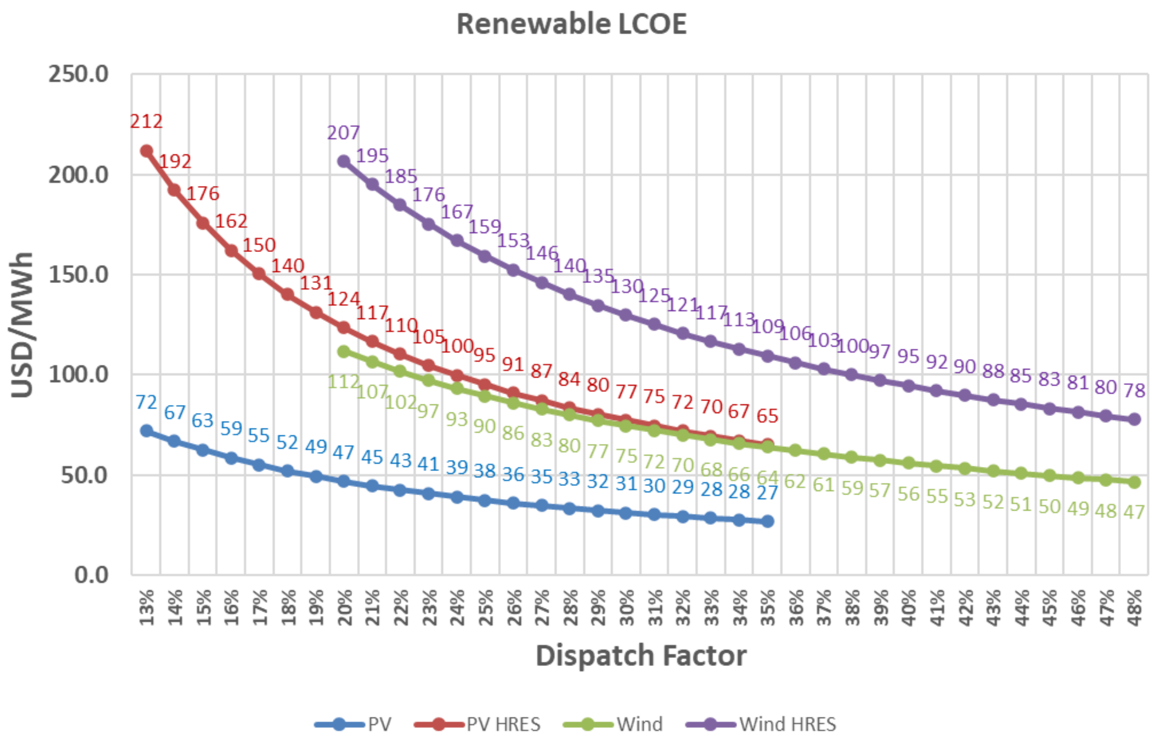
Renewable LCOE vs Dispatch Factor

In the case of PV (solar photovoltaic), the LCOE starts at 72 USD/MWh with a dispatch factor of 13% and gradually decreases to 47 USD/MWh as the dispatch factor reaches 38%. This makes solar PV technology with the lowest costs across the entire range of dispatch factors.
For PV HRES (solar photovoltaic with storage), the LCOE begins significantly higher at 212 USD/MWh, due to the added cost of battery storage. However, it decreases rapidly as the dispatch factor increases, reaching 65 USD/MWh at 38% dispatch. The inclusion of battery storage initially raises the LCOE but enhances dispatchability and system integration for solar energy.

In contrast, Wind starts with a higher LCOE than PV at 112 USD/MWh, but its cost also follows a decreasing trend, dropping to 59 USD/MWh as the dispatch factor increases. While wind has a higher initial cost than solar PV, it shows substantial cost reductions as dispatchability improves.

For Wind HRES (wind with battery storage), the LCOE starts at 207 USD/MWh and gradually declines to 78 USD/MWh. Like the solar case, the addition of battery storage significantly increases the initial LCOE, but it allows for higher dispatch factors, improving the flexibility and reliability of wind energy generation.

Figure 18 LCOE vs Dispatch Factor estimation for Renewables - Morocco



Source: own elaboration

EXPLORING PATHWAYS FOR MOROCCO'S POWER SYSTEM TRANSFORMATION

3. Developing Three Scenarios for Morocco’s Power System

This chapter outlines a comprehensive technical solution to address Morocco's electricity demand on an hourly basis. By utilizing standard parameters for thermal plants, this solution incorporates key adjustments to enable the integration of increased renewable energy generation. The approach involves evaluating various expansion scenarios - Business As Usual (BAU), Advanced, and Strengthened - to ensure the solution is both practical and feasible within Morocco’s current energy system.

The scenarios explore different strategies for balancing renewable energy generation with the existing grid, especially under growing solar and wind capacities. The Advanced and Strengthened scenarios integrate Hybrid Energy Storage Systems (HRES), providing essential flexibility to meet peak demand and address the intermittent challenges of renewable sources. Furthermore, a cost-benefit analysis comparing these scenarios to assess their operational efficiency, emission impacts, and overall sustainability has been included.

3.1 Projecting Energy Demand

Demand Projection

A projection of energy demand in Morocco has been made considering a growth rate of 3.9%, as proposed by NREL in the medium scenario of the 2021 report "Load Forecasting for the Moroccan Electricity Sector". This projection provides a detailed estimate of the increase in annual energy consumption and peak system demand from 2023 to 2050, allowing for effective planning to meet the country's future energy needs.

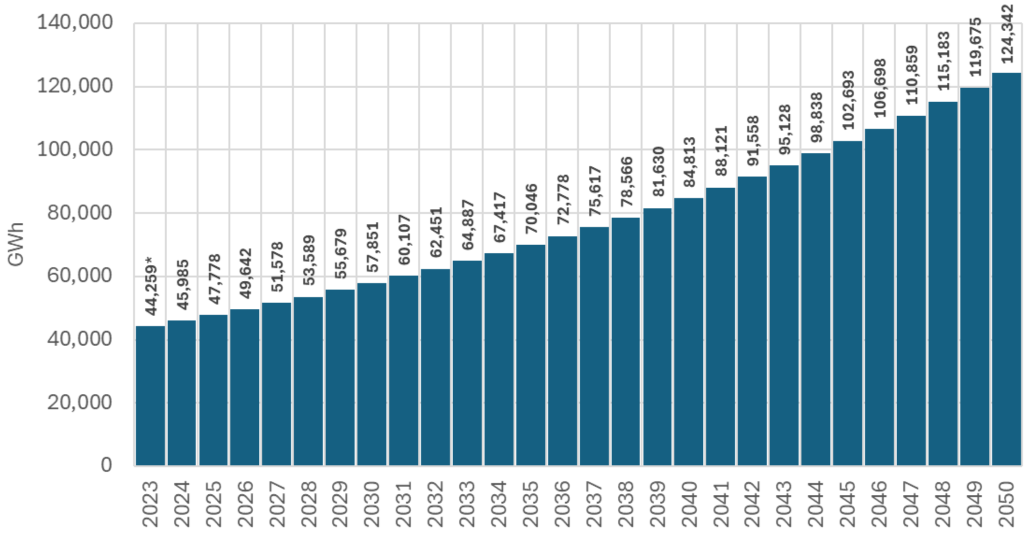
Figure 19 Demand Projection - Morocco

Year	Growth Rate (%)	Demand Projection (GWh)	Demand Projection (MW)	Load Factor (%)
	NREL (2021)	Base Case		
2023	3.4%	44,259*	7,400*	68.3%
2024	3.9%	45,985	7,689	68.3%
2025	3.9%	47,778	7,988	68.3%
2026	3.9%	49,642	8,300	68.3%
2027	3.9%	51,578	8,624	68.3%
2028	3.9%	53,589	8,960	68.3%
2029	3.9%	55,679	9,309	68.3%
2030	3.9%	57,851	9,673	68.3%
2031	3.9%	60,107	10,050	68.3%
2032	3.9%	62,451	10,442	68.3%
2033	3.9%	64,887	10,849	68.3%

2034	3.9%	67,417	11,272	68.3%
2035	3.9%	70,046	11,712	68.3%
2036	3.9%	72,778	12,168	68.3%
2037	3.9%	75,617	12,643	68.3%
2038	3.9%	78,566	13,136	68.3%
2039	3.9%	81,630	13,648	68.3%
2040	3.9%	84,813	14,181	68.3%
2041	3.9%	88,121	14,734	68.3%
2042	3.9%	91,558	15,308	68.3%
2043	3.9%	95,128	15,905	68.3%
2044	3.9%	98,838	16,526	68.3%
2045	3.9%	102,693	17,170	68.3%
2046	3.9%	106,698	17,840	68.3%
2047	3.9%	110,859	18,536	68.3%
2048	3.9%	115,183	19,258	68.3%
2049	3.9%	119,675	20,009	68.3%
2050	3.9%	124,342	20,790	68.3%

Source: Energíe Electrique Chiffres clés 2023 (www.one.ma)

Figure 20 Demand Projection - Morocco



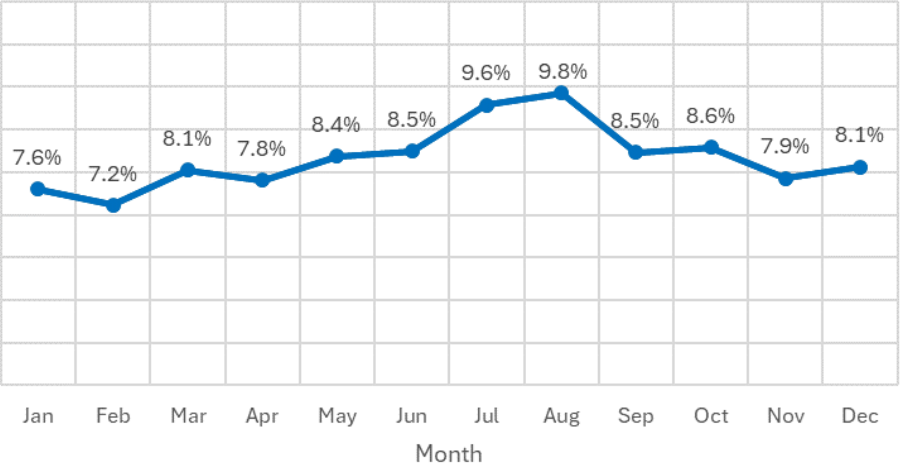
Source: Energíe Electrique Chiffres clés 2023 (www.one.ma)

The Base Case energy demand projection in Morocco, based on a 3.9% growth scenario, shows a sustained increase in both annual energy consumption and peak system demand. According to the data presented, energy demand will grow from 44,259 GWh in 2023 to 57,851 GWh in 2030 and 124,342 in 2050, with a constant annual growth rate. This increase reflects moderate economic growth.

Monthly Demand Share

The monthly demand share analysis for 2023 provides insights into the distribution of electricity consumption throughout the year, highlighting seasonal variations and specific demand patterns. The data, which is derived from the operators' information, is presented as follows:

Figure 21 Monthly Demand Share (2023) - Morocco



Source: own elaboration based on NREL data[12]

The data shows that the lowest demand in the first three months of the year coincides with the winter season in the Northern Hemisphere and the celebration of Ramadan in Morocco, which typically sees a reduction in energy consumption due to changes in daily routines and reduced industrial activity. January and February have the lowest demand shares, at 7.6% and 7.2% respectively, reflecting these factors.

In contrast, the highest demand occurs in July and August, with shares of 9.6% and 9.8% each. These months correspond to the summer season, where higher temperatures lead to increased use of air conditioning and cooling systems, significantly boosting electricity consumption. This seasonal peak is a critical period for energy planning, as it requires ensuring that the power grid can handle the increased load. The rest of the year shows stable demand, with slight increases in October (8.6%) and steady shares of 8% in other months. This stability indicates a consistent baseline demand driven by regular residential, commercial, and industrial activities. Understanding these monthly variations helps in optimizing generation schedules and planning maintenance activities to ensure reliable supply throughout the year.

Hourly Demand Profile

A demand profile analysis was conducted using estimated data (NREL, 2021). The hourly demand data was compiled for each month from January to December, providing a comprehensive view of the electricity consumption patterns throughout the year. The data is as follows:

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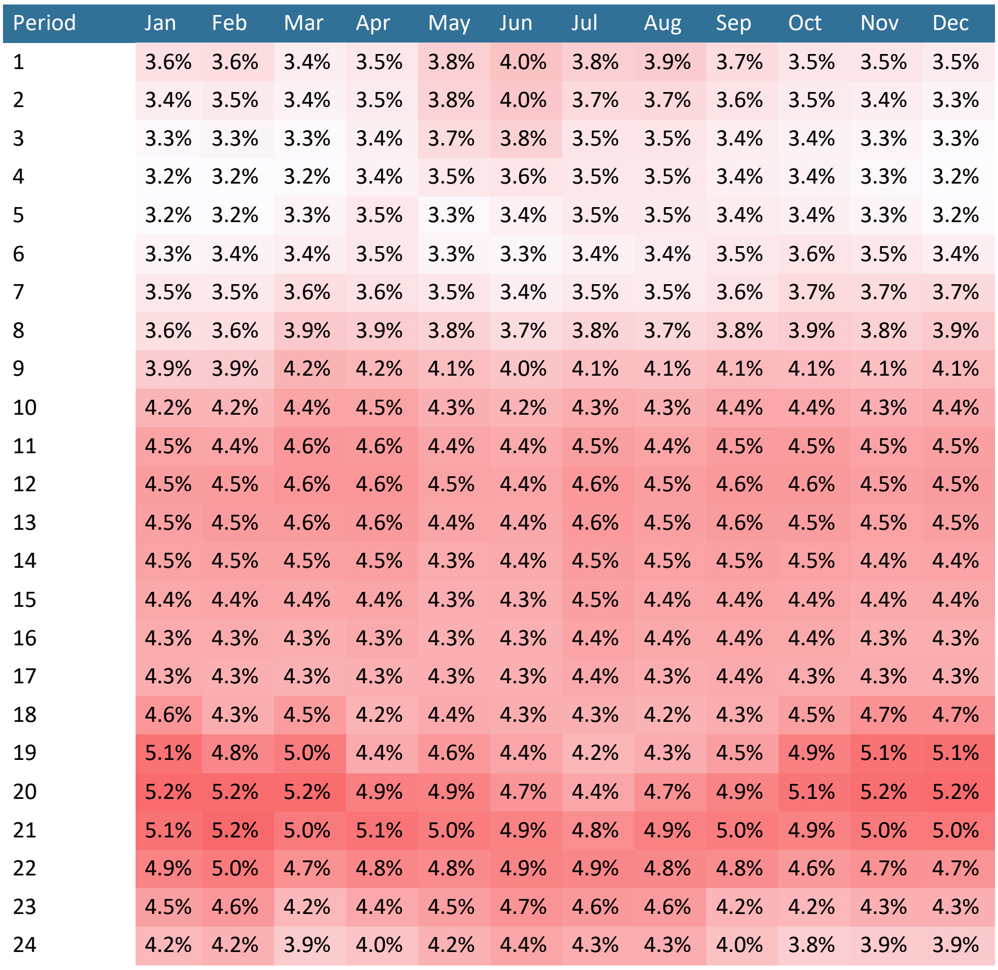
[12] **(Cox, de Silva, Jorgenson, & O'Neill, 2021)**

Figure 22 Hourly Demand Share – Morocco



Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	3.6%	3.6%	3.4%	3.5%	3.8%	4.0%	3.8%	3.9%	3.7%	3.5%	3.5%	3.5%
2	3.4%	3.5%	3.4%	3.5%	3.8%	4.0%	3.7%	3.7%	3.6%	3.5%	3.4%	3.3%
3	3.3%	3.3%	3.3%	3.4%	3.7%	3.8%	3.5%	3.5%	3.4%	3.4%	3.3%	3.3%
4	3.2%	3.2%	3.2%	3.4%	3.5%	3.6%	3.5%	3.5%	3.4%	3.4%	3.3%	3.2%
5	3.2%	3.2%	3.3%	3.5%	3.3%	3.4%	3.5%	3.5%	3.4%	3.4%	3.3%	3.2%
6	3.3%	3.4%	3.4%	3.5%	3.3%	3.3%	3.4%	3.4%	3.5%	3.6%	3.5%	3.4%
7	3.5%	3.5%	3.6%	3.6%	3.5%	3.4%	3.5%	3.5%	3.6%	3.7%	3.7%	3.7%
8	3.6%	3.6%	3.9%	3.9%	3.8%	3.7%	3.8%	3.7%	3.8%	3.9%	3.8%	3.9%
9	3.9%	3.9%	4.2%	4.2%	4.1%	4.0%	4.1%	4.1%	4.1%	4.1%	4.1%	4.1%
10	4.2%	4.2%	4.4%	4.5%	4.3%	4.2%	4.3%	4.3%	4.4%	4.4%	4.3%	4.4%
11	4.5%	4.4%	4.6%	4.6%	4.4%	4.4%	4.5%	4.4%	4.5%	4.5%	4.5%	4.5%
12	4.5%	4.5%	4.6%	4.6%	4.5%	4.4%	4.6%	4.5%	4.6%	4.6%	4.5%	4.5%
13	4.5%	4.5%	4.6%	4.6%	4.4%	4.4%	4.6%	4.5%	4.6%	4.5%	4.5%	4.5%
14	4.5%	4.5%	4.5%	4.5%	4.3%	4.4%	4.5%	4.5%	4.5%	4.5%	4.4%	4.4%
15	4.4%	4.4%	4.4%	4.4%	4.3%	4.3%	4.5%	4.4%	4.4%	4.4%	4.4%	4.4%
16	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%	4.4%	4.4%	4.4%	4.4%	4.3%	4.3%
17	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%	4.4%	4.3%	4.4%	4.3%	4.3%	4.3%
18	4.6%	4.3%	4.5%	4.2%	4.4%	4.3%	4.3%	4.2%	4.3%	4.5%	4.7%	4.7%
19	5.1%	4.8%	5.0%	4.4%	4.6%	4.4%	4.2%	4.3%	4.5%	4.9%	5.1%	5.1%
20	5.2%	5.2%	5.2%	4.9%	4.9%	4.7%	4.4%	4.7%	4.9%	5.1%	5.2%	5.2%
21	5.1%	5.2%	5.0%	5.1%	5.0%	4.9%	4.8%	4.9%	5.0%	4.9%	5.0%	5.0%
22	4.9%	5.0%	4.7%	4.8%	4.8%	4.9%	4.9%	4.8%	4.8%	4.6%	4.7%	4.7%
23	4.5%	4.6%	4.2%	4.4%	4.5%	4.7%	4.6%	4.6%	4.2%	4.2%	4.3%	4.3%
24	4.2%	4.2%	3.9%	4.0%	4.2%	4.4%	4.3%	4.3%	4.0%	3.8%	3.9%	3.9%

Source: own elaboration based on NREL data[13]

This demand profile reveals key insights into Morocco's electricity consumption patterns. The data indicates a clear peak in demand during the evening hours, particularly around 20:00 to 22:00, which is consistent across all months. This peak is due to increased residential usage as people return home from work, turn on lighting, appliances, and heating or cooling systems. Additionally, there is a smaller peak in the morning hours around 9:00 and 10:00, which can be attributed to commercial and industrial activities commencing for the day.

Throughout the day, the demand fluctuates, with lower values observed during the night hours from 0:00 to 6:00. This is expected as industrial activities slow down, and residential usage decreases when people are asleep. The demand starts to rise gradually from early morning, reaching its first peak mid-morning, then stabilizing in the afternoon before climbing again in the evening.

Seasonal variations are also evident in the data, with higher demand during the summer months (July and August), due to the extensive use of air conditioning systems. Conversely, demand is lower

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[13] (Cox, de Silva, Jorgenson, & O'Neill, 2021)

during the spring and autumn months, where moderate temperatures reduce the need for heating or cooling. Winter months show an increase in evening demand, due to heating requirements.

Understanding these demand patterns is crucial for effective energy planning and management. It helps in optimizing the generation schedule, ensuring that sufficient capacity is available during peak hours, and improving the integration of renewable energy sources, which may have variable outputs.

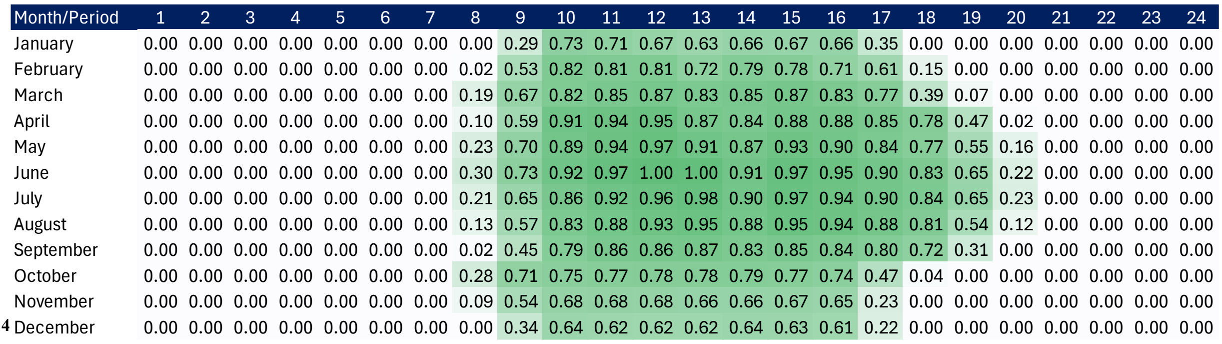
3.2 Assessing Renewable Energy Profiles

Solar Profile

The normalized solar profile data provided by some operators outlines the hourly solar generation potential across different months. This information is critical for understanding the availability of solar energy throughout the year and for planning the integration of solar power into the energy mix.

This normalized solar profile highlights the periods of maximum solar generation, which typically occur between 9:00 AM and 6:00 PM, with peaks around midday. During June, the solar generation reaches its highest potential, achieving a normalized value of 1.00, indicating full utilization of solar capacity. July and August also exhibit high solar generation, which is crucial for meeting the increased electricity demand during the summer months. In contrast, the winter months, such as December and January, show lower solar generation potential, reflecting the seasonal variations in solar irradiance. This data is essential for designing hybrid systems and deploying BESS to manage the variability of solar power. The data is presented as follows:

Figure 23 Solar Profile – Morocco



Month/Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
January	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	0.73	0.71	0.67	0.63	0.66	0.67	0.66	0.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00
February	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.53	0.82	0.81	0.81	0.72	0.79	0.78	0.71	0.61	0.15	0.00	0.00	0.00	0.00	0.00	0.00
March	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.67	0.82	0.85	0.87	0.83	0.85	0.87	0.83	0.77	0.39	0.07	0.00	0.00	0.00	0.00	0.00
April	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.59	0.91	0.94	0.95	0.87	0.84	0.88	0.88	0.85	0.78	0.47	0.02	0.00	0.00	0.00	0.00
May	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23	0.70	0.89	0.94	0.97	0.91	0.87	0.93	0.90	0.84	0.77	0.55	0.16	0.00	0.00	0.00	0.00
June	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.73	0.92	0.97	1.00	1.00	0.91	0.97	0.95	0.90	0.83	0.65	0.22	0.00	0.00	0.00	0.00
July	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.65	0.86	0.92	0.96	0.98	0.90	0.97	0.94	0.90	0.84	0.65	0.23	0.00	0.00	0.00	0.00
August	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.57	0.83	0.88	0.93	0.95	0.88	0.95	0.94	0.88	0.81	0.54	0.12	0.00	0.00	0.00	0.00
September	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.45	0.79	0.86	0.86	0.87	0.83	0.85	0.84	0.80	0.72	0.31	0.00	0.00	0.00	0.00	0.00
October	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.71	0.75	0.77	0.78	0.78	0.79	0.77	0.74	0.47	0.04	0.00	0.00	0.00	0.00	0.00	0.00
November	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.54	0.68	0.68	0.68	0.66	0.66	0.67	0.65	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00
[14] December	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.34	0.64	0.62	0.62	0.62	0.64	0.63	0.61	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00

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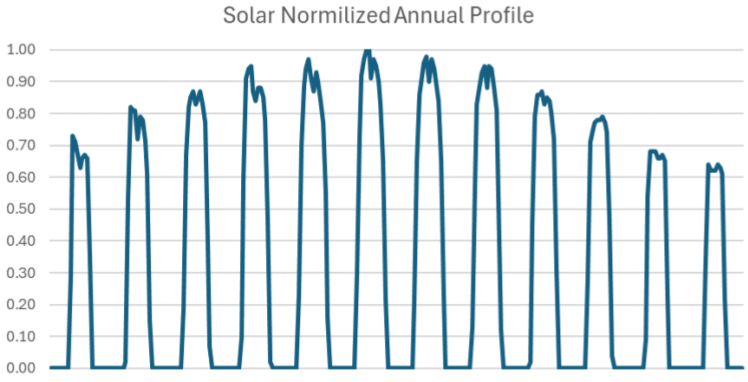
[14] Normalized table where a value of 1 indicates full utilization



Source: Own elaboration

The curve showing a drop in solar panel output during peak hours can be explained by the combined effects of high temperatures and the inherent properties of photovoltaic (PV) cells. As highlighted in the article "Integration of Vertical Solar Power Plants into a Future German Energy System" (Reker, 2022), solar panels lose efficiency as temperatures rise due to the temperature coefficient of the semiconductor materials. The temperature coefficient refers to the reduction in power output that occurs with each degree Celsius increase in temperature. For crystalline silicon solar panels, every 1°C increase in temperature can reduce efficiency by 0.25–0.45%, depending on the design of the panel. During peak sunlight hours, intense solar irradiance causes the temperature of the panels to rise. This heat generation is inevitable due to the nature of semiconductor materials, which absorb and convert sunlight into electricity. As the temperature increases, the bandgap of the semiconductor narrows, leading to increased electron-hole recombination, thus reducing the panel's ability to convert sunlight into electricity. Additionally, factors like panel orientation and geographic location play a role in the daily variation of energy generation. At peak times, solar panels face both high levels of irradiance and higher temperatures, which together cause a significant drop in their efficiency.

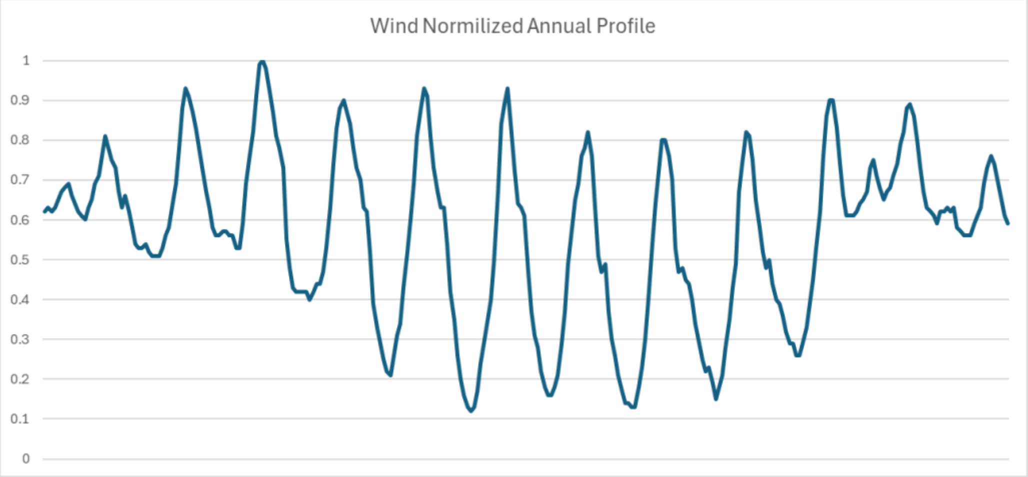
Wind Profile

The normalized wind profile data provided by some operators offers insights into the hourly wind generation potential across different months. This data is essential for planning the integration of wind power into the energy mix and for designing hybrid systems that maximize the use of renewable energy sources.

This normalized wind profile highlights the periods of maximum wind generation potential, which typically occur in the late afternoon and evening hours. For example, during the month of March, wind generation peaks around 18:00 with a normalized value of 1.00, indicating full utilization of wind capacity. Similarly, high wind generation values are observed in February and November, with notable peaks around 17:00 and 19:00. In contrast, the summer months, such as July and August, show lower wind generation potential, reflecting the seasonal variations in wind speed. The data is presented as follows:

Figure 24 Wind Profile – Morocco

Month/Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
January	0.62	0.63	0.62	0.63	0.65	0.67	0.68	0.69	0.66	0.64	0.62	0.61	0.60	0.63	0.65	0.69	0.71	0.76	0.81	0.78	0.75	0.73	0.67	0.63
February	0.66	0.62	0.58	0.54	0.53	0.53	0.54	0.52	0.51	0.51	0.51	0.53	0.56	0.58	0.63	0.69	0.78	0.88	0.93	0.91	0.87	0.83	0.78	0.73
March	0.67	0.63	0.58	0.56	0.56	0.57	0.57	0.56	0.56	0.53	0.53	0.59	0.69	0.75	0.82	0.91	0.99	1.00	0.98	0.92	0.87	0.81	0.78	0.73
April	0.55	0.48	0.43	0.42	0.42	0.42	0.42	0.40	0.42	0.44	0.44	0.47	0.53	0.63	0.74	0.83	0.88	0.90	0.87	0.84	0.78	0.73	0.70	0.63
May	0.62	0.52	0.39	0.33	0.29	0.25	0.22	0.21	0.26	0.31	0.34	0.43	0.52	0.60	0.69	0.81	0.88	0.93	0.91	0.81	0.73	0.67	0.63	0.63
June	0.54	0.42	0.35	0.26	0.20	0.16	0.13	0.12	0.13	0.17	0.24	0.30	0.35	0.40	0.50	0.67	0.84	0.89	0.93	0.84	0.72	0.64	0.63	0.61
July	0.47	0.37	0.31	0.28	0.22	0.18	0.16	0.16	0.18	0.21	0.29	0.37	0.49	0.56	0.65	0.69	0.76	0.78	0.82	0.76	0.63	0.51	0.47	0.49
August	0.37	0.30	0.26	0.21	0.17	0.14	0.14	0.13	0.13	0.18	0.23	0.30	0.40	0.54	0.64	0.72	0.80	0.80	0.76	0.70	0.53	0.47	0.48	0.45
September	0.44	0.40	0.34	0.29	0.25	0.22	0.23	0.19	0.15	0.18	0.21	0.28	0.35	0.43	0.49	0.67	0.74	0.82	0.81	0.75	0.65	0.58	0.52	0.48
October	0.50	0.44	0.40	0.39	0.36	0.32	0.29	0.29	0.26	0.26	0.29	0.33	0.39	0.45	0.53	0.62	0.76	0.86	0.90	0.90	0.83	0.74	0.66	0.61
November	0.61	0.61	0.62	0.64	0.65	0.67	0.73	0.75	0.71	0.68	0.65	0.67	0.68	0.71	0.74	0.79	0.82	0.88	0.89	0.86	0.80	0.73	0.67	0.63
December	0.62	0.61	0.59	0.62	0.62	0.63	0.62	0.63	0.58	0.57	0.56	0.56	0.56	0.59	0.61	0.63	0.69	0.73	0.76	0.74	0.70	0.66	0.61	0.59

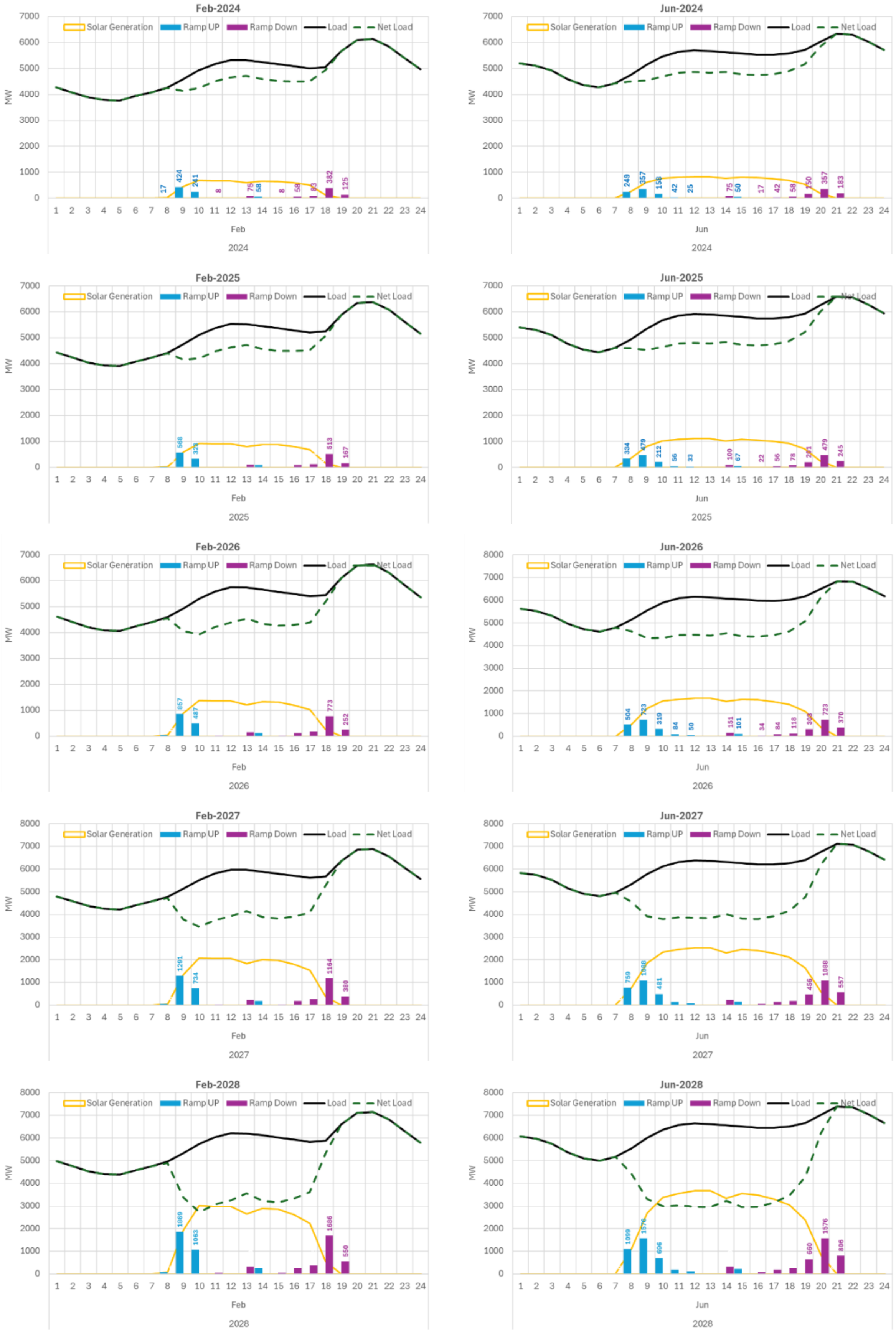


Source: own elaboration

Ramp up/Down Analysis

The figure below illustrates the maximum ramp-up and ramp-down rates resulting from the solar profile and expansion for each year. The analysis focuses on the months of February (which experiences the highest ramp rates between 8 AM and 9 AM each day) and June (which has maximum solar irradiation). Maximum ramp-up and ramp-down rates were included to illustrate the system's flexibility requirements in managing the variability of solar generation. This analysis is essential for understanding how the expansion of solar capacity impacts on the system's ability to respond to rapid changes in production, especially during peak demand periods. The annual increase in solar generation is projected based on modeled capacity expansions and real-world generation profiles. By analyzing these ramping rates, the system can be better equipped to integrate renewable energy while maintaining stability.

Figure 25 Daily curve demand vs Solar penetration– Morocco



Source: own elaboration

3.3 Three scenarios for Renewable Energy Expansion in Morocco

In this section, the criteria considered for estimating the expansion of generation plants and battery storage systems in Morocco’s electric system model are elaborated and three scenarios were created, as presented below.

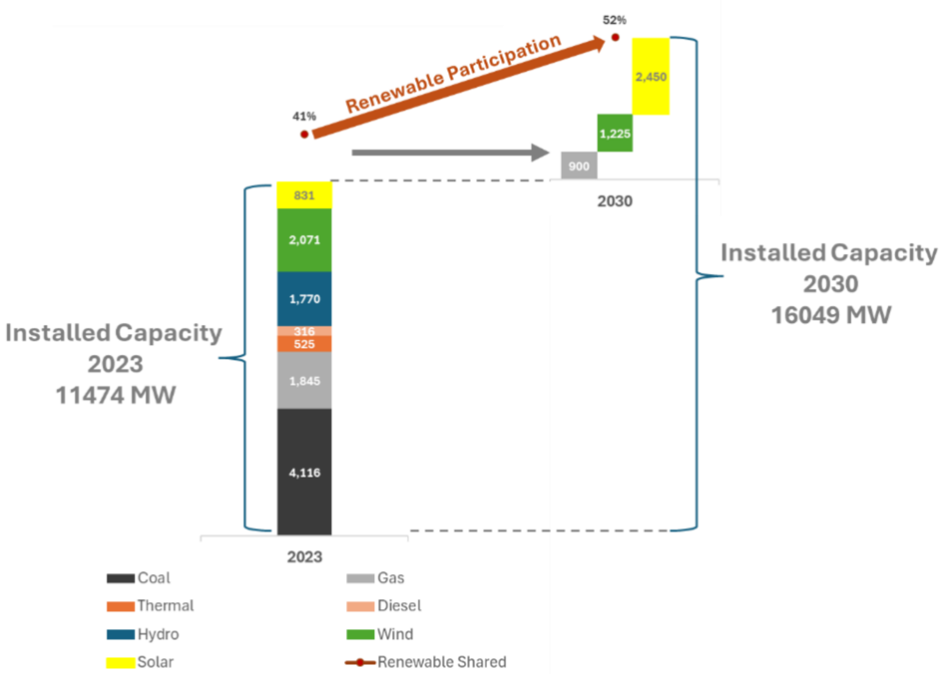
Due to the lack of information regarding the electrical grid of the Morocco system, battery banks connected to the same bus of renewable systems (Solar + BESS or Wind + BESS) were modeled, characterizing, according to the concepts presented in Section 1, a virtual Hybrid Renewable Energy System model. From an operational perspective for the system, this choice results in the same pricing behavior and plant dispatch, as all energy is allocated to the same bus, and the dispatch optimization dynamics are based on this characteristic.

BAU Scenario

The main criteria guiding Morocco's renewable energy expansion between 2024 and 2030 are driven by the need to meet the 52% renewable installed capacity target by 2030. To reach this goal, the required amount of renewable generation was estimated, while considering the planned tender for a 900 MW combined cycle gas plant.

The expansion strategy follows a distribution of 2/3 solar photovoltaic (PV) and 1/3 wind to achieve the renewable energy share by 2030. The renewable capacity increase is applied linearly between 2025 and 2030, ensuring a smooth progression toward the target. By 2030, Morocco is expected to install 2,450 MW of solar PV and 1,225 MW of wind capacity, allowing the country to balance its energy demand with system reliability and sustainability goals. As shown in the following figure, this approach highlights the year-on-year additions to both solar and wind capacity in alignment with the national renewable energy objectives:

Figure 26 Capacity Expansion Estimation – Morocco



Source: own elaboration

Next Figure shows the annual increase of capacity following the structured plan for each year:

Figure 27 Capacity Expansion Estimation by year – Morocco – BAU Scenario

Capacity Expansion (MW)			
Year	Gas	Wind	Solar
2025	0	204	408
2026	0	408	816
2027	225	612	1,224
2028	450	816	1,632
2029	675	1,020	2,040
2030	900	1,225	2,450

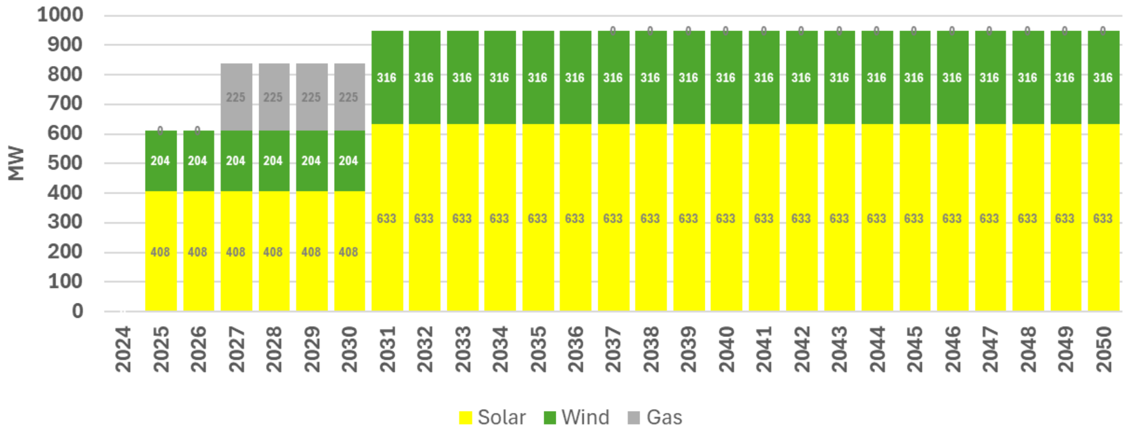
Source: own elaboration

In this first scenario, no battery storage was included in the expansion plan. The goal is to allow for a comparison between the benefits of storage expansion and renewable energy expansion alone.

The next chart illustrates the gradual increases in gas, wind, and PV capacities. To present a complete expansion scenario, Figure 29 shows the entire power matrix with this expansion plan.

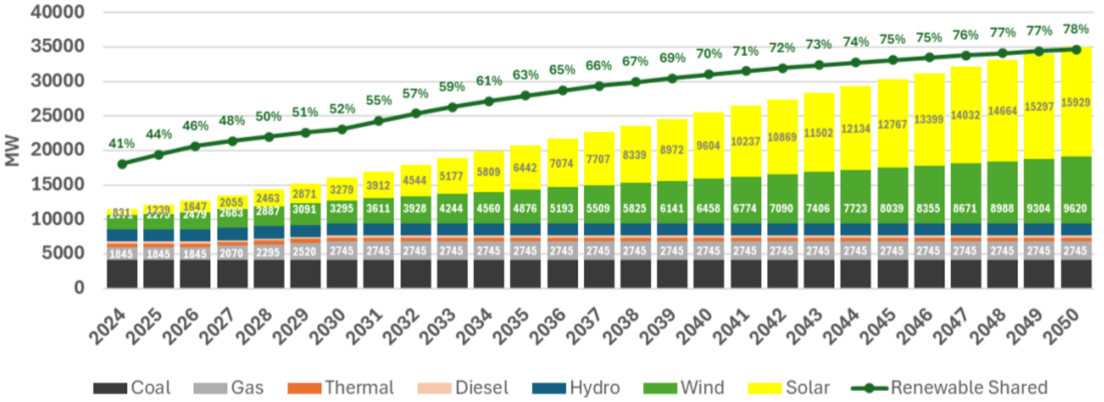
In this scenario, the share of renewables reaches 52% of the total installed capacity by 2030 and 78% by 2050. The capacity mix is made up of one-third wind and two-thirds PV, with a small portion of gas included to ensure the necessary capacity expansion.

Figure 28 Capacity Expansion – Morocco – BAU Scenario



Source: own elaboration

Figure 29 Installed Capacity – Morocco – BAU Scenario



Source: own elaboration

Advanced Scenario

For this scenario, all gas expansion was replaced with a combination of renewable sources and storage facilities in a Hybrid Renewable Energy System. As a result, the renewable share reaches 59% of the total installed capacity by 2030 and 81% by 2050. The ratio of wind to PV capacity remains the same as in the BAU scenario, with one-third from wind and two-thirds from PV.

Figure 30 Capacity Expansion Estimation by year – Morocco – Advanced Scenario

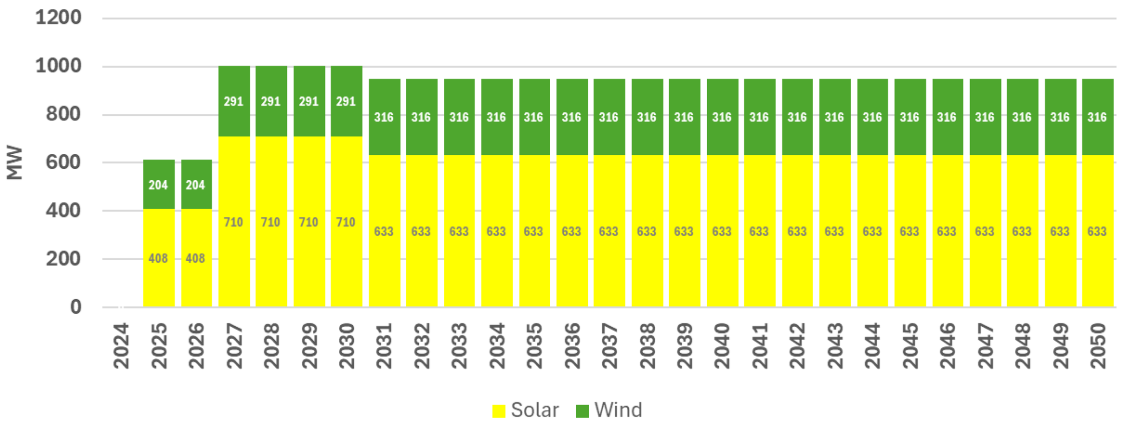
Capacity Expansion (MW)			
Year	Gas	Wind	Solar
2025	0	204	408
2026	0	408	816

2027	0	699	1,526
2028	0	991	2,236
2029	0	1,282	2,946
2030	0	1,573	3,656

Source: own elaboration

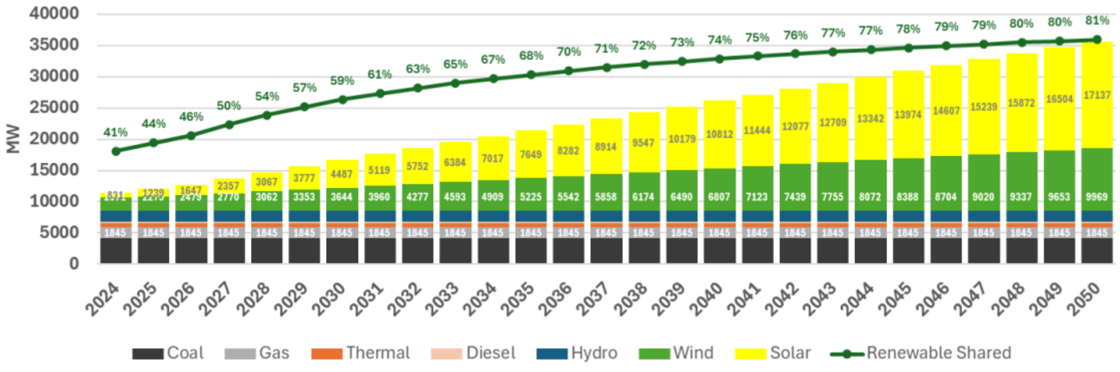
The next chart illustrates the gradual increases in wind and PV capacities. To present a complete expansion scenario, Figure 32 shows the entire power matrix with this expansion plan.

Figure 31 Capacity Expansion – Morocco – Advanced Scenario



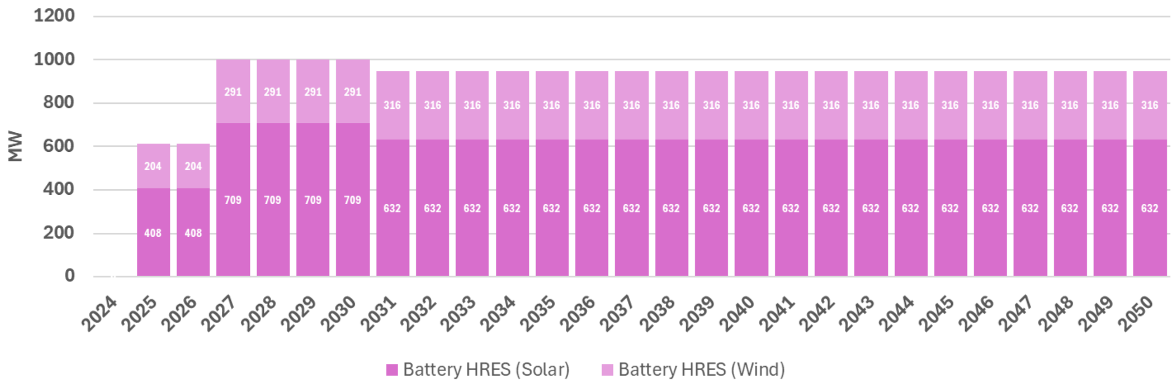
Source: own elaboration

Figure 32 Installed Capacity – Morocco – Advanced Scenario



Source: own elaboration

Figure 33 Capacity Storage Expansion – Morocco – Advanced Scenario



Source: own elaboration

Regarding storage, the average ratio of battery capacity within the HRES is 100%, which serves as a key reference point for the reliability of renewable sources. This means that the total energy storage capacity is equal to the total generation capacity of the renewable energy sources, ensuring a balance between energy production and storage. With this 100% ratio, the system can store all the energy produced by the renewable sources, providing a reliable backup during periods of low generation (e.g., at night for solar). This setup enhances the reliability of the system by stabilizing energy availability and reducing dependency on external power sources.

Strengthened Scenario

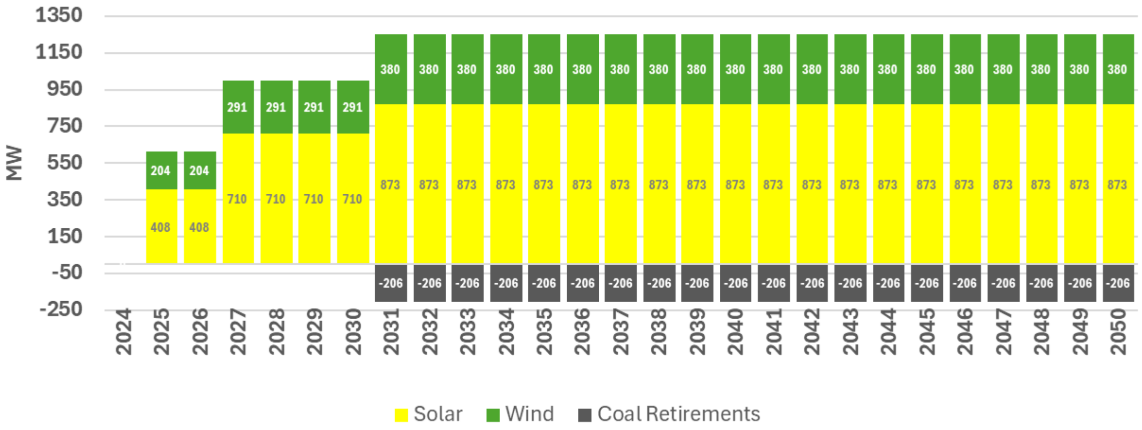
The Strengthened scenario follows the Advanced scenario until 2030. Starting in 2031, it initiates a decarbonization process that will conclude in 2050, by replacing coal energy with HRES. The storage ratio remains at 100%.

Figure 34 Capacity Expansion Estimation by year – Morocco – Strengthened Scenario

Capacity Expansion (MW)			
Year	Gas	Wind	Solar
2025	0	204	408
2026	0	408	816
2027	0	699	1,526
2028	0	991	2,236
2029	0	1,282	2,946
2030	0	1,573	3,656

Source: own elaboration

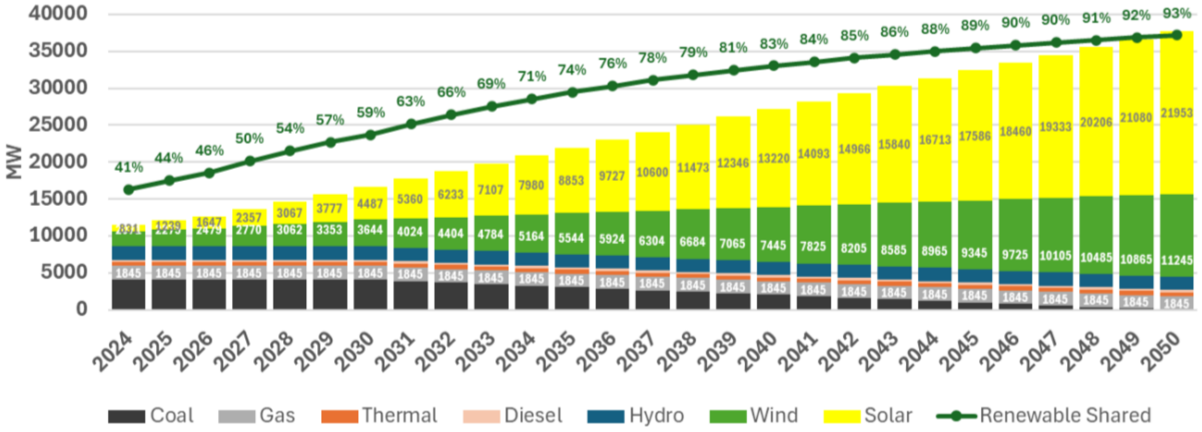
Figure 35 Capacity Expansion – Morocco – *Strengthened* Scenario



Source: own elaboration

This enables the renewable share to reach 59% by 2030 and 93% by 2050, as shown in Figure 36.

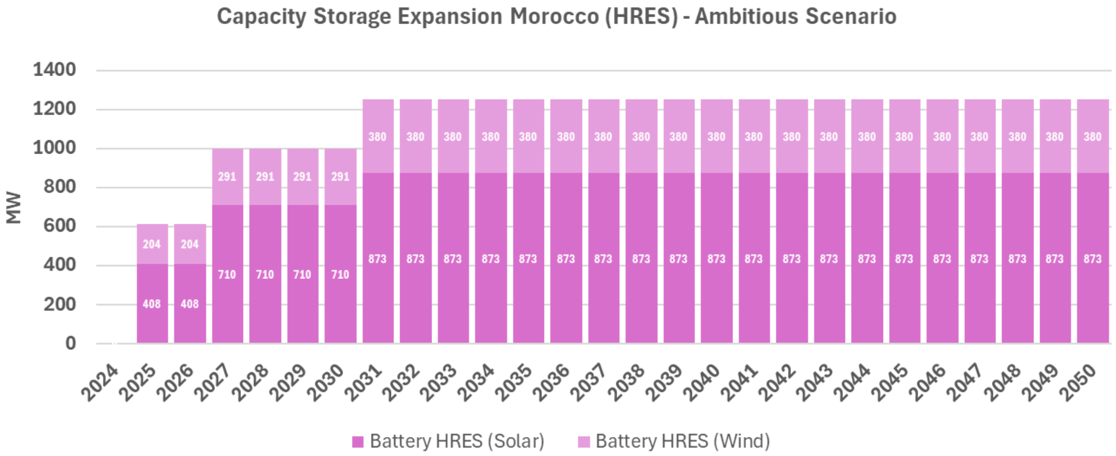
Figure 36 Total Installed Capacity – Morocco – *Strengthened* Scenario



Source: own elaboration

Additionally, in this case, the storage capacity is designed to supply power to the disconnected coal power plants.

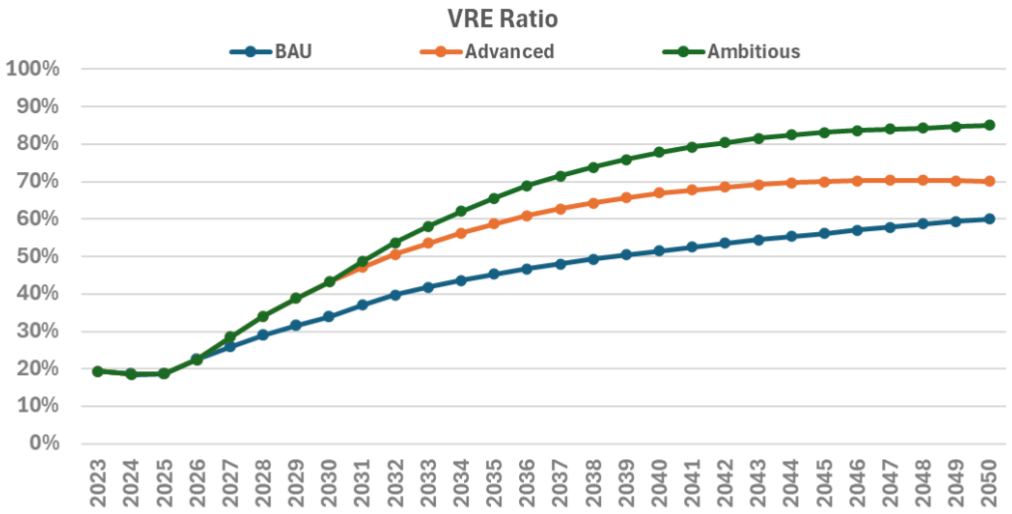
Figure 37 Capacity Storage Expansion – Morocco – *Strengthened* Scenario



Source: own elaboration

Next figure shows the evolution of the VRE Ratio (Variable Renewable Energy Ratio) in the Moroccan electricity system from 2023 to 2050. The values of 2023 represent historical data, while the values from 2024 to 2050 are projections based on future renewable energy growth perspectives, for the three scenarios. The VRE Ratio is following the impact of the assumptions: as long the Advanced and Strengthened scenario projects a more relevant renewable expansion, the BAU Scenario keeps without storage systems to improve reliability of the system. Over the period analyzed, there is a continuous increase in the penetration of variable renewable energy, from low levels (under 20% between 2023 and 2025) to reaching values between 60% and 85% in 2050.

Figure 38 VRE Ratio for Morocco projection



Source: own elaboration

4. Simulation and Results: Technical Considerations, Costs and Benefits

In this chapter, the detailed approach to simulating the electricity market model of Morocco to address the hourly electricity demand is presented. The goal is to evaluate the economic dispatch behavior under various expansion scenarios from 2024 to 2050, ensuring the integration of renewable energy sources. The following methodology steps are considered for analysis:

1. **Main Assumptions for Simulation**: The main parameters that are used for the system simulation, ensuring an accurate and detailed representation of market behavior during the analysis period: Fuel prices, Demand forecast, Generation expansion, Modeling Timeframe, Ramp Up/Down Analysis.
2. **Medium-Term Model Results**: The medium-term results from the simulation highlighting the impacts of each scenario on the market from 2024 to 2050 are presented. This analysis provides insights into how the proposed expansions and integrations perform over time.
3. **Evaluation of Results**: Results from these scenarios will be analyzed to determine the effectiveness of each approach. This analysis includes a comprehensive assessment of how each scenario influences market stability, renewable energy integration, and overall system performance. Key performance indicators such as cost-effectiveness, and the ability to meet peak demand periods will be evaluated. By comparing these results, the most optimal technical solution that balances economic considerations can be identified, ensuring a sustainable electricity market for Morocco.
4. **HRES Results**: The simulation results related to the integration of HRES are examined. This section will focus on how hybrid systems handle fluctuations in energy supply. The performance of HRES across different scenarios is analyzed, particularly their role in reducing reliance on conventional power sources and mitigating peak demand challenges.
5. **Cost-Benefit Analysis**: A thorough cost-benefit analysis is conducted for each scenario, incorporating both the operational costs and the potential savings from improved efficiency, reduced emissions, and enhanced energy security. This section compares the financial viability of each approach, weighing the long-term benefits of renewable energy integration and energy storage solutions against the upfront investments. The analysis ultimately recommends the most economically sustainable solution that ensures a balanced and secure energy future for Morocco.
6. **Technical Evaluation of Results**: This section summarizes the technical performance of each scenario. It evaluates the integration of renewable energy sources, grid stability, and overall system reliability. This summary provides a clear picture of the technical strengths and potential limitations of the proposed solutions.
7. **Economic Evaluation of Results**: This section provides an economic summary of the scenarios, focusing on cost-effectiveness and financial viability. This economic overview highlights which scenario offers the best balance between cost and long-term value for Morocco’s energy market.

4.1 Main Assumptions for Simulation

The following are the main parameters used for the system simulation, ensuring an accurate and detailed representation of market behavior during the analysis period:

- **Fuel Assumptions**: Fuel price projections outlined in the previous chapter are assumed. This step ensures that the model reflects the expected cost dynamics of different fuel sources over the analysis period.
- **Demand and Generation** Projections: Demand projections, renewable generation profiles, and the generation expansion plan described in the previous chapter are assumed. The proposed expansion aims to achieve a base case scenario with 52% of installed renewable capacity by 2030.
- **Modeling Timeframe**: The system behavior will be modeled from 2023 to 2050, with 2023 serving as the baseline year. This baseline year allows us to calibrate the model against actual market performance, ensuring its accuracy and reliability.
- **Cost of Unserved Energy**: For this report, we have considered the cost of unserved energy at 500 USD/MWh as a reference value, in line with the values used by countries in Latin America.

4.2 Medium-Term Model Results

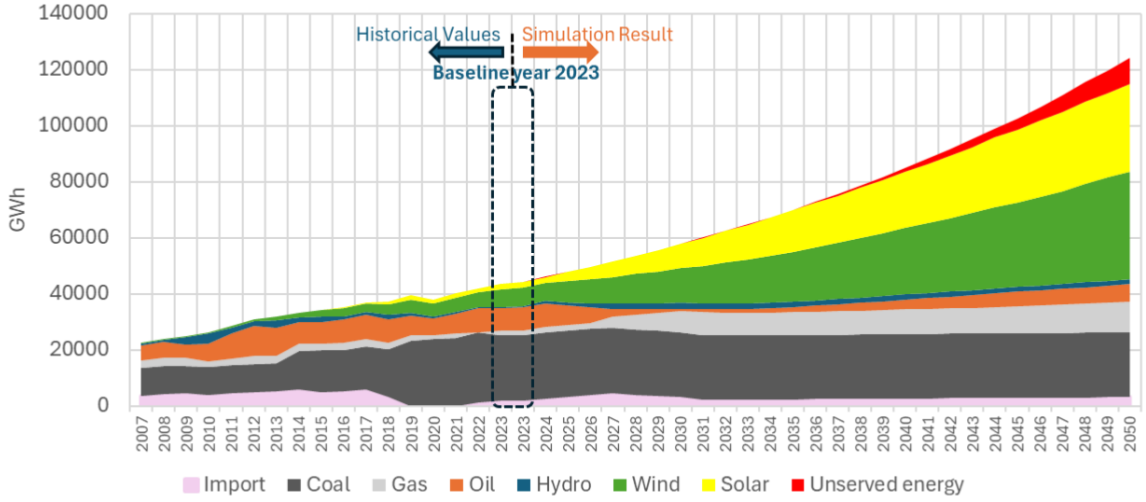
This section presents three scenarios for Morocco's energy future:

- **The Business as Usual (BAU) scenario** aims to achieve a 52% renewable energy share by 2030 and 78% by 2050, without expanding any type of battery storage systems.
- **The Advanced scenario** integrates battery energy storage systems and demonstrates the potential benefits of creating a Hybrid Renewable Energy System to support Morocco's ambitious renewable energy goals, aiming for an 81% renewable energy share by 2050.
- **The Strengthened scenario** is similar to the Advanced scenario but replaces coal power plants with a Hybrid Renewable Energy System, achieving a 93% renewable energy share by 2050.

BAU Scenario

In this scenario, 2023 is used as the reference year (baseline year) to project future energy needs and sources. The renewable energy generation share in 2023 stands at approximately 21%, with significant growth expected, reaching 40% by 2030 and continuing to rise significantly through 2050. The scenario considers that imports and hydropower generation remain depressed due to the ongoing six-year drought in Morocco. However, it is expected that both imports and hydropower will return to average values over the next five years as conditions improve.

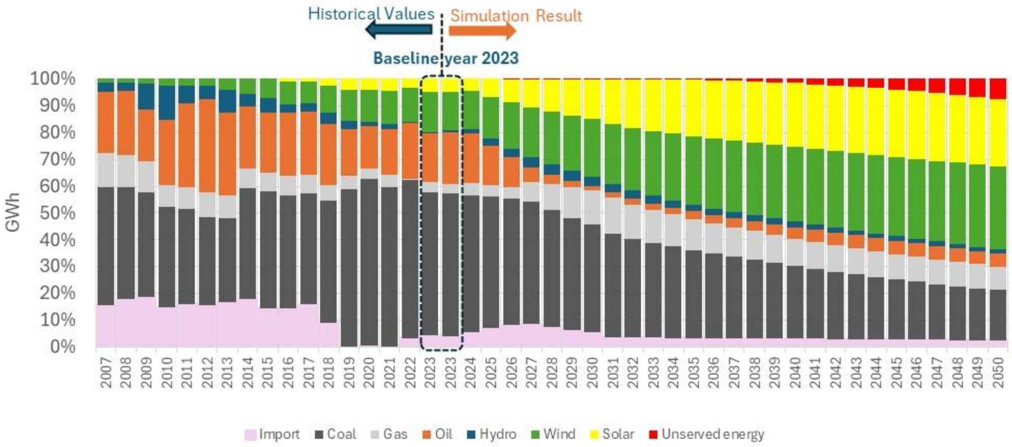
Figure 39 Annual Energy Generation – Morocco BAU Scenario (GWh)



Source: results of the simulation

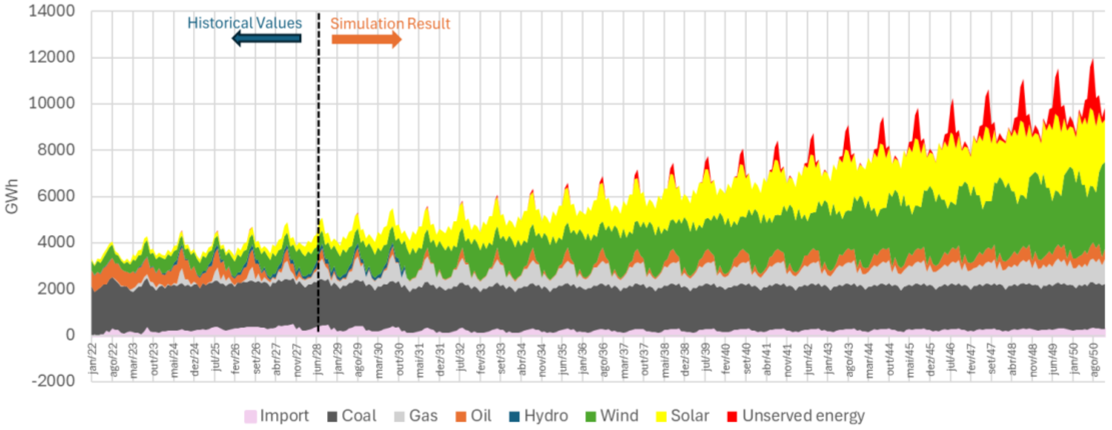
Despite the substantial growth in renewable energy expected through 2050, the model highlights a growing concern with Unserved Energy (USE), especially from 2030 onwards. This increase is primarily driven by the lack of firmness in the renewable energy expansion. As solar and wind energy continue to expand, their intermittent nature, combined with slower-than-anticipated development of firm capacity solutions such as energy storage, results in a growing gap between supply and demand. By 2050, this issue becomes more pronounced, indicating the need for strategies that enhance system reliability and flexibility to mitigate the risk of unserved energy, particularly during periods of peak demand or low renewable output.

Figure 40 Annual Energy Generation Participation – Morocco BAU Scenario (%)



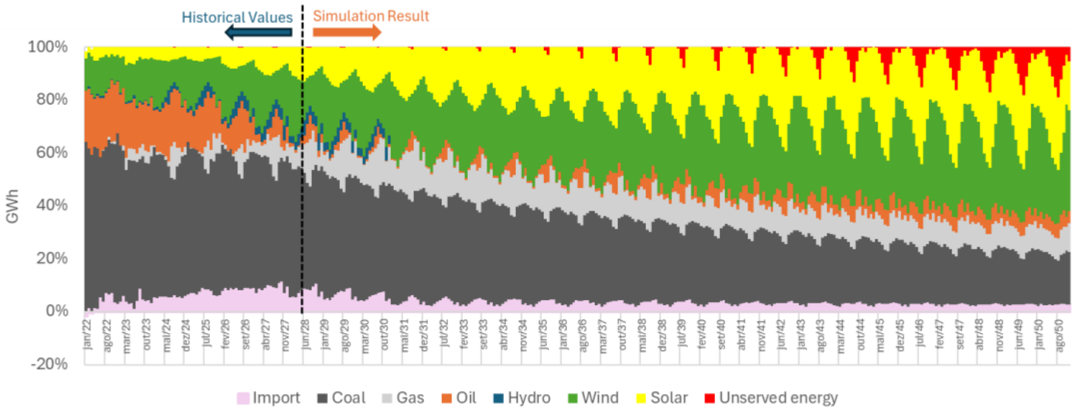
Source: results of the simulation

Figure 41 Monthly Energy Generation – Morocco BAU Scenario (GWh)



Source: results of the simulation

Figure 42 Monthly Energy Generation Participation – Morocco BAU Scenario (%)



Source: results of the simulation

The monthly figure shows the evolution of energy production by source, highlighting the increase in solar and wind generation. However, without battery storage, a significant portion of renewable energy, particularly solar and wind, cannot be fully utilized, especially during times of high demand or when generation exceeds immediate consumption. This issue becomes especially critical during the peak summer months (July to September), when electricity demand surges due to increased use of air conditioning and other cooling systems. Without storage systems to capture and store excess solar and wind energy during off-peak periods, much of that generated energy goes unused, leaving some of the demand unmet, resulting in unserved energy (USE).[15]

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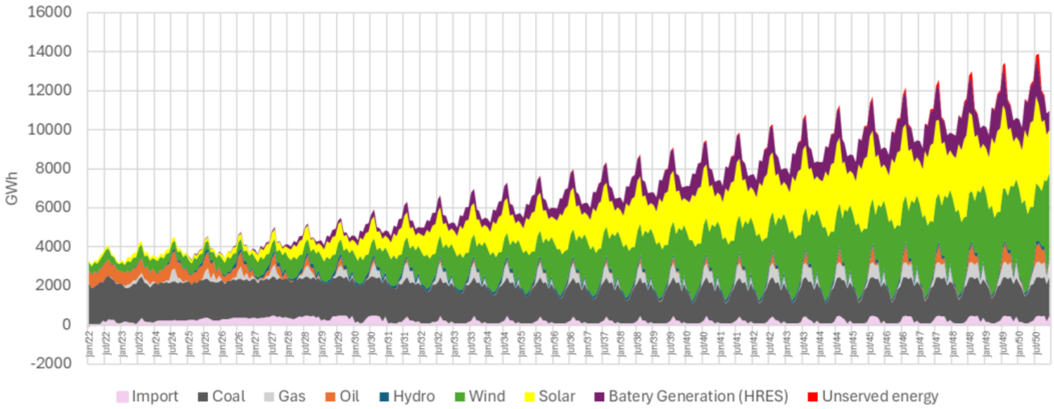
[15] Unserved energy (USE) refers to the electricity demand that cannot be met due to insufficient supply, which can arise from variability in generation (e.g., fluctuating solar or wind output) or lack of storage to capture excess energy during periods of low demand for use later.

Advanced Scenario

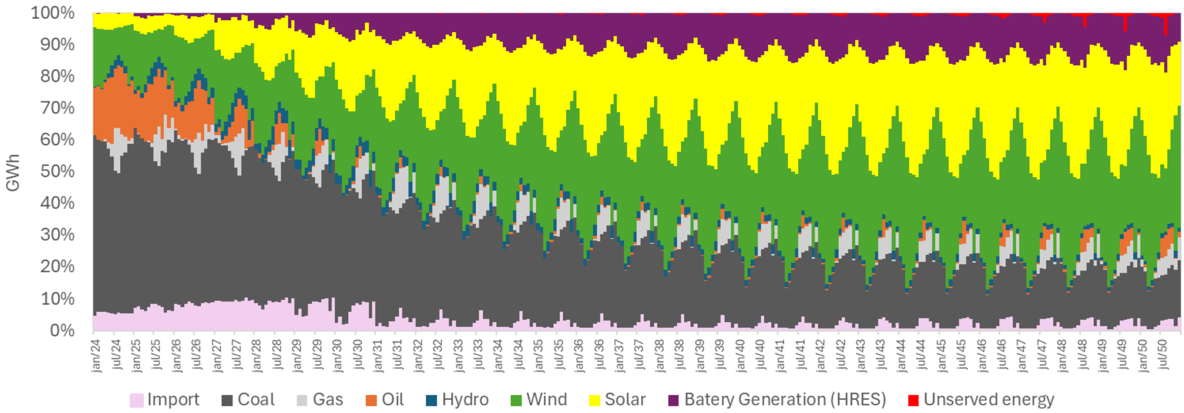
The Advanced Scenario incorporates the participation of HRES, significantly reducing the occurrence of USE in the long-term compared to the BAU scenario. The following figures illustrate the impact of this integration on the energy mix and overall system performance.

Figure 43 Monthly Energy Generation – Morocco Advanced Scenario (GWh)



Source: results of the simulation

Figure 44 Monthly Energy Generation Participation – Morocco Advanced Scenario (%)



Source: results of the simulation

The figure displays the evolution of Morocco's energy generation profile from 2024 to 2035, highlighting the contribution of various energy sources including imports, coal, gas, oil, hydropower, wind, solar, and the storage facilities. The figure clearly shows the seasonal variations and the increased role of renewable energy sources over the years. Notably, the incorporation of HRES generation is evident, which helps to mitigate the USE (highlighted in red) especially during peak demand periods.

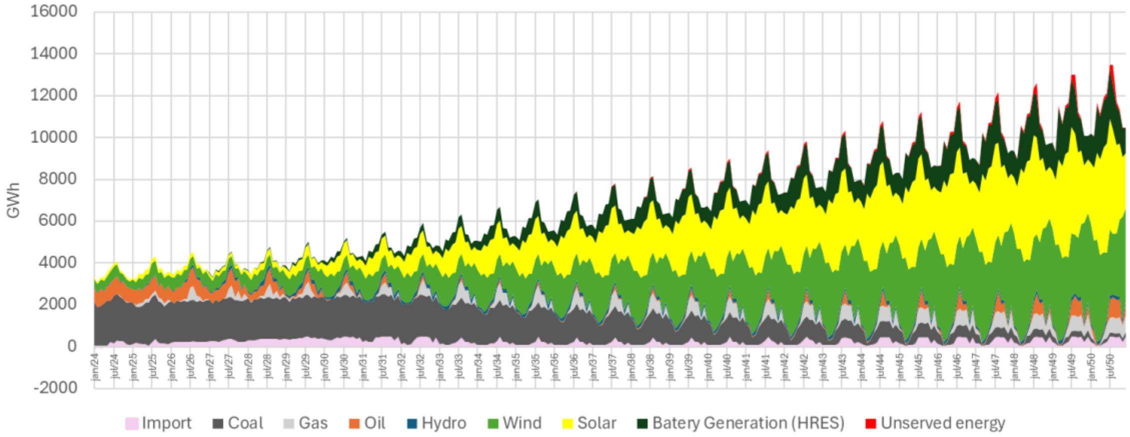
In the BAU scenario, significant amounts of USE were observed, particularly during the summer months from July to September due to increased demand. The Advanced Scenario, with the addition of HRES, effectively addresses these shortages, ensuring a more reliable and resilient energy supply.

This scenario demonstrates that incorporating battery storage can significantly enhance grid reliability by providing additional flexibility and capacity to meet peak demand and smooth out fluctuations in renewable energy generation.

Strengthened Scenario

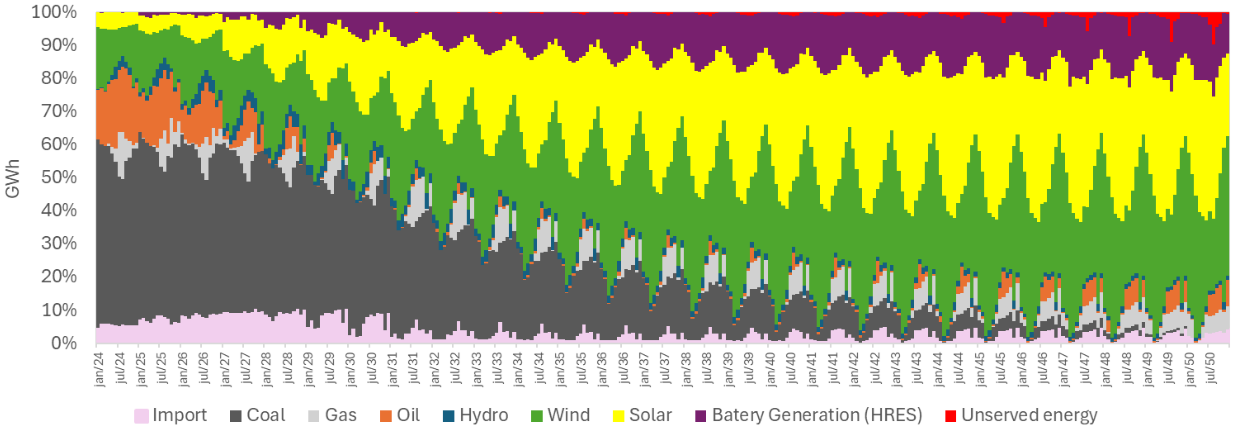
Like what occurs in the Advanced model, the Strengthened model reduces unserved energy by incorporating HRES. However, with the reduction of energy production from coal, it is possible to achieve a gain in emissions reduction, reaching a scenario of 90% renewable share in annual generation.

Figure 45 Monthly Energy Generation – Morocco Strengthened Scenario (GWh)



Source: results of the simulation

Figure 46 Monthly Energy Generation Participation – Morocco Strengthened Scenario (%)



Source: results of the simulation

In both the Advanced and Strengthened scenarios, the use of HRES significantly reduces the occurrence of unserved energy (USE), demonstrating the potential of energy storage to alleviate supply shortages, especially during peak demand periods. Although USE is not entirely eliminated, the integration of HRES plays a crucial role in mitigating these gaps, particularly as coal generation is phased out. However, to ensure long-term system reliability, additional firm capacity is still necessary, which could be provided by new hybrid energy systems or peaking gas turbines. The most cost-effective solution will require a detailed least-cost planning analysis to identify the optimal technology mix, which falls outside the scope of this current study.

4.3 HRES Result

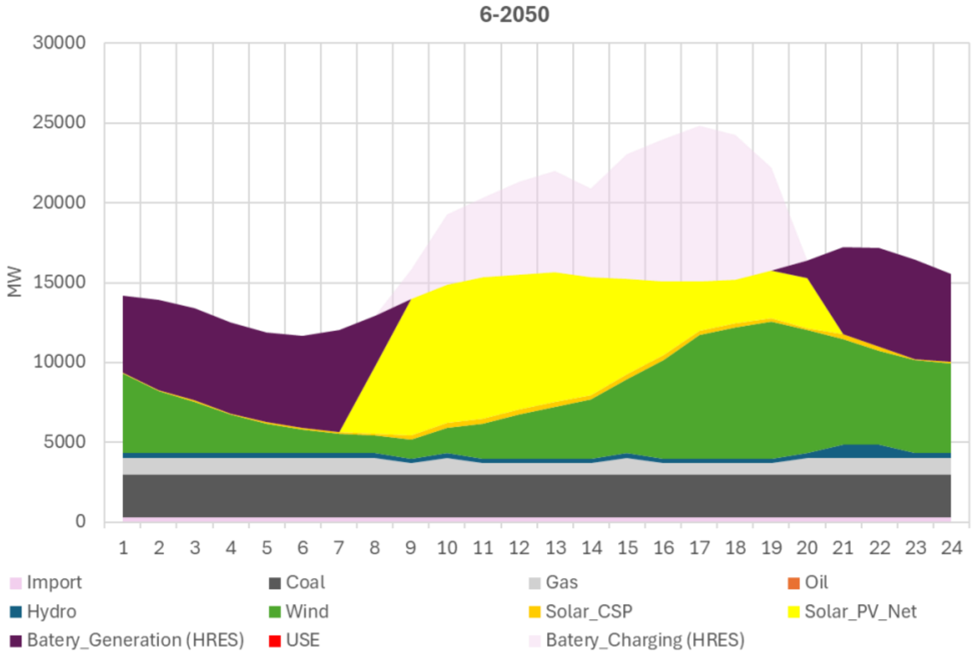
In this section, the performance of hybrid energy projects is evaluated, focusing on their ability to manage peak demand and ensure system reliability through the integration of renewable energy sources and battery storage. The concept of peak shaving is explored, demonstrating how hybrid systems utilize battery energy storage to absorb excess energy during periods of high solar and wind generation and redistribute it during peak demand hours. This approach not only enhances the flexibility of the energy system but also reduces the risk of USE and increases the overall efficiency of renewable resources.

Figure 47 presents the overall energy generation mix for June 2050, highlighting how solar PV, wind, and battery systems operate together. During midday hours, when solar and wind generation peak, the battery system stores excess energy. Later, during the evening peak, this stored energy is discharged, helping to meet the demand and avoid USE. The contribution of the battery system is clearly seen in the way it smooths out fluctuations in generation and demand.

Figure 48 focuses on the solar PV resource, showing how the battery system stores surplus solar energy during the day when generation is higher than the immediate load requirement. This stored energy is released in the evening, after solar generation has declined, to help meet the demand peaks and reduce the need for conventional generation.

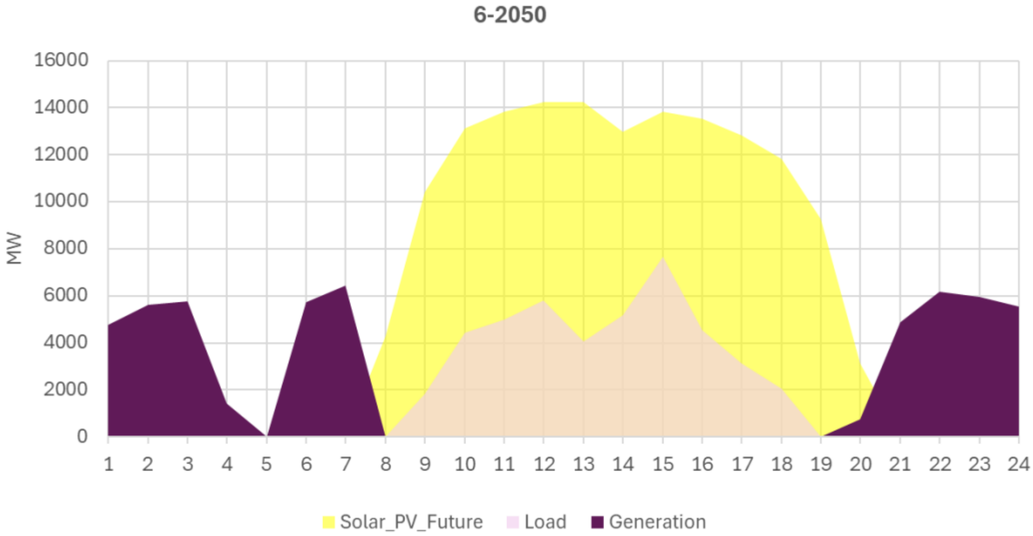
Figure 49 examines the wind energy resource. Here, the battery system captures excess wind generation during early morning hours when demand is low and releases this energy during higher demand periods in the late afternoon and evening. This highlights the ability of wind-battery hybrid systems to provide consistent power supply, even when wind generation does not perfectly align with demand patterns.

Figure 47 Hourly demand for June-2050 Test Day – Advanced Scenario



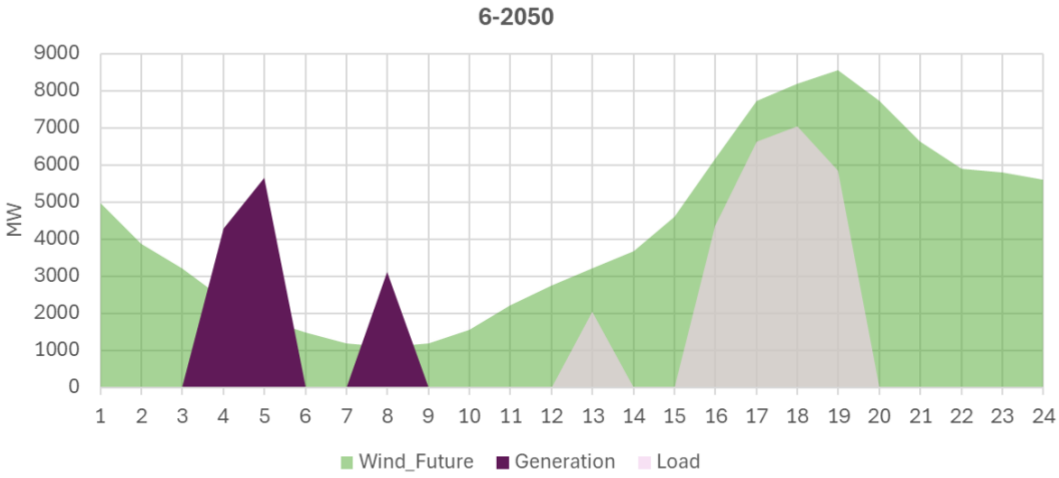
Source: results of the simulation

Figure 48 Hybrid PV+BESS for June-2050 Test Day – Advanced Scenario



Source: results of the simulation

Figure 49 Hybrid Wind+BESS for June-2050 Test Day – Advanced Scenario



Source: results of the simulation

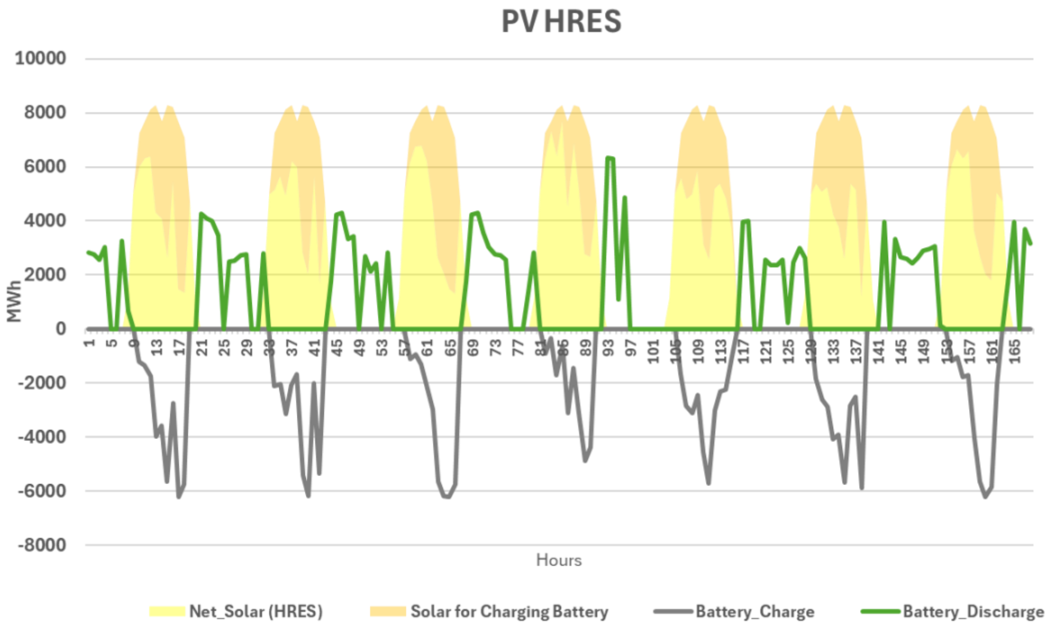
PV - HRES Week Operation

Figure 50 illustrates the operational performance of the PV HRES over a week in August 2040, showcasing the system’s ability to store and redistribute solar energy throughout each day. The yellow area represents the net solar generation available for both direct consumption and battery charging, while the dark grey and green lines represent the battery charging and discharging activities, respectively.

During daytime hours, especially from around 8:00 AM to 6:00 PM, the solar PV system generates a significant amount of energy, as seen in the yellow area. A portion of this energy is immediately used to meet demand, while excess is directed toward charging the batteries, indicated by the grey negative values during these periods.

As the solar generation peaks around midday, the system stores this surplus energy in the battery system, allowing it to handle fluctuations in solar availability and prepare for later use. In the evenings and early mornings, when solar output is low or zero, the battery system discharges energy to cover the energy demand, as shown by the green positive lines. This behavior is consistent throughout the week, with the battery effectively smoothing out the supply-demand mismatch, reducing the reliance on other energy sources during non-solar hours.

Figure 50 PV HRES Test week - Advanced Scenario



Source: results of the simulation

Wind - HRES Week Operation

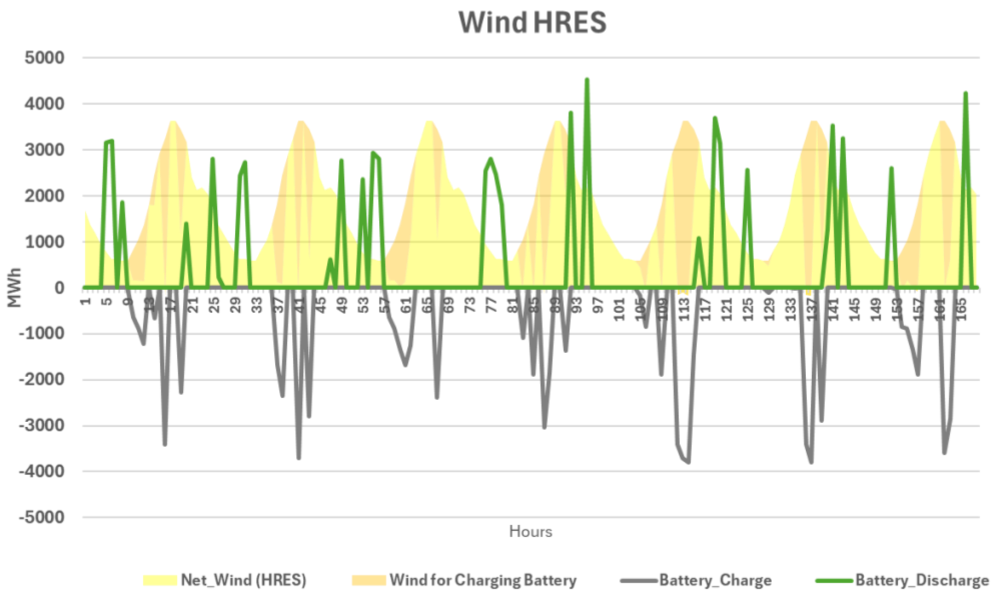
Figure 51 illustrates the operational performance of the Wind HRES over a week in August 2040. The yellow area represents the net wind generation available for both immediate use and battery charging, while the grey and green lines show the battery charging and discharging activities, respectively.

Throughout the week, wind energy exhibits a more variable pattern compared to solar, with distinct peaks and troughs in generation. During periods of high wind output, especially in the late evening and early morning hours, excess wind energy is stored in the battery, as indicated by the grey areas representing battery charging. This stored energy is then discharged (green lines) during periods of low wind generation or when demand peaks, ensuring a steady supply of electricity even when wind resources are insufficient.

The battery system is most active during the non-wind periods, releasing the stored energy to smooth out the fluctuations in wind generation and meet the demand when wind production alone cannot suffice. This behavior is particularly evident during the midday and afternoon hours, where battery discharges supplement the lower wind output, ensuring grid stability.

Overall, the Wind HRES system plays a vital role in absorbing excess wind energy during high-generation periods and releasing it when wind speeds drop, effectively balancing supply and demand over the week and reducing the reliance on other generation sources during peak hours.

Figure 51 Wind HRES Test week - Advanced Scenario



Source: results of the simulation

4.4 Economic and financial considerations

PV+BESS

In this cash flow projection for the advanced scenario, the PV HRES project begins operations in January 2025 with an installed capacity of 408 MW of solar PV coupled with a 408 MW BESS capable of 4 hours of storage. The choice to match the capacity between the solar plant and the battery plant aims to optimize the storage of generated energy, ensuring that all solar production is stored for later use, minimizing losses and improving efficiency. This also helps reduce periods of unserved energy and enhances supply continuity, especially during low solar generation. Additionally, it simplifies system planning and operation, providing a balanced and cost-effective solution.

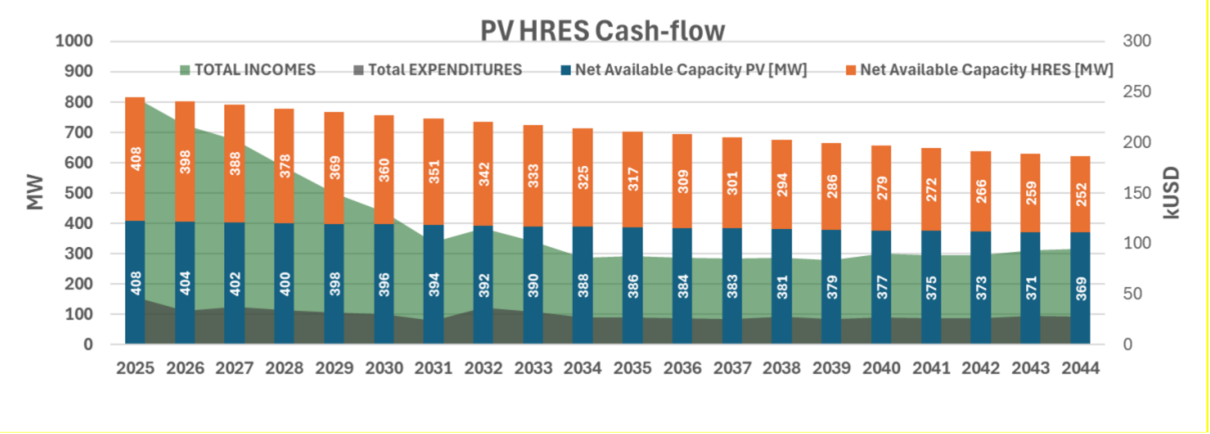
The graph shows total income (green area) and total expenditures (grey area) over the project lifetime, along with the net available capacity of both PV and BESS (orange and blue bars, respectively). The income data is based on the prices derived from the Plexos optimization model, reflecting the energy costs at each moment of system operation. The expenditures, in turn, are calculated using the same assumptions applied in the LCOE calculation presented earlier. Finally, the investments are disbursed during the first two years of the project, prior to the start of operations.

- Total Income gradually declines over the years, starting from a peak in 2025 as energy prices and production incentives diminish. Despite this, the project continues to generate revenue by taking advantage of peak solar production, storing excess energy during the day, and selling it during high-demand periods when prices are higher.
- Total Expenditures remain relatively stable, but a gradual reduction is observed, likely due to decreasing operational and maintenance costs as the system ages and technology

improvements lower costs.
- The Net Available Capacity for both PV and BESS shows a slight decline as the system operates, reflecting a reduction in system efficiency over time, which is a common characteristic of renewable energy technologies. By 2044, the available capacity for PV decreases to 369 MW, while the BESS capacity decreases to 252 MW.

Overall, the cash flow projection indicates that, while revenue generation decreases over time, the project remains financially viable throughout its lifecycle. The combination of PV and battery storage ensures that the system can effectively shift energy to higher-priced periods, thus maximizing revenue in Morocco's advanced scenario with increased renewable energy penetration.

Figure 52 PV HRES Cashflow - Advanced Scenario



Source: own elaboration

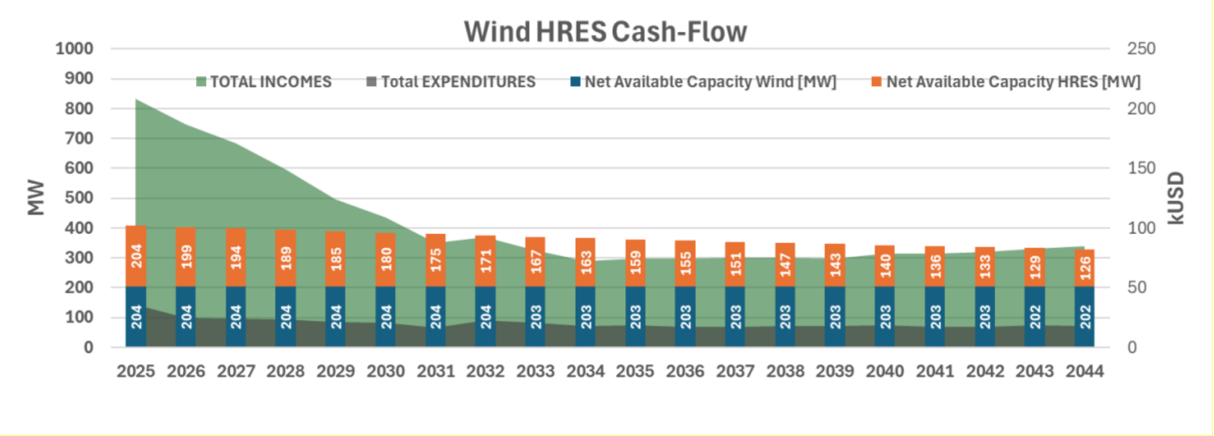
Wind+BESS

The Wind HRES project, which also begin in 2025, combines 204 MW of wind generation with a 204 MW BESS (4-hour storage).

- Total Income again peaks in the early years, leveraging the high market prices during peak demand periods, supported by energy stored in the BESS during times of high wind generation. However, as energy prices decrease and the system ages, the income gradually declines.
- Total Expenditures remain stable and slightly decrease over time, similar to the PV HRES project. The operation and maintenance costs are expected to decrease as technology improves and operational efficiencies are gained.
- Net Available Capacity for wind and BESS follows a similar trend to the PV project. By 2044, the wind capacity reduces slightly to 202 MW, while the BESS drops to 126 MW, reflecting system degradation over time.

The Wind HRES project shows a similar cash flow pattern to the PV HRES project, with a gradual decline in revenue over time, but it remains financially feasible by utilizing stored wind energy during non-windy periods. This project also maximizes revenue by storing excess energy and selling it during high-priced peak periods, crucial in the advanced scenario where wind power plays a growing role in Morocco's energy mix.

Figure 53 Wind HRES Cashflow - Advanced Scenario



Source: own elaboration

4.5 Cost-Benefit Analysis

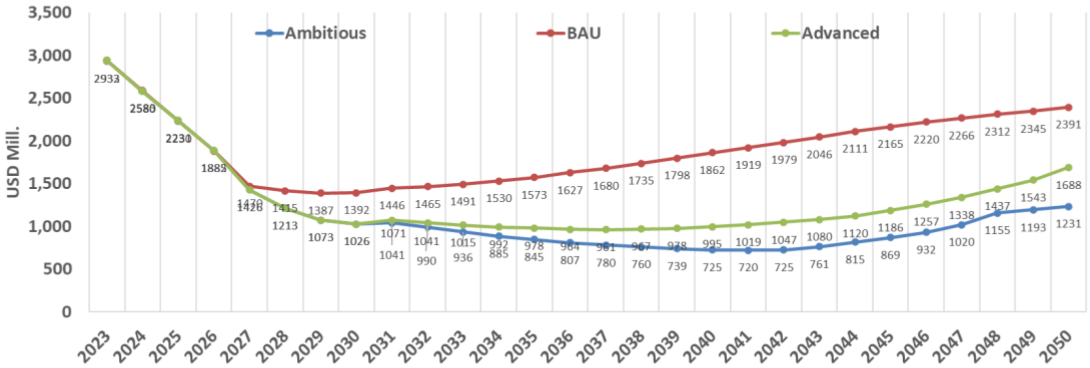
In this section we will evaluate and compare the three energy expansion scenarios for Morocco. Each scenario represents a different strategy for meeting future electricity demand, with the objective of identifying the costs and benefits of each option in terms of generation costs, operational efficiency, emission-related costs, and the ability to reduce unserved energy.

All the costs in this analysis are derived from the Plexos optimization, using the cost assumptions presented for the system's LCOE, including fuel costs, emissions, and unserved energy.

Generation Cost

The following figure compares the total system costs, highlighting significant cost reductions over time. The Advanced and Strengthened scenarios show the most substantial decline, with system costs steadily decreasing to USD 1,544 million by 2030, following the same expansion plan. In the long term, as coal is phased out, the Strengthened scenario achieves the lowest costs at USD 1,231 million, resulting in the greatest overall savings compared to the other scenarios. Conversely, in the Advanced scenario, the increase in costs over the longer horizon is related to the need to activate peaking plants, which become necessary to ensure the reliability of the system with the proposed expansion plan.

Figure 54 Generation Cost by Scenario



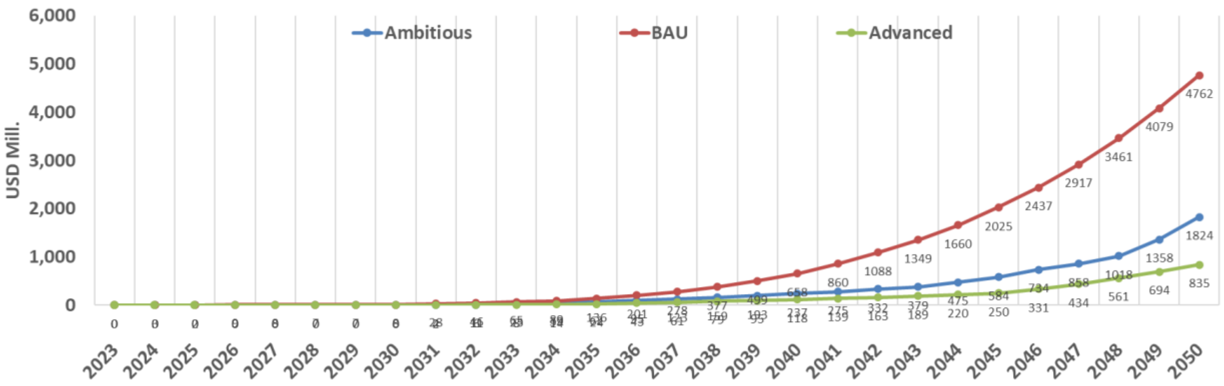
Source: own elaboration, results of the simulation

Unserved Energy

In the BAU scenario, the graph indicates a significant increase in unserved energy over time, peaking at USD 4,762 million by 2050. This highlights a system heavily reliant on gas, lacking sufficient capacity to meet peak demand, especially during critical months like July and August, particularly when the system is expanded to 80% renewable sources without any storage. In contrast, the Advanced scenario shows improved system reliability, with unserved energy reduced by about 83% compared to the initial proposal, although it still does not fully address peak demand periods. Importantly, despite these improvements, unserved energy continues to be an issue during high-demand months, reflecting ongoing challenges in balancing supply and demand during critical times.

On the other hand, the Strengthened scenario represents a reduction of around 60% compared to the BAU scenario; however, the replacement of coal plants reduces the reliability of the system, which is then supported 90% by non-dispatchable renewables. And despite the reliability ensured by the coupled BESS, it is still not enough to fully meet peak demand periods, resulting in a higher cost of unserved energy compared to the Advanced scenario.

Figure 55 Unserved Energy by Scenario



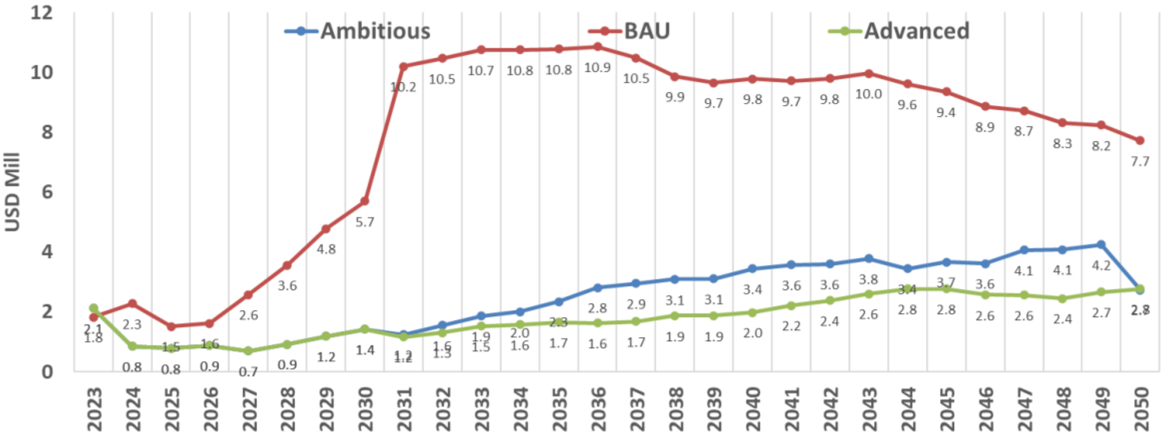
Source: own elaboration, results of the simulation

Start and Shutdown Generation Cost

In the Start-and-Shutdown-Generation-Cost variable, the Advanced Expansion scenario stands out for its significant cost reductions compared to the other two scenarios. This reduction is primarily due to the incorporation of HRES, which helps mitigate the frequent starting and stopping of generators. In the BAU scenario, generators experience frequent ramping and cycling, particularly during fluctuations in renewable energy, leading to increased wear and operational stress. The BESS in the Advanced and Strengthened scenarios enables smoother transitions and greater operational stability by storing excess renewable energy and discharging it when needed. Consequently, the system avoids unnecessary generator ramp-ups and shutdowns, which are costly in terms of fuel consumption and mechanical stress. This reduction in start-and-shutdown cycles results in substantial savings for the energy system, as reflected in the much lower costs in the Advanced scenario.

The Strengthened scenario, however, relies more on diesel plants due to the system's reliability not being fully met by renewable sources alone. This reliance on diesel also increases operational and fuel costs, though not as significant as in the BAU scenario.

Figure 56 Start and Shutdown Generation Cost

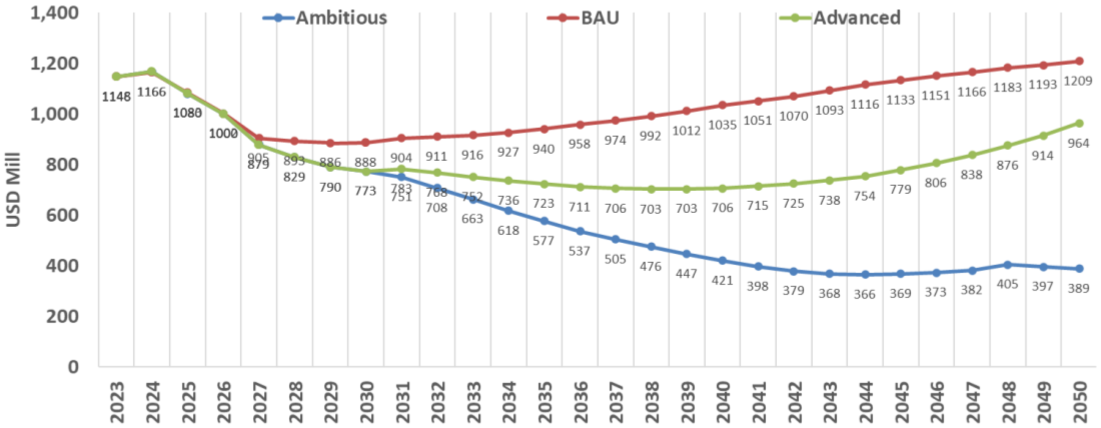


Source: results of the simulation

Emissions - Cost and Production

For the emission costs variable, the BAU scenario results in the highest costs over time, with a steady increase due to the growing reliance on gas without significant renewable energy integration. The Advanced scenario, incorporating more renewables, shows a reduction in costs, despite increasing again in the long term due to the dispatch of plants with higher emissions to meet peak demand. The Strengthened scenario, which also replaces coal with HRES, results in the lowest emission costs due to the sharp reduction in carbon emissions, as a larger portion of energy comes from clean sources and battery storage. A carbon cost of 0.05 USD/kg has been assumed for the scenarios[16].

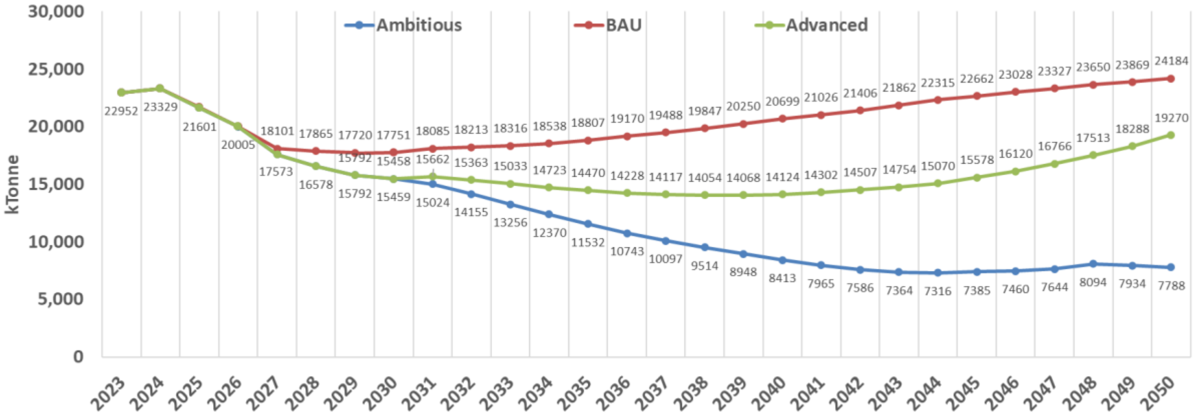
Figure 57 Emissions Cost



Source: results of the simulation

Next graph represents the total CO2 emissions, where a similar trend is evident. The BAU scenario remains the largest emitter of greenhouse gases due to heavy reliance on fossil fuels. The Advanced scenario sees a gradual reduction in emissions as more renewables are integrated, but there remains a dependency on gas and coal. The Strengthened scenario achieves the most significant emissions reductions, utilizing both renewable energy sources and BESS to minimize the use of carbon-emitting energy production.

Figure 58 Emission Production



Source: results of the simulation

Total costs in the BAU Scenario

The generation cost remains the largest contributor, accounting for 65% to 72% of the total costs over the short-term period and representing about 50% of the entire period average. However, as

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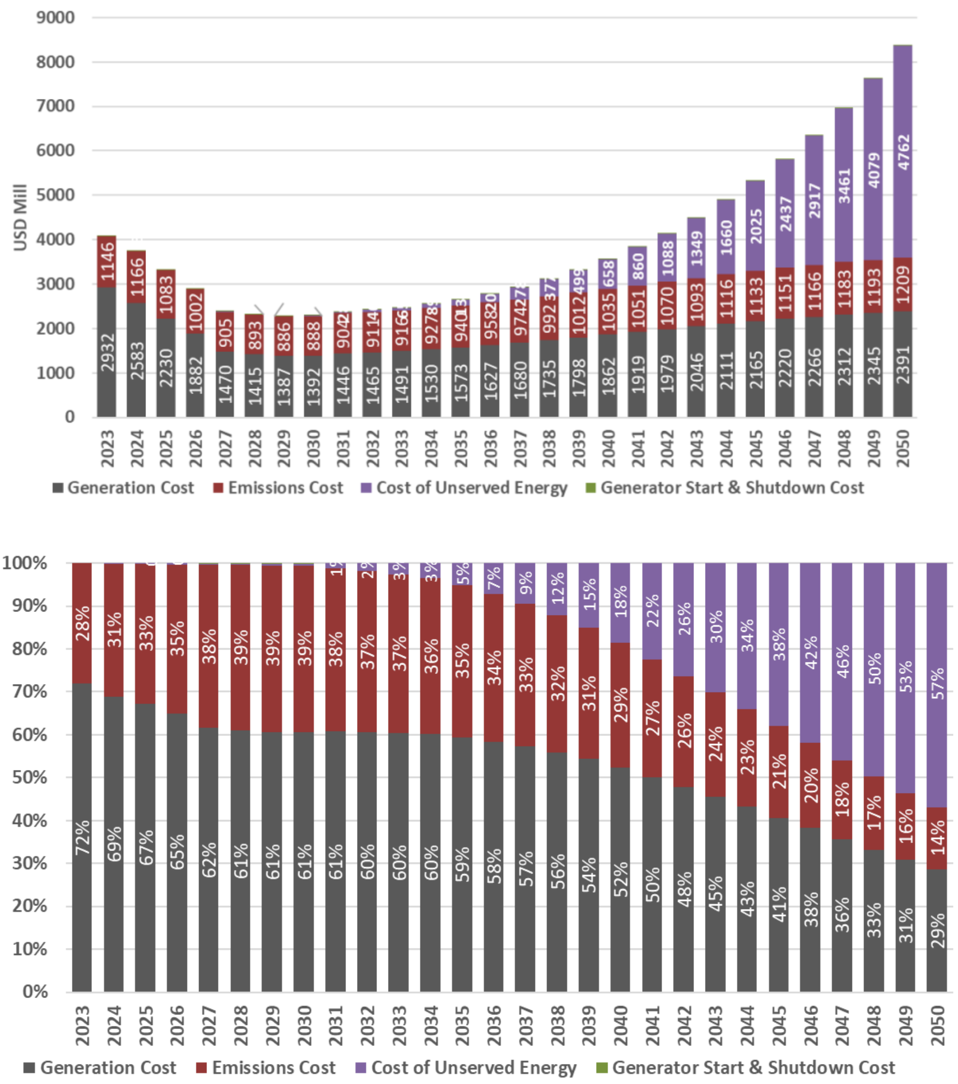
[16] 0.05 USD/kg for 2024. https://carbonpricingdashboard.worldbank.org/compliance/price

the years progress, the unserved energy costs become more significant, increasing from 1% in 2031 to around 57% by 2050. This growth reflects the impact of renewable expansion without any capacity system accoupled (like the storage systems in HRES proposal).

Meanwhile, costs related to emissions and generator start and shutdown remain relatively low in comparison, with the minimal impact on the total costs, especially since no new thermal power plants are expected in this expansion plan. These smaller costs show little variation across the years, reflecting the stable nature of gas-based generation systems in terms of reliability and operational costs.

Next figures illustrate the total costs for the BAU scenario, where the overall cost gradually increases from 2023 to 2050. The first chart breaks down these costs into generation, emissions, unserved energy, and generator start and shutdown components.

Figure 59 Total Cost USD and % - BAU Scenario

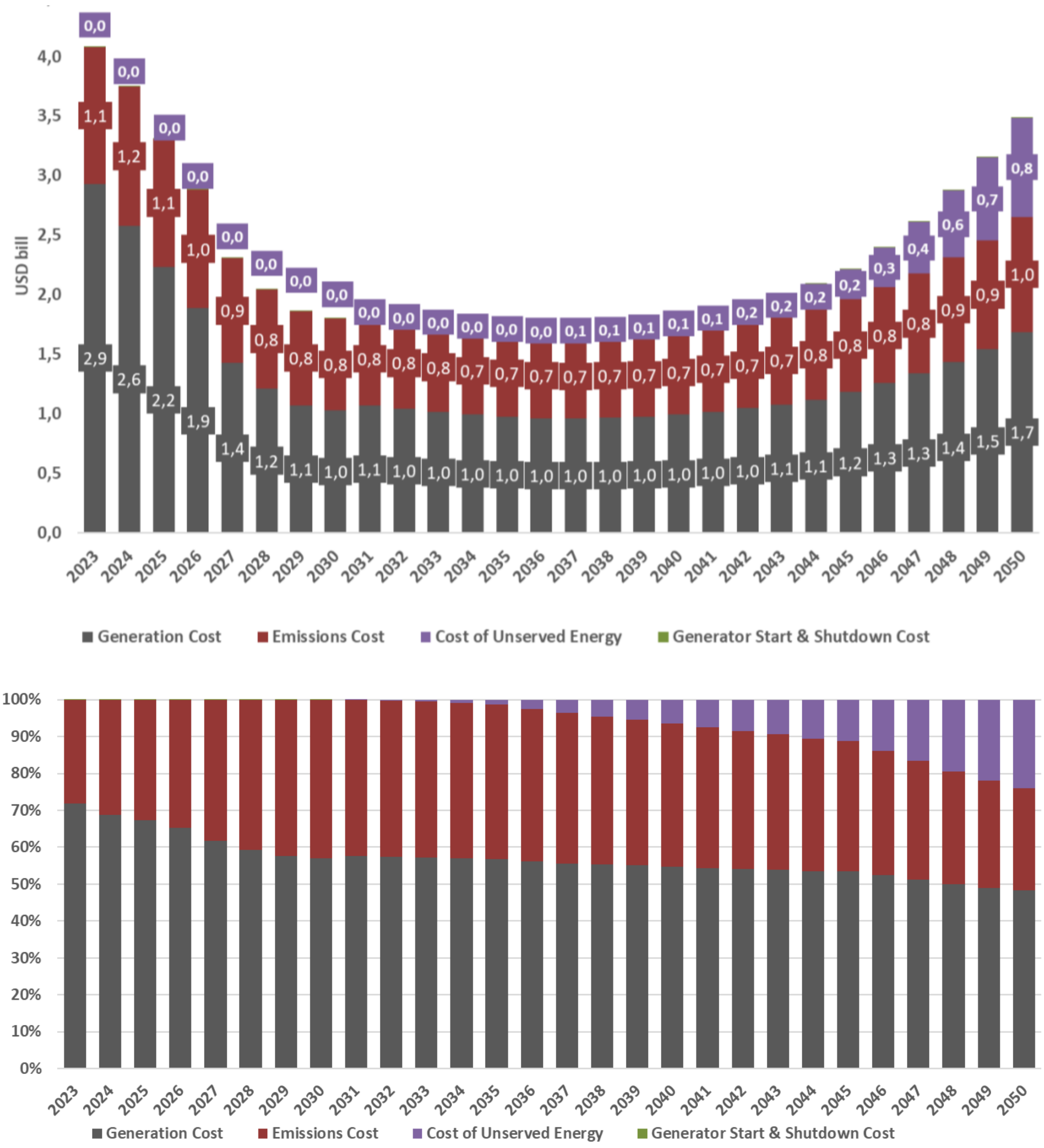


Source: own elaboration

Total costs in the Advanced Expansion Scenario

In terms of absolute costs (USD), the total system costs decrease significantly from 2023 to 2040, moving from around $4,000 million to $1,800 million. This is primarily driven by reductions in Generation Costs and a stabilization of Emissions Costs around $1,700 million. Meanwhile, Unserved Energy Costs begin to increase from 2040 on, reinforcing the participation of this cost in the total amount and achieving almost 25% in 2050. The generation and emissions costs rise again in this period, focusing on reducing the unserved energy with the coal and diesel plants.

Figure 60 Total Cost USD and % - Advanced Expansion Scenario



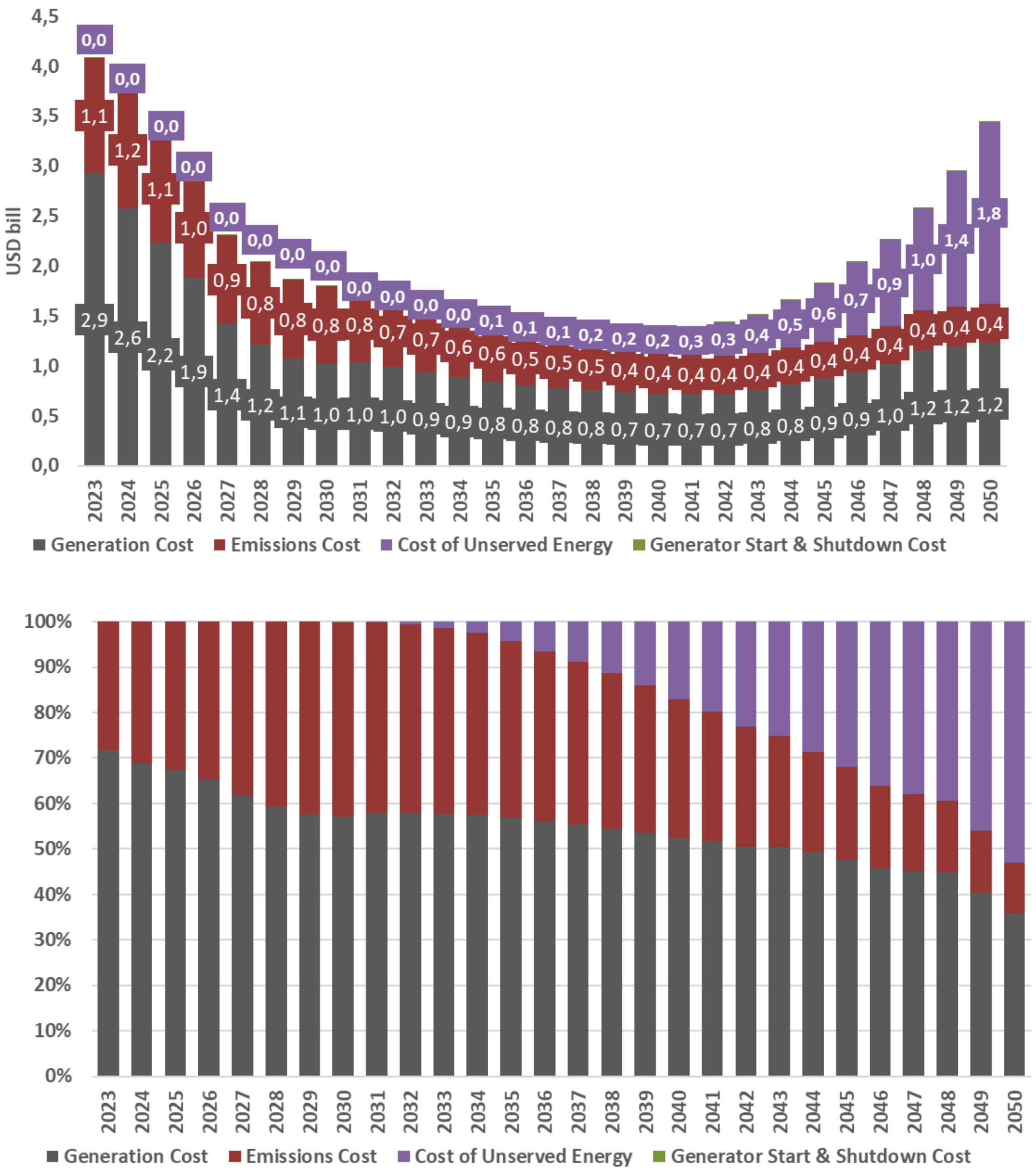
Source: own elaboration

Total costs in the Strengthened Expansion Scenario

The Strengthened expansion scenario demonstrates a considerable reduction in overall system costs compared to other expansion scenarios. Initially, in 2023, the total system cost is driven by generation and emissions, with no noticeable contributions from unserved energy or start-up/shutdown costs. However, as time progresses, Strengthened Expansion shows marked reductions in all cost categories.

Beginning in 2040, however, Unserved Energy costs start to increase steadily, nearly matching the levels of emissions reductions. This indicates that replacing coal plants solely with renewable sources is not as effective as other potential expansion plans.

Figure 61 Total Cost USD and % - Strengthened Expansion Scenario



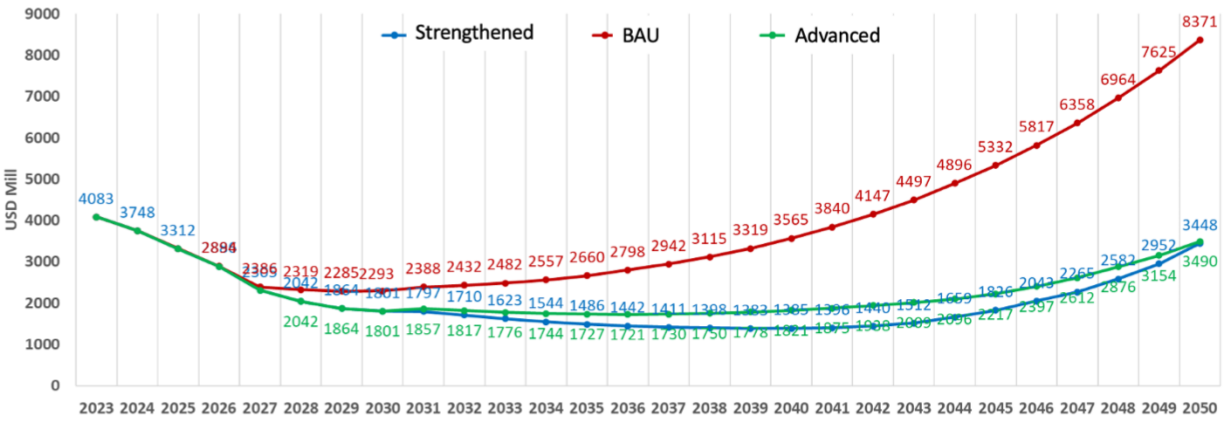
Source: own elaboration

4.6 Comparation between scenarios

In this section, we present the comparison of total system costs for the three scenarios. These costs are analyzed in terms of their net present value (NPV) and show significant system savings for both the Advanced and Strengthened Expansion scenarios when compared to the baseline of BAU.

The NPV for the BAU scenario reaches approximately USD 44,000 million by 2050, making it the most expensive option. The Advanced scenario shows considerable savings, reducing the NPV of system costs by USD 29,972million, or 32% lower than the baseline. However, the most cost-effective scenario is the Strengthened Expansion, which replace also the coal plants with renewable energy and battery storage (HRES), resulting in a total system cost NPV of USD 27,801million. This represents a reduction of USD 16,582million, or 37%, compared to the BAU scenario. Compared to the Advanced scenario, the Strengthened scenario results in a 7% reduction in total costs, along with a significant decrease in emissions.

Figure 62 Total Cost Comparation by Scenario



Source: own elaboration

Figure 63 Net Present Value of System Cost by Scenario

Scenarios for a IRR = 6%	NPV of System Cost [MM.USD]	NPV of System Savings [MM.USD]	NPV of System Savings [%]
BAU	44,383	-	-
Advanced	29,972	14,411	32%▼
Ambitious	27,801	16,582	37%▼

Source: own elaboration

Overall, the incorporation of hybrid solutions with renewable energy and BESS not only decreases the total system costs but also maximizes system efficiency, demonstrating the financial and operational advantages of pursuing a more sustainable energy mix for Morocco's future power generation needs.

In both the Advanced and Strengthened scenarios, the use of HRES significantly reduces the occurrence of unserved energy (USE), demonstrating the potential of energy storage to alleviate supply shortages, especially during peak demand periods. Although USE is not entirely eliminated, the integration of HRES plays a crucial role in mitigating these gaps, particularly as coal generation is phased out. However, to ensure long-term system reliability, additional firm capacity is still necessary, which could be provided by new hybrid energy systems or peaking gas turbines. The most cost-effective solution will require a detailed least-cost planning analysis to identify the optimal technology mix, which falls outside the scope of this current study.

Technical Evaluation of Results

Three scenarios for Morocco's energy future were developed: the Business as Usual, the Advanced and the Strengthened Scenario.

- BAU Scenario projects a 52% renewable energy share by 2030 without expanding any battery energy storage systems (BESS or HRES). Using 2023 as the reference year, it is observed that the renewable energy share will increase from 21% to 78% by 2050. However, this scenario identified an amount of USE, especially during the high-demand months (July to September).
- Advanced Scenario incorporates the participation of HRES, significantly reducing USE in the long-term. The integration of HRES improves grid reliability by providing great flexibility to smooth out fluctuations in renewable energy generation and providing capacity to meet peak demand.
- The Strengthened Scenario, conversely, by replacing the coal plants with HRES systems, reduce the reliability of the system, and increase the USE observed.

The existence of USE in the three scenarios indicates that a more robust expansion plan is needed, to guarantee a better planning approach.

Economic Evaluation of Results

The economic evaluation of the three expansion scenarios - Business as Usual, Advanced and Strengthened Expansion - provides crucial insights into the cost-effectiveness and sustainability of each approach for Morocco’s energy sector. The analysis demonstrates that while each scenario has its strengths, Advanced expansion emerges as the most financially and operationally sound strategy for the country's long-term energy transition.

The BAU scenario, while straightforward in its reliance on expanding Morocco’s gas generation capacity by 900 MW, results in the highest overall system costs. This scenario relies heavily on fossil fuels, making it highly susceptible to fluctuations in global gas prices. Furthermore, the lack of renewable energy sources or storage solutions means the system is less flexible and incurs significant operational costs, especially during periods of peak demand.

In comparison, the Strengthened scenario offers a cheaper approach by incorporating renewable energy sources, such as solar and wind, and the HRES into the generation mix. This integration helps to reduce overall generation costs and emissions when compared to the gas-only scenario. However, the absence of robust plants limits the full potential of renewable energy. While this scenario does reduce system costs over time, it is not able to completely address the challenge of unserved energy, particularly during high-demand periods like the summer months. This shortfall in supply increases operational stress on gas generators, which must ramp up production to compensate for the intermittent nature of renewable energy sources.

The Advanced Expansion scenario, which includes both HRES and Coal plants, presents the most comprehensive and forward-looking solution. By integrating storage, the system can better manage supply and demand imbalances, especially during periods of high renewable generation. This not only reduces the need for costly and inefficient generator start-ups but also significantly decreases the volume of unserved energy. The Advanced Expansion scenario maximizes the use of renewable resources by storing excess energy generated during off-peak periods and dispatching it when demand is highest. This reduces reliance on gas generation and lowers fuel and operational costs. The cost-benefit analysis shows that the Advanced Expansion scenario achieves the greatest reduction in system costs, delivering almost the same that Strengthened Scenario (around USD 4,900 million in 2050) in savings over the analysis period when compared to the BAU scenario. This corresponds to a 60% reduction in total system costs, highlighting the economic benefits of a diversified energy mix supported by storage technologies.

Furthermore, the Net Present Value (NPV) of the Advanced Expansion scenario confirms its long-term viability. The integration of HRES ensures that the system is not only cost-effective but also resilient to fluctuations in demand and supply. By reducing both emissions and operational inefficiencies, the Advanced Expansion scenario positions Morocco for a cleaner, more sustainable energy future while also addressing key financial concerns. The significant decrease in emission costs—thanks to the reduced reliance on gas—adds to the overall cost-effectiveness of this approach.

5. Conclusions and Recommendations

Integrating renewable energy sources (RES) with Battery Energy Storage Systems (BESS) marks a significant step forward in improving the stability and reliability of the grid. As highlighted, the growing dependence on RES, which are inherently variable, calls for strong regulatory policies to facilitate smooth integration and optimal functioning. BESS is vital in mitigating the issues related to the fluctuations of RES, offering key grid services such as frequency regulation, energy shifting, and peak shaving. However, the effectiveness of these technologies in the grid is largely determined by the current regulatory frameworks and the associated challenges they pose.

The establishment of adaptive and forward-thinking regulatory policies is vital for nurturing a resilient and sustainable energy framework. The recommendations outlined below offer a blueprint for policymakers to facilitate the integration of BESS with RES, maintain grid reliability amid renewable energy expansion, and ensure a seamless transition towards a sustainable energy landscape.

Creating adaptive and future-oriented regulatory policies necessitates a proactive stance that foresees technological progress and shifts in market conditions. Policymakers should aim to design flexible regulatory frameworks capable of evolving in response to new technologies and market changes. A pertinent example is the introduction of performance-based regulations that reward grid services offered by BESS, such as frequency regulation and peak shaving, which can foster innovation and ensure effective contributions of storage systems to grid stability. Moreover, incorporating adaptive mechanisms for regular updates to regulations in line with technological advancements and market trends will help keep pace with industry requirements and standards.

To improve the integration of BESS with RES, several strategic measures should be considered. Initially, policymakers must prioritize the creation of standardized grid interconnection protocols that enable the smooth incorporation of storage systems with renewable energy sources. Standardization can diminish technical obstacles and simplify the deployment of BESS, ensuring compatibility with existing grid infrastructure and maximizing their potential. Additionally, establishing comprehensive performance metrics and standards for BESS can clarify operational requirements and expectations, aligning the efforts of various stakeholders and enhancing the dependable provision of grid services. Finally, supporting research and development (R&D) initiatives focused on advancing energy storage technologies will drive innovation and improve the efficacy and cost-efficiency of BESS.

Achieving a balance between grid reliability and the expansion of renewable energy necessitates careful consideration of both technical and regulatory factors. Policymakers should embrace integrated planning strategies that take into account the variability of RES alongside the capabilities of BESS. This involves devising storage strategies that optimize resource utilization and mitigate the impacts of intermittent renewable generation on grid stability. Furthermore, incorporating grid modernization efforts such as the implementation of smart grid technologies—can enhance the grid's capacity to manage variable energy inputs and adapt to real-time changes. By merging these strategies, policymakers can ensure reliable grid performance while accommodating the increasing presence of renewable energy.

Additionally, the development of hybrid renewable energy systems that combine multiple RES can significantly benefit future developments in Morocco, such as the deployment of desalination infrastructure and the production of green hydrogen. Policymakers should encourage the implementation of these hybrid systems, which can provide a stable and sustainable energy supply for desalination plants and hydrogen production facilities. This approach not only supports water and energy security but also contributes to the reduction of carbon emissions in these sectors.

In conclusion, long-term policy considerations for a sustainable energy transition encompass several key components. Firstly, establishing clear and ambitious long-term objectives for renewable energy and energy storage can guide efforts and spur investment in these domains. Policies that define targets for renewable energy adoption and storage capacity can foster a stable policy landscape that encourages private sector investment and innovation. Secondly, promoting public-private partnerships and collaborative initiatives can aid in sharing knowledge, resources, and risks associated with energy storage projects. Such partnerships can accelerate the deployment of BESS and improve their integration with renewable energy sources. Lastly, addressing regulatory challenges and streamlining permitting processes can decrease the time and costs linked to the rollout of energy storage systems, facilitating stakeholder contributions to the sustainable energy transition.

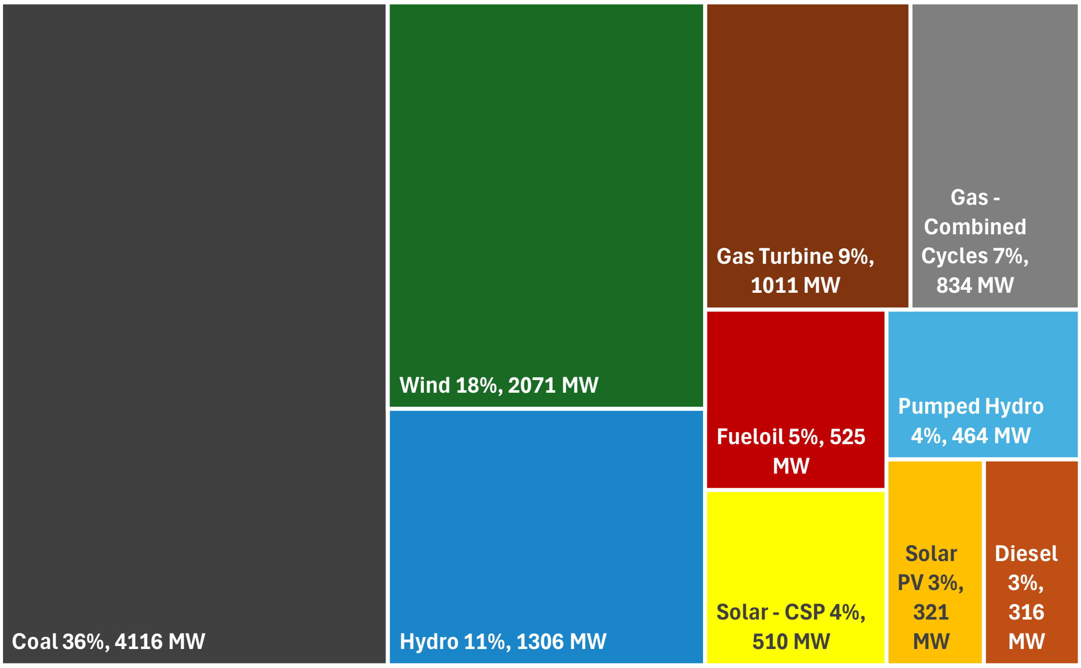
CURRENT SITUATION OF MOROCCO POWER SYSTEM

Installed Capacity

Morocco's energy generation mix is currently dominated by coal, providing a backbone for the nation's electricity needs. However, significant efforts have been made in recent years to diversify the energy mix and increase the share of renewable energy sources such as solar and wind. This shift reflects Morocco's commitment to sustainable development and energy security.

According to the 2023 statistical report[17] published by the Office National De l'Electricité et De l'Eau Potable (ONEE), Morocco's generating capacity amounts to 11,474 MW. Of this, coal accounts for 4,116 MW (36% of the capacity), while renewable energy sources total 4,672 MW (40% of the capacity). The following figure shows the capacity share by resource.

Figure 64 Generating Capacity – Morocco (2023)



Source: ONEE

Generation-Mix

Morocco's total annual energy generation has grown from 19,110 GWh in 2007 to 44,259 GWh in 2023. This growth reflects Morocco's expanding energy infrastructure to meet increasing demand and its strategic shift towards a more sustainable energy mix. As mentioned above, Morocco's energy generation mix has traditionally been dominated by coal, providing stable base-load power. However, since 2015, there has been significant growth in renewable energy capacities, particularly solar and wind. This shift highlights Morocco's efforts to diversify its energy sources and reduce reliance on fossil fuels, aligning with its goals for sustainable development and energy security. The increasing integration of renewables, supported by natural gas and hydropower, is transforming

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[17] Depliant_Francais_2023.pdf (one.org.ma)

Morocco's energy landscape, making it more resilient and environmentally friendly. An important indicator in analyzing the flexibility needs of Morocco’s electrical system is the Variable Renewable Energy (VRE) ratio, which represents the proportion of energy generated by non-dispatchable sources like wind and solar PV. This ratio will be estimated in this report and is crucial for understanding the growing role of renewables in Morocco's energy mix as the country works to diversify its sources.

According to the Chiffres Clés du Secteur de l'Énergie 2023[18], published by the Ministry of Energy Transition and Sustainable Development, Morocco's annual energy generation has seen significant changes over the years, reflecting a dynamic energy landscape.

Coal has been the dominant energy source for Morocco, with annual generation consistently high, peaking at 23,386 GWh in 2023. This reliance on coal underscores its role as the backbone of the country's electricity generation, providing stable and reliable base-load power. However, coal implies the well-known highest levels of greenhouse gas emissions and the inflexibility of such plants.

In second place, wind energy has shown a steady increase, rising from 279 GWh in 2007 to 6,481 GWh in 2023. The strategic deployment of wind farms in regions with high wind potential has significantly contributed to the renewable energy mix.

Hydropower generation has varied, reaching a high of 3,412 GWh in 2010 before stabilizing around 286 GWh in 2023 due to six consecutive years of drought. Hydropower, including pumped hydro power remains a reliable source for peak demand periods.

Natural gas plants have fluctuated over the years, peaking at 2,823 GWh in 2007 and stabilizing around 1,676 GWh in 2023. Natural gas plants provide the necessary flexibility to balance the intermittent nature of renewable sources, reaching the 4th place in the installed capacity mix.

The annual generation from oil-fired plants went from 5,202 GWh in 2007 to 7,934 GWh in 2023, although their relative contribution decreased. Oil and diesel plants are typically used as supplementary sources during high demand periods or when other plants are offline. This increase in oil-fired generation is primarily due to the ongoing drought in Morocco, which has significantly reduced hydroelectric generation. Hydropower output dropped from 1,592 GWh per year in 2018 to 330 GWh per year in 2023, necessitating greater reliance on thermal generation to compensate for the deficit.

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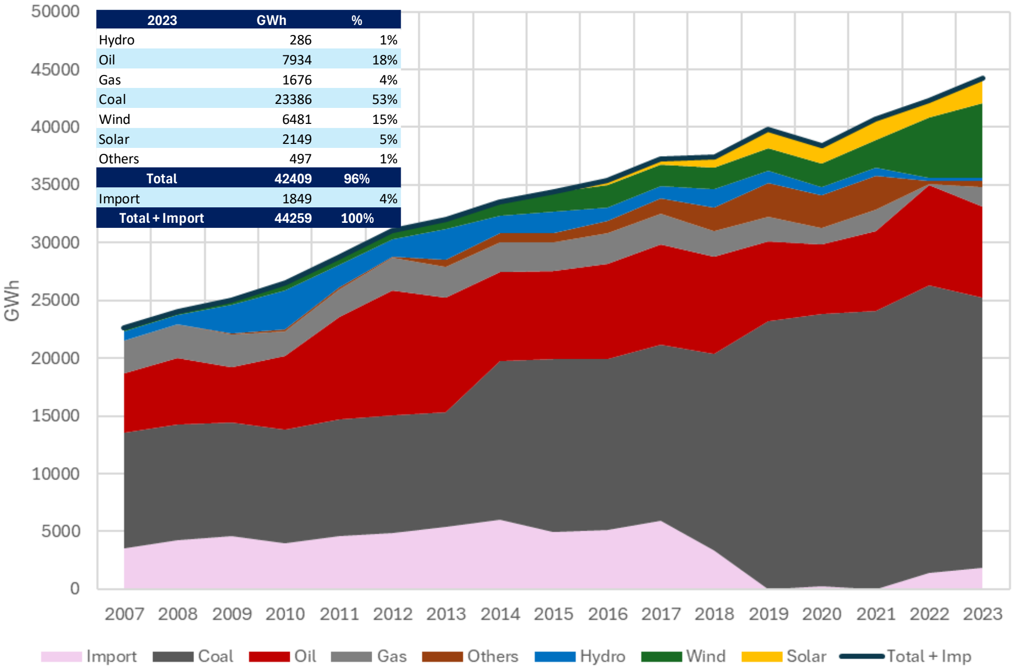
[18] https://www.mem.gov.ma/Lists/Lst_rapports/Attachments/41/Chiffres%20cl%C3%A9s%20F%C3%A9vrier%202023.pdf

Finally, solar energy, which had no presence in the early years, began to make a noticeable impact from 2015 onwards, with generation increasing from 6 GWh in 2015 to 2,149 GWh in 2023. This rapid expansion highlights Morocco's commitment to harnessing its abundant solar resources.
Morocco has historically relied on electricity imports to meet its demand, peaking at 6,010 GWh in 2014. However, there has been a trend towards reducing imports as domestic capacity, particularly renewables, has increased.

The following figure shows the historical generation mix of Morocco for the last 17 years.

Figure 65 Energy Generation – Morocco (2007-2023)



2023	GWh	%
Hydro	286	1%
Oil	7934	18%
Gas	1676	4%
Coal	23386	53%
Wind	6481	15%
Solar	2149	5%
Others	497	1%
Total	**42409**	**96%**
Import	1849	4%
Total + Import	**44259**	**100%**

Source: MEM

Following sections are a brief description of the plants installed in the country by fuel technology, which is summarized in Figure 66.

Figure 66 Main Power Plants

Plant	Source	Capacity (MW)
Mohammedia	Coal	600
Jorf Lasfar	Coal	2000
Safi Steam	Coal	1300
Jerada	Coal	350
Tarfaya	Wind	301.3
Akhfennir	Wind	197.1
Boujdour	Wind	301
Essaouira	Wind	60.4
Jbel Lahdid	Wind	270 (planned)
Midelt	Wind	180

Afourer-1	Hydro	93.6
Al Massira	Hydro	128
Al Wahda	Hydro	240
Allal El Fassi	Hydro	240
Bine El Ouidane	Hydro	135
Idriss	Hydro	40
Mohammed V	Hydro	23
Talambot	Hydro	14.1
Afourer-2	Pumped Storage	464
Ain Beni Mathar	Natural Gas	472
Mohammedia	Natural Gas	412
Tahaddart	Natural Gas	384
Agadir Gas Plant	Liquid Fuels	40
Agadir IC Plant	Liquid Fuels	26.4
Casablanca	Liquid Fuels	152
Casablanca Zi	Liquid Fuels	102
Kenitra Gas Plant	Liquid Fuels	315
Kenitra Steam Plant	Liquid Fuels	300
Tan Tan IC Plant	Liquid Fuels	117
Tanger	Liquid Fuels	40
Tetouan	Liquid Fuels	105
Tit Mellil	Liquid Fuels	204
Safi	Liquid Fuels	2.2
Noor Ouarzazate	CSP	510
Others	-	1625
Total		11474

Coal

Coal-fired power plants constitute the largest share of Morocco's installed capacity. These plants have traditionally provided firm capacity.[19] Despite their reliability, coal plants are not well-suited for rapid adjustments in output. This inflexibility poses a challenge when integrating renewable energy sources, which can be intermittent. Managing the grid with a high proportion of coal can be difficult when renewable generation fluctuates due to changing weather conditions.

Morocco has four coal-fired power plants, three of which are located along the Atlantic coast from north to south: the Mohammedia Steam Plant (600 MW), the Jorf Lasfar Steam Plant (2,000 MW), and the Safi Steam Power Plant (1,300 MW). Inland, near the city of Hasi-Bilal, is the Jerada Steam Plant (350 MW). This brings the total installed coal capacity to 4,250 MW. However, the capacity reported by ONEE for these coal plants is 4,116 MW, indicating an availability for generation of 97%. However, in line with Morocco's commitment made at **COP26 in November 2021** to **halt the**

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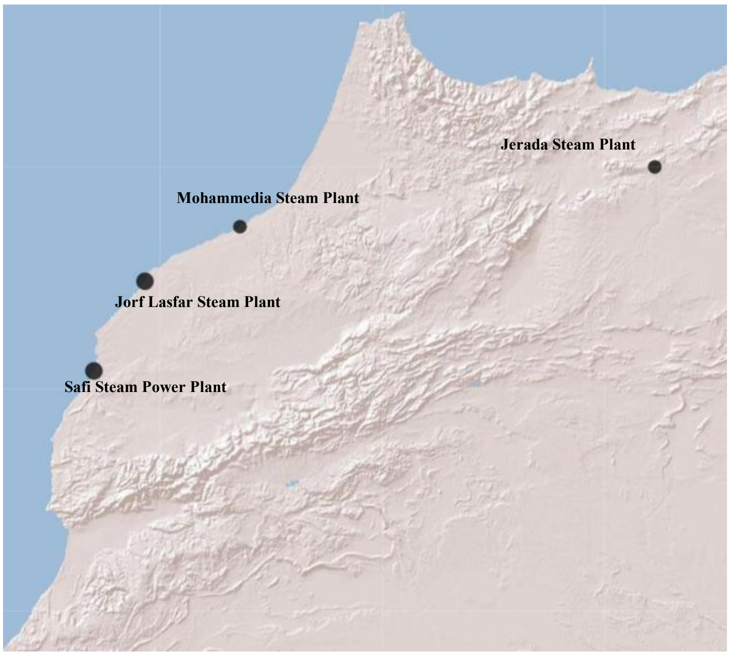
[19] Firm capacity refers to the ability to generate consistent power regardless of external conditions, which is crucial for meeting base-load demand.

construction of new coal-fired power plants, major projects such as the **planned 1,320 MW Nador coal plant** and the **expansion of the Jerada facility** have been **formally cancelled**.[20] These actions mark a significant shift in national energy policy as Morocco moves toward phasing out coal and accelerating its transition to renewable energy.

Figure 67 Operative Coal Plants - Morocco



Morocco is not a producer of coal, which means it must import the raw material necessary for energy production. This reliance on imported coal subjects the country to international market fluctuations and potential supply chain disruptions. The need to secure and transport coal from foreign sources adds to the complexity and cost of operating coal-fired power plants. In 2022, Morocco imported approximately 12.8 million short tons of coal[21], a slight increase from 12.6 million short tons in 2021. This dependency on foreign coal adds both logistical and financial challenges to maintaining coal-fired generation in the country.

Wind Energy

Morocco's wind energy potential is vast, as illustrated by the wind resource maps[22]. These maps show high wind speeds along the Atlantic coast and in inland areas such as Laâyoune-Sakia El Hamra and the northern regions near Tangier. The darker regions on the map, indicating wind speeds exceeding 10 m/s, highlight the most promising areas for wind energy development. The geographic advantages, combined with the existing infrastructure, position Morocco as a leader in wind energy

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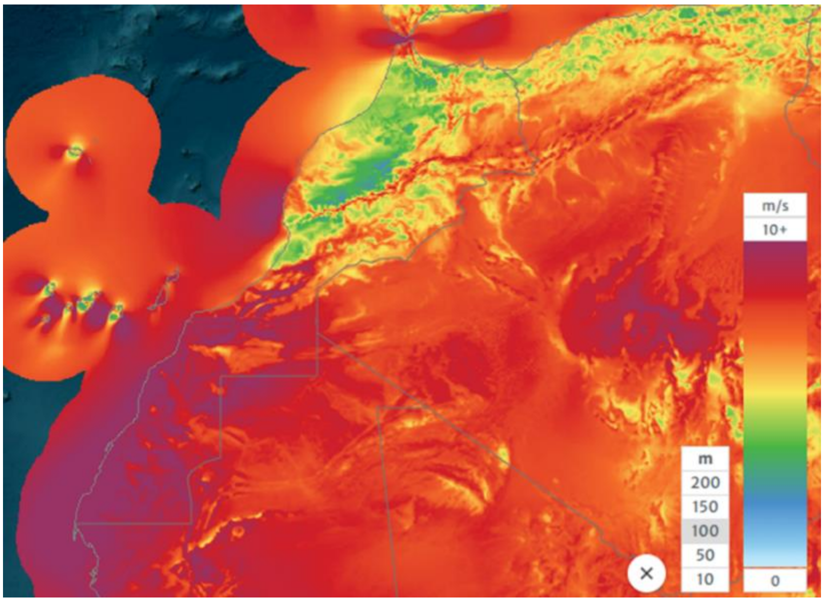
[20] Press conference, 10 May 2024

[21] https://www.theglobaleconomy.com/Morocco/coal_imports/

[22] Global Wind Atlas

within the region. The focus on expanding wind capacity aligns with the country's broader energy strategy to reduce reliance on fossil fuels and increase the share of renewables.

Figure 68 Mean Wind Speed - Morocco



Source: Global Wind Atlas

Morocco's wind energy infrastructure is robust and strategically developed, with wind farms concentrated primarily in regions with high wind potential. According to ONEE, installed wind capacity is 2,071 MW in 2023, divided into 13 operational wind farms. Notable wind farms include the Tarfaya Wind Plant, with a capacity of 301.3 MW, and the Akhfennir Wind Plant, with 197.1 MW. The Boujdour and Essaouira wind plants further contribute to the country's wind energy capacity with 301 MW and 60.4 MW, respectively. The Jbel Lahdid Wind Plant and Midelt Wind Plant are also significant, with capacities of 270 MW (in operation) and 180 MW (in operation), respectively. Koudia Al Baida Wind Farm, with an upgraded capacity of 100 MW, also entered into operation in 2024. In addition, the Essaouira (Amougdoul) Wind Farm, with a capacity of 60 MW, remains operational.

These wind farms are distributed across various regions, including Tanger-Tétouan-Al Hoceïma, Marrakech-Safi and Dakhla-Oued Ed-Dahab. This strategic placement leverages the geographical diversity and high wind speeds in these areas, optimizing energy production and contributing significantly to Morocco's renewable energy mix.

Figure 69 Wind Plants - Morocco

Source: MASEN

Hydropower

Morocco has a well-established hydroelectric infrastructure, comprising both traditional hydroelectric plants and pumped storage facilities.

Traditional Hydroelectric Plants

Morocco's traditional hydroelectric plants are dispersed across various regions, taking advantage of the country's river systems and reservoirs. Some of the key traditional hydroelectric plants include:

- Afourer-1 Hydro Plant: Located in the Béni Mellal-Khénifra region, this plant has an operating capacity of 93.6 MW.
- Al Massira Hydro Plant: Situated in the Casablanca-Settat region, it contributes 128 MW to the grid.
- Al Wahda Hydro Plant: This significant facility in the Tanger-Tétouan-Al Hoceïma region has an operating capacity of 240 MW.
- Allal El Fassi Hydro Plant: Located in the Fès-Meknès region, it also provides 240 MW.
- Bine El Ouidane Hydro Plant: Another major plant in the Béni Mellal-Khénifra region, with a capacity of 135 MW.

Other notable plants include the Idriss the First Hydro Plant in Fès-Meknès (40 MW), the Mohammed V Hydro Plant in L'Oriental (23 MW), and the Talambot Hydro Plant in Tanger-Tétouan-Al Hoceïma (14.1 MW).

Pumped Storage Plants

Pumped storage plants are crucial for balancing supply and demand, particularly when integrating intermittent renewable sources like wind and solar. Morocco has notable pumped storage facilities, such as Afourer-2 Pumped Storage Plant (PSP) with 464 MW, located in the Béni Mellal-Khénifra region, this plant provides significant storage and grid stabilization capabilities. These facilities are strategically distributed to optimize water resources and support regional energy needs. The hydroelectric plants are located along Morocco's major rivers (Al Massira Dam on the Oum Er-Rbia River) and around the central mountainous region, known as the Middle Atlas Mountains.

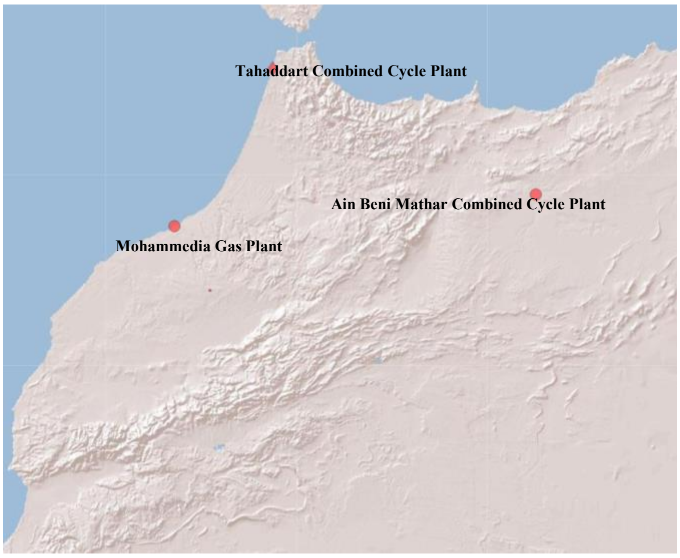
Figure 70 Hydro Plants - Morocco

Source: MASEN

Natural Gas

Morocco's natural gas infrastructure plays a critical role in the country's energy mix, providing essential flexibility. According to the 2023 ONEE statistic, Morocco has several key natural gas power plants, contributing significantly to the national grid. One of the primary facilities is the Ain Beni Mathar Combined Cycle Plant, operated by ONEE. This plant has an operating capacity of 472 MW, utilizes a combined cycle technology, and it is Located near Oujda in the L'Oriental region. The Mohammedia Gas Plant, also operated by ONEE, contributes an additional 412 MW to the grid and it is situated in the Casablanca-Settat region. Another significant facility is the Tahaddart Combined Cycle Plant, a multi-owned project operated by ONEE. This plant, located near Tangier, has an operating capacity of 384 MW,

Figure 71 Gas Plants - Morocco



Source: own elaboration

According to the energy mix report from ONEE, Morocco's total installed capacity for gas turbines is 1,011 MW, while combined cycle plants contribute 834 MW. In addition, ONEE is evaluating proposals for a new 900 MW open-cycle thermal power plant[23]. This plant will operate for five years and utilize dual-fuel gas turbines, with diesel fuel as a backup.

Liquid fuels

Energy infrastructure includes several fuel oil and diesel power plants. According to the 2023 ONEE statistic, the total installed capacity for fuel oil and diesel plants is 525 MW for fuel oil and 316 MW for diesel, these plants are distributed across various regions. Some of the key fuel oil and diesel power plants include:

- Agadir Gas Plant: Located in the Souss-Massa region, this plant has an operating capacity of 40 MW.
- Agadir Internal Combustion Plant: Also, in Souss-Massa, this plant contributes 26.4 MW to the grid.
- Casablanca Steam Plant: Situated in the Casablanca-Settat region, it has a capacity of 152 MW.
- Casablanca Zi Gas Plant: Another significant facility in Casablanca-Settat, with a capacity of 102 MW.
- Kenitra Gas Plant: Located in Rabat-Salé-Kénitra, this plant has an operating capacity of 315 MW.
- Kenitra Steam Plant: Also, in Rabat-Salé-Kénitra, with a capacity of 300 MW.
- Tan Tan Internal Combustion Plant: Located in the Guelmim-Oued Noun region, this plant has a capacity of 117 MW.

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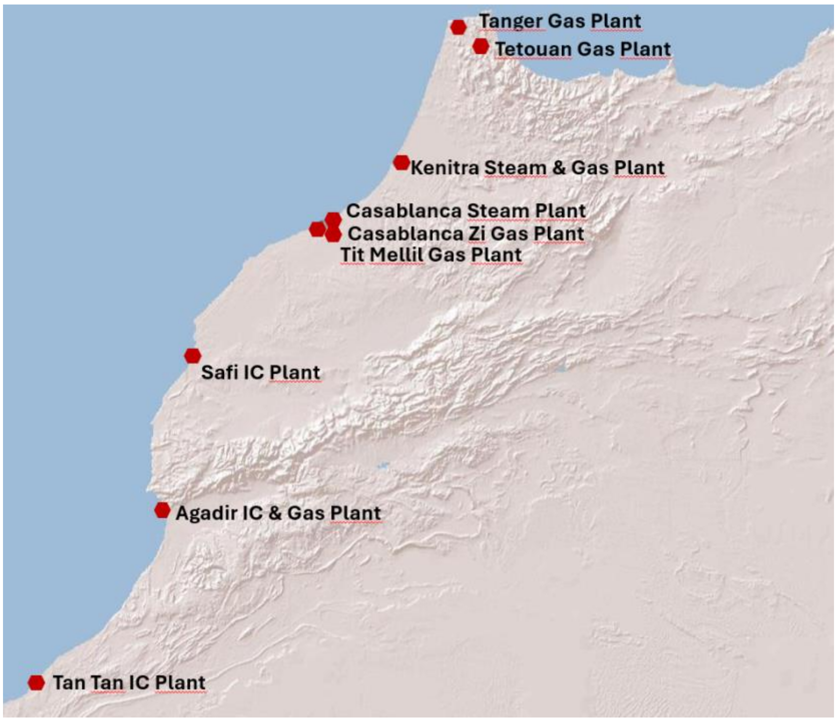
[23] https://www.meed.com/morocco-evaluates-900mw-power-plant-bids

- Tanger Gas Plant: Situated in Tanger-Tétouan-Al Hoceïma, with a capacity of 40 MW.
- Tetouan Gas Plant: Also, in Tanger-Tétouan-Al Hoceïma, with a capacity of 105 MW.
- Tit Mellil Gas Plant: Located in Casablanca-Settat, it contributes 204 MW.
- Safi Internal Combustion Plant: A smaller facility in Marrakech-Safi, with a capacity of 2.2 MW.

These plants utilize various technologies, including gas turbines, steam turbines, and internal combustion engines, to generate electricity. Next figure illustrates the geographic distribution of these fuel oil and diesel power plants across Morocco, some of them located at the same place. These plants are primarily located near the demand centers along Morocco's coast, such as Agadir, Safi, Casablanca, Rabat, and Tangier. This strategic placement ensures that critical regions have access to reliable backup power, enhancing overall grid stability.

Figure 72 Fuel oil and diesel Plants - Morocco



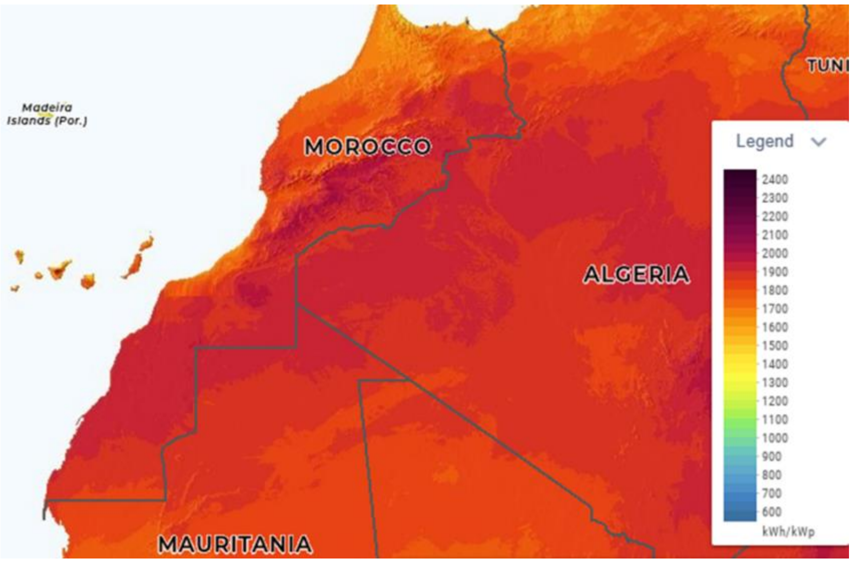
Source: own elaboration

Solar Energy

Morocco possesses substantial solar energy potential, making it a cornerstone of the country's renewable energy strategy. The nation benefits from over 3,000 hours of sunshine annually, with average solar irradiation levels reaching approximately 5 kWh/m²/day. This high level of solar irradiation positions Morocco as one of the most promising regions globally for solar energy development. The country's favorable climatic conditions and extensive sunlight hours provide an excellent foundation for both photovoltaic (PV) and concentrated solar power (CSP) projects. The geographical diversity, from the coastal regions to the inland deserts, allows for varied applications of solar technology, optimizing the energy yield based on local conditions.

The attached figure from SolarAtlas[24] visually represents Morocco's solar resource potential, highlighting areas with the highest solar irradiation. The darker regions indicate higher solar potential, particularly in the southern and southeastern parts of the country, where irradiation can exceed 2,400 kWh/kWp. This abundant solar resource is crucial for Morocco's energy transition goals, aiming to reduce reliance on imported fossil fuels and increase the share of renewables in its energy mix. By leveraging its solar potential, Morocco not only advances its sustainable development objectives but also positions itself as a regional leader in renewable energy.

Figure 73 Solar Irradiation - Morocco



Source: Solar Global Atlas

Morocco has made substantial progress in expanding its solar energy infrastructure. Significant investments in large-scale solar projects, such as the Noor Ouarzazate Solar Complex, have increased the share of solar power in the energy mix. The country has an installed solar capacity of 831 MW. Of this total, 321 MW comes from photovoltaic (PV) power plants, which are dispersed throughout the inland regions of the territory, while the remaining 510 MW are from the Noor Ouarzazate Concentrated Solar Power (CSP) plant. Distributed solar energy, in turn, is beginning to gain relevance as a promising solution to diversify the energy mix and improve electricity access in remote areas, although it still represents a small fraction of the total solar energy generated in the country.

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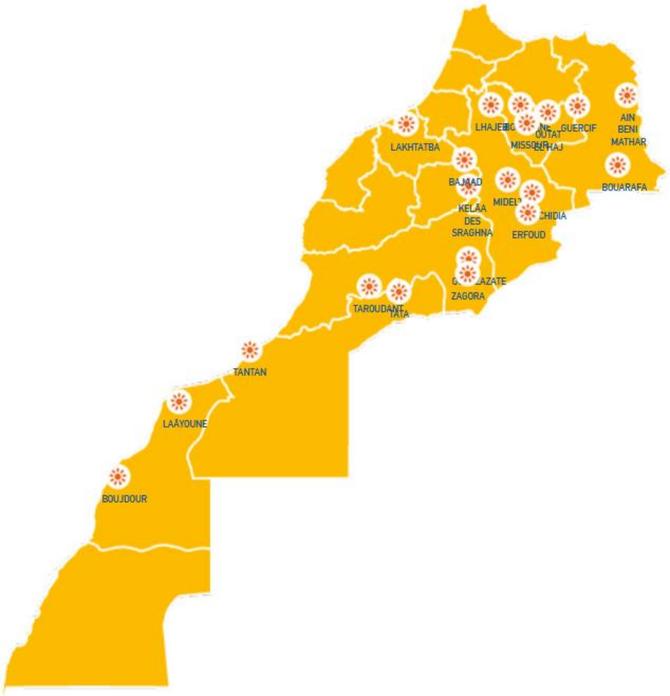
[24] **Global Solar Atlas**

Figure 74 Solar Plants - Morocco



Source: MASEN

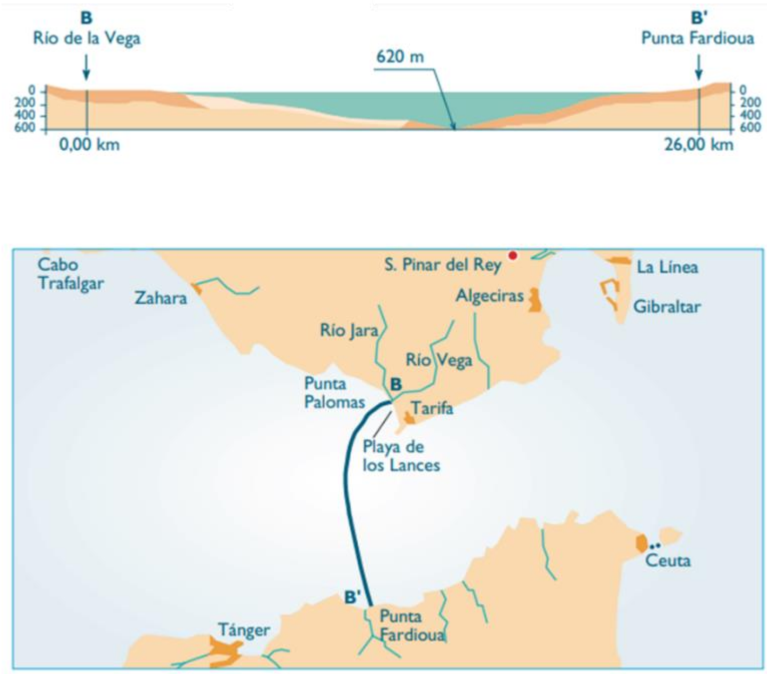
Interconnections

Morocco's grid is currently interconnected with Spain and Algeria. The electrical interconnection between Morocco and Spain is a notable example of energy cooperation between Europe and the southern Mediterranean countries, supported by the European Community. The first interconnection, which began operating in 1997, connects the terminal stations of Tarifa in Spain and Fardioua in Morocco. This initial connection, with a length of 26 km, provided an exchange capacity of 700 MW. In 2006, a second line was inaugurated, doubling the technical exchange capacity to 1,400 MW, allowing a net commercial capacity of 800 MW though. According to Spain's Red Eléctrica, the main reason for this limitation is congestion in the Spanish electrical grid, which prevents the full available capacity from being used efficiently. At certain times, internal demand within Spain can also restrict the flow of electricity to or from Morocco to ensure the stability of its own electrical system.

This infrastructure not only facilitates energy exchange but also improves the frequency and voltage stability of the Moroccan electrical grid and optimizes the technical and economic operation of the energy generation and transmission systems in both countries.
Currently, Morocco and Spain are evaluating proposals for a third interconnection that will enable a greater flow of energy between the two countries. Additionally, future interconnections with Portugal are being explored, which will further consolidate the western Mediterranean electrical grid and enhance the stability of energy supply in the region. These initiatives are part of the REMO

project[25], which aims to increase the security and reliability of electrical supply and promote socio-economic development through closer energy cooperation.

Figure 75 Spain-Morocco Interconnection



The figure above illustrates the geographical and technical layout of the interconnection, highlighting the route from Tarifa, Spain, to Fardioua, Morocco, crossing a maximum depth of 620 meters over 26 km.

Concerning the interconnection between Morocco and Algeria, there are currently two 400 kV transmission lines and two 220 kV transmission lines, theoretically enabling an estimated Net Transfer Capacity of 1000 MW. Unfortunately, the interconnection was suspended due to political tensions between the two countries, particularly related to the Western Sahara conflict. In 2021, Algeria officially severed diplomatic relations with Morocco, which led to the discontinuation of this interconnection. Furthermore, the Maghreb-Europe gas pipeline contract was not renewed. Plans also include an ambitious project interconnecting Morocco with England. The so called “Xlinks Morocco-UK Power Project” is a proposal to create 11.5 GW of renewable generation, 22.5 GWh of battery storage and a 3.6 GW high-voltage direct current interconnector to carry solar and wind-generated electricity from Morocco to the United Kingdom. In addition to this, three other electricity interconnection projects are currently under discussion. The first is with Portugal,[26] involving a planned 1,000 MW HVDC line between Béni Harchane and Tavira, with feasibility and technical studies underway. The second is with France,[27] where a strategic interconnection project

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[25] Proyecto REMO (ree.es)

[26] Press link

[27] Press link

is progressing under a high-level energy cooperation agreement aimed at integrating renewable energy systems and enhancing energy security. The third is with Mauritania,[28] following a memorandum of understanding signed in January 2025 to establish an interconnection that will support regional energy integration, facilitate rural electrification, and promote cooperation in renewable energy development.

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