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Review

Solar Energy Resource and Power Generation in Morocco: Current Situation, Potential, and Future Perspective

Rania Benbba [1], Majd Barhdadi [2], Antonio Ficarella [3], Giovanni Manente [3], Maria Pia Romano [3], Nizar El Hachemi [2], Abdelfettah Barhdadi [4], Ahmed Al-Salaymeh [5] and Abdelkader Outzourhit [1,*]

1 Laboratory of Materials Energy and Environment, Faculty of Sciences Semlalia, Cadi Ayyad University, Marrakech 40000, Morocco; rania.benbba@ced.uca.ma
2 Modeling and Decision Support Systems Team, Mohammadia School of Engineers, Mohammed V University, Rabat 10000, Morocco; majd.barhdadi@research.emi.ac.ma (M.B.); elhachemi@emi.ac.ma (N.E.H.)
3 Department of Engineering for Innovation, University of Salento, 73100 Lecce, Italy; antonio.ficarella@unisalento.it (A.F.); giovanni.manente@unisalento.it (G.M.); mariapia.romano@unisalento.it (M.P.R.)
4 Semiconductors Physics and Solar Energy Team, Energy Research Centre, Ecole Normale Supérieure, Mohammed V University, Rabat 10000, Morocco; abdelfettah.barhdadi@ens.um5.ac.ma
5 Mechanical Engineering Department, School of Engineering, The University of Jordan, Amman 11942, Jordan; salaymeh@ju.edu.jo
* Correspondence: aoutzour@uca.ac.ma

Abstract: The world's attention is currently focused on the energy transition to sustainable energy. The drive to reduce greenhouse gas emissions in order to limit global warming, energy security, and the generalization of access to energy have contributed to the adoption of the Moroccan Energy Strategy, with a strong focus on renewable energy (RE). Morocco is notoriously poor in conventional primary fossil energy resources, with energy dependence on the order of 90%. In addition, the energy crisis that resulted from the COVID-19 pandemic and geopolitical conflicts, compounded with steady increase in demand, has heavily affected the security and stability of the country's energy situation. The transition to RE by strongly engaging in the implementation of several solar, wind, and hydro energy projects has made the country the leader in RE in Africa. These projects benefit from the country's excellent solar and wind energy potential. As a consequence, by 2030, the share of RE in the installed capacity is expected to reach 52%. An overview of the current situation of RE (particularly solar energy) in Morocco is provided, including the potentials, obstacles, challenges, and future perspectives. Thanks to its high solar potential, it is predictable that Morocco's effort will be focused on this field: the Erasmus plus INNOMED project is a virtuous example of international cooperation, aiming at promoting solar energy through capacity building and the creation of solar energy networks, in synergy with EU Partners.

Keywords: solar energy; photovoltaic; CSP; solar thermal; Morocco; renewable energy; sustainable development; strategic investment

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1. Introduction

Population growth, urbanization, and global economic development are gradually increasing the demand for energy. Historically, fossil fuels, particularly coal, natural gas, and oil, have been the main sources of energy to meet these needs. However, fossil-fuel resources are limited, and their exploitation leads to greenhouse gas emissions (CO_2), which contribute directly to global warming, causing devastating effects on a global scale [1].

Coal is the most dominant irreversible energy source worldwide, with a global reserve estimated at 1150 billion tons in 2022. Coal consumption has reached 8.4 billion tons (Bt), of which 5.68 Bt is required for electricity production, while the rest is destined for non-electric uses [2]. Figure 1 summarizes the International Energy Agency (IEA)'s analysis

and prediction of global coal consumption between 2002 and 2026. The IEA estimated a 1.4% increase in coal demand by 2023. China, India, and the ASEAN countries accounted for three-quarters of the global demand. Moreover, coal consumption in China accounts for more than half of the global demand, which is still rising [2]. High dependence on coal for power generation and industrial activities, combined with the country's vast coal reserves, justifies this trend and makes China the world's largest emitter of greenhouse gas emissions [3]. Significant declines are expected in the European Union and the United States between 2024 and 2026 due to the rapid transition to renewable electricity, as well as a reduction in industrial activity.

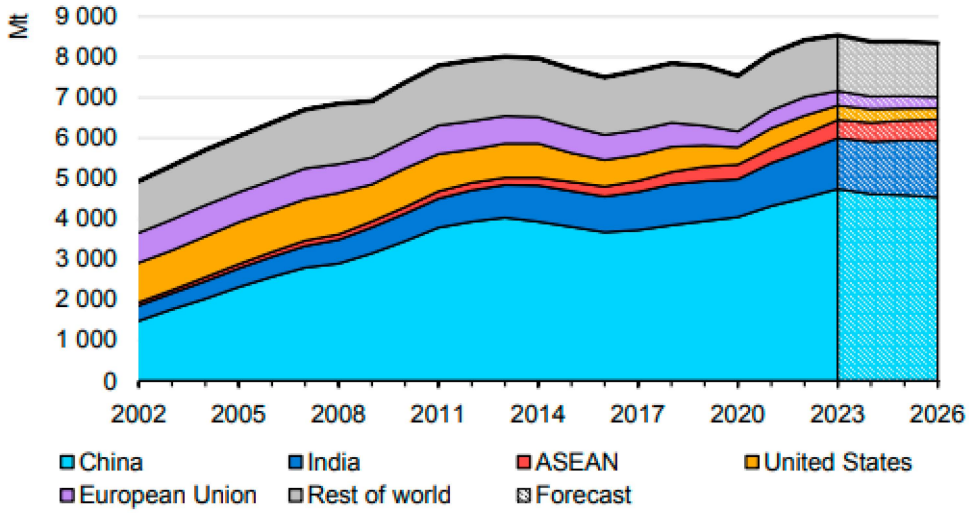


Figure 1. Global coal consumption, 2002–2026. Source: [2].

Natural gas and oil are two other irreversible energy sources concentrated in certain regions of the world and used for electricity generation, heating, transport, and as primary materials in some industrial sectors. Variations in natural gas and oil consumption from 2019 to 2023 for various regions of the world are illustrated in Figure 2 [4]. This figure indicates that the total average annual consumption grew by 1.3% in 2023 compared with 2.2% in 2022, marking a slowdown for the second year running after the recovery in 2021. This trend is explained by the slowdown in the global economy and volatile energy prices observed after the COVID-19 pandemic and the energy crisis. Additionally, volatile fuel costs could lead to economic uncertainty and imbalances in global energy markets. In light of these effects, it is imperative to diversify the energy mix, encourage the adoption of alternative and sustainable energy sources, and accelerate the electrification process worldwide [4]. Investments in RE, such as solar, wind, hydro, and geothermal, are necessary to reduce the dependency on fossil fuels and mitigate the effects of climate change. Effective supply- and demand-side energy management, as well as energy-efficiency measures, will also contribute to reducing the overall energy demand. These align closely with one of the goals of the United Nations General Assembly, which adopted a global development program for the period 2015–2030, raising major challenges on a number of fronts (e.g., clean water and sanitation, quality education, and poverty reduction). In particular, strong emphasis was placed on achieving universal access to reliable, sustainable, modern, and affordable energy services for all. Increasing the share of RE in the global energy mix is one of the key aspects of the program. In addition, diversifying green energy sources aims to increase energy security and resilience while also reducing greenhouse gas emissions. Indeed, the shift to renewable energy is necessary to support sustainable economic growth, enhance public health, and facilitate environmental protection [5].

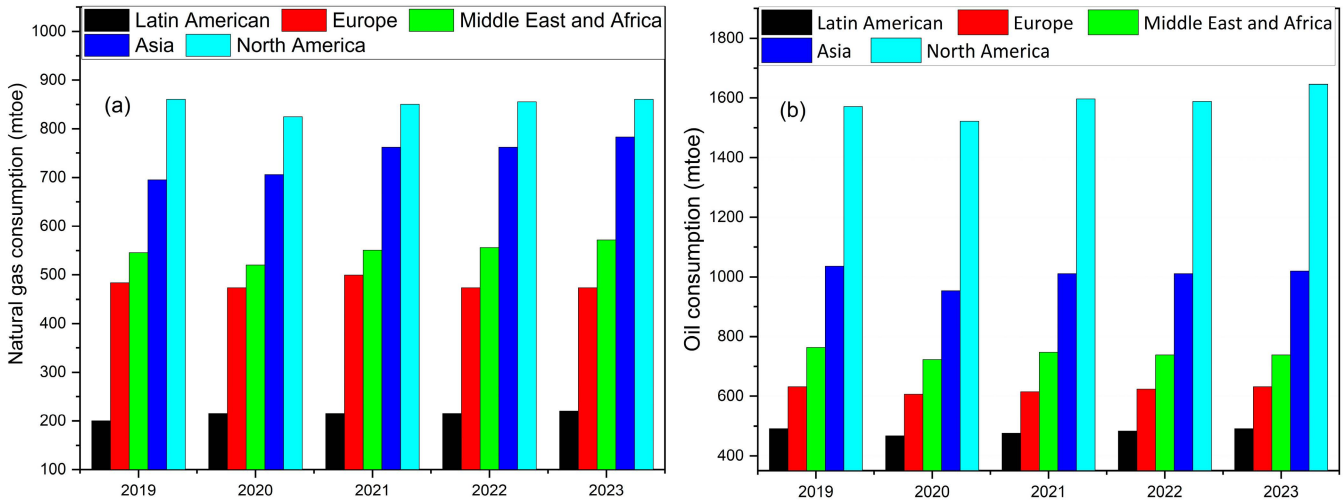


Figure 2. (**a**) Natural gas and (**b**) oil consumption by regions, 2019–2023. From the Economist Intelligence Unit, International Energy Agency. https://www.rivistaenergia.it/2023/01/6-tendenze-dellenergia-nel-2023-secondo-economist-intelligence/ Accessed on: 5 August 2024.

The world's attention is currently focused on the energy transition, characterized by the rise in the share of RE for electricity production with an additional emphasis on energy efficiency. According to the International Renewable Energy Agency (IRENA), the world's average renewable electricity capacity rose to 3865 GW at the end of 2023, an increase of almost 14% compared with the end of 2022 [6]. In 2023, a significant increase in the installed capacity was recorded. This is attributable to the adoption of new systems and technologies [6]. The solar and wind power sectors have enjoyed increased growth, driven by high energy prices and favorable government policies. In addition, carbon capture and storage (CCS) technologies have gained interest in recent years, thanks to the commitment of several companies and the political support of governments. In particular, several decarbonization projects will be commissioned, thus increasing carbon capture and storage by 2.3 million tons per year [4,7]. At the same time, the production of green hydrogen has gained strength, particularly in Europe following the REPOWEREU strategy, as well as in developing countries such as Morocco [4], and will certainly boost the share of renewables in the energy mix.

At a continental level, Africa remains the least electrified region globally, with certain areas still grappling with electrification challenges compounded by the effects of climate change. According to IRENA, the total RE capacity in Africa reached 62.1 GW in 2023, marking a 4.6% increase from 2022. This capacity accounts for a mere 1.6% of the world's installed renewable electricity generation capacity [6]. Despite these challenges, the efforts of African nations in energy development show promise and perseverance amidst increasing demographic pressures, the urgency of climate change, and the need for substantial investment.

According to the African Union Commissioner for Infrastructure and Energy, Morocco is positioned as the African leader in RE and as an increasingly important player on the world stage [7]. Taking advantage of its vast potential in sustainable resources, particularly solar and wind, Morocco initiated RE projects as early as 2009 and 2010, with the launch of two national programs aimed at integrating solar (2 GW) and wind (2 GW) electricity by 2020. The country heavily invested in RE infrastructure, such as the Noor Ouarzazate complex, with a capacity of 580 MW, representing one of the world's largest CSP power plants. REs have increasingly become the focal point of strategic and policy discussions in Morocco. The country reinforced these efforts by accelerating the energy transition with various reliable and competitive technologies to address energy security and environmental protection. Overall, since the adoption of the Moroccan Energy Strategy (MES) in 2009, the installed electrical power capacity has grown at a global growth rate of 74.2%, increasing from 6.34 GW in

2010 to 11.05 GW in 2022 (Figure 3). This growth is partly attributable to the share of RE, accounting for 37.6% of the total installed capacity in 2022, which is equivalent to 4154 MW (including wind, solar, hydro, and pumped hydro storage technologies) [8]. The wind and solar capacity installed in 2022 represented 37.4% and 20%, respectively, in the RE mix [8]. By 2030, Morocco aims to raise the share of RE to 52% of the installed capacity, with a reduction in greenhouse gas emissions by 18% [9,10]. In parallel, the gradual liberalization strategy of the electricity sector (since 1994) and the establishment of a favorable regulatory and institutional framework for RE development encourage public–private investment at both national and international levels. The country also launched the National Investment Pact, aimed at enhancing private-sector involvement in investment and reaching MAD 550 billion (equivalent to approximately to USD 53.9 billion) by 2026 [8]. This initiative will undoubtedly intensify and accelerate the energy transition by supporting RE development projects, seawater desalination, and the emerging green hydrogen sectors, which are promising sectors requiring substantial investments. However, the large-scale integration and development of solar energy in Morocco faces a number of challenges. Indeed, massive deployment of intermittent RE sources into the electricity grid requires investment in power-system flexibility, including energy storage, grid management, and eventually cross-sector coupling through the development of power-to-X in order to mitigate the effects of uncertainty in supply (intermittence) and demand (absence of demand-side management). Financing solar energy projects is also still a challenge, particularly for developing countries [11].

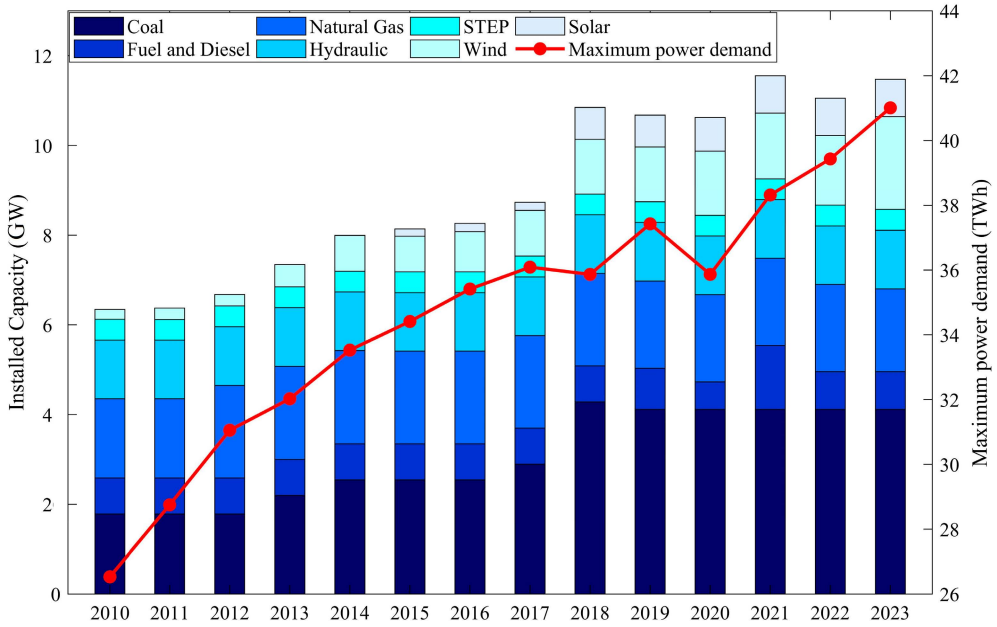


Figure 3. Installed capacity by energy source in MW and maximum power demand in MW (2010–2023) in Morocco. Data from: http://www.one.org.ma/ Accessed on: 5 August 2024.

The wide exploitation of RE and solar in particular represents a significant opportunity for Morocco to reduce its reliance on fossil fuels, contribute to combating climate change, and foster sustainable economic development. Since the launch of renewable energies in Morocco, several articles have delved into the country's energy potential, emphasizing the development of the national energy strategy as well as the future outlooks and barriers to be addressed [12,13]. A more recent analysis of energy sources (including solar, hydroelectric, tidal, wave, and geothermal) and their potential in Morocco was presented by Nakach et al. [14]. Additionally, Boulakhbar et al. [15] examined a scenario for 2030 regarding the Moroccan electrical system and identified challenges to accelerate the integration of renewable energies into the Moroccan energy mix. Kettani et al. [16] highlighted ambitious

prospects in solar energy that will enable the country to become a regional leader and proposed a typology of possible trajectories.

The present work provides a comprehensive analysis of the renewable energy situation, particularly solar energy, in Morocco. It evaluates the developments in renewable energies within the framework of the national energy strategies, as well as the barriers to achieving the objectives outlined, especially after the delays caused by the global health and energy crises. By demonstrating Morocco's solar energy potential, we have detailed the development of large- and medium-scale solar projects. In parallel, the document outlines the policies and regulations involved in the development of RE sources, as well as the challenges facing it and the promising prospects ahead. The remainder of this paper is organized as follows. Section 2 presents an overview of Morocco's energy landscape. Section 3 presents the solar resource potential in Morocco. Section 4 gives the current state of solar energy in Morocco, including the policies and regulations, the installed capacity, the investments, and the challenges. Section 5 presents an outlook on solar energy in Morocco.

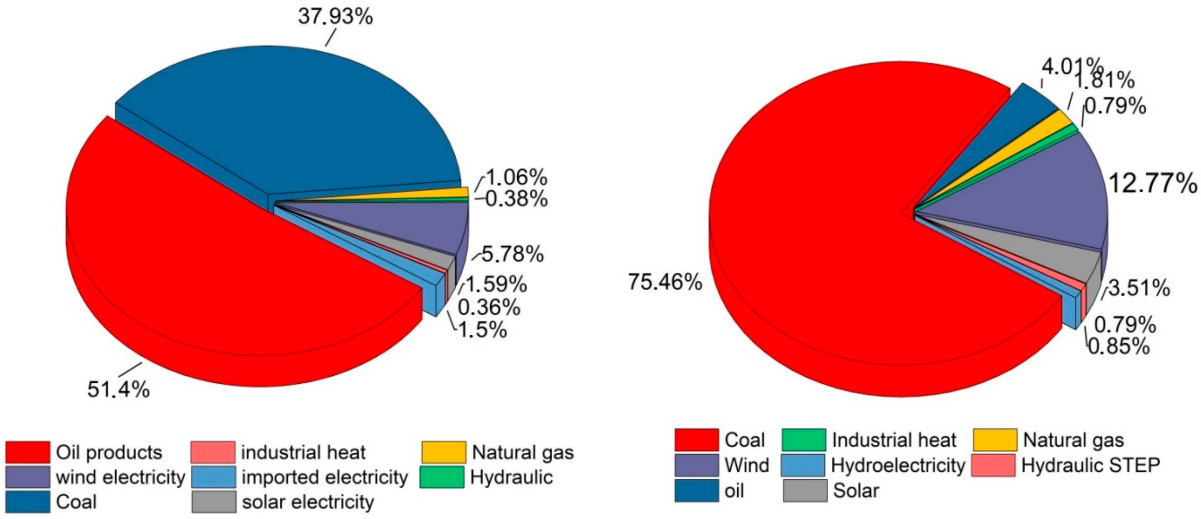
2. Overview of Morocco's Energy Landscape

In the absence of yet-to-be-exploited major fossil-fuel reserves in the country, Morocco's energy sector heavily depends on imported fuels. As such, the Moroccan government endeavors to increase the security of supply by reducing its dependency on energy imports, primarily through increasing the use of renewables for electricity generation, as stressed in the MES put forward in 2009.

2.1. Moroccan Energy Sector in Numbers

With limited domestic oil and natural gas resources, Morocco is energy-poor in terms of fossil fuels, a situation that poses a significant threat to the country's energy security and independence. According to the World Bank and the High Commission in Planning (HCP), approximately 90% of Morocco's primary energy relies heavily on imported fossil fuels (refined oil, gas, and coal). The total primary energy consumption has been increasing at a rate of approximately 5% per year since 2004 [17]. The total primary energy demand in 2022 was 23.37 million tons of oil equivalents (Mtoe), a significant increase of 35.3% compared with 2009 (15.1 Mtoe). Oil products dominated with 51% of the demand (12,237 Mtoe), closely followed by coal with 38% (9031 Mtoe), while primary energy from renewable sources accounted for 8.8% of the total. The total energy produced was 41.41 TWh, of which 22% was generated from renewable sources. The distribution of national primary energy demand and the total energy consumption of electricity is shown in Figure 4a,b, respectively. A detailed analysis of the total energy consumption in Morocco for 2021/2022, as well as forecasts for 2023, is provided by [18–20]. Recent figures can be found in the annual reports of the National Office of Electricity and Drinking Water (ONEE) and the High Commission in Planning [21].

To meet growing electricity demand and address the challenges posed by expanding RE, Morocco aims to diversify its energy sources by increasing the use of liquefied natural gas (LNG). In May 2021, the Moroccan Office of Hydrocarbons and Mines (ONHYM) started plans for an integrated floating storage regasification unit (FSRU) terminal. The ONHYM intends to issue tenders or explore public–private partnership (PPP) options in the future. The initial goal of the FSRU project in Morocco was to meet an annual natural gas requirement of 1.1 billion cubic meters (bcm) by 2025, rising to 1.7 bcm in 2030 and 3 bcm in 2040. Additionally, a roadmap for natural gas development (2021–2050) unveiled by the Moroccan Ministry of Energy, Mines, and the Environment in August 2021 prioritized industrial needs while gradually integrating domestic and electricity generation requirements. As a net energy importer, Morocco seeks to reduce reliance on foreign oil and coal by attracting investment in oil and gas exploration [22]. The government has proactively embarked on a series of long-term and medium-term strategic plans. These plans prioritize exploring all available RE sources to enhance energy security by reducing dependence on imported fuels and safeguarding the environment.



(**a**) (**b**)

Figure 4. (**a**) Distribution of primary energy demand in 2022. (**b**) Total energy consumption in Morocco in 2022. Data from: [20].

2.2. Moroccan Energy Strategy

The Moroccan Energy Strategy launched in 2009 is one of the main sectorial strategies based on the development of RE as a national priority, the improvement of energy efficiency, and regional integration. It is a roadmap toward energy independence based largely on RE. The strategy's four principal objectives are to strengthen the security of supply, generalize access to energy at competitive prices, control demand, and, lastly, preserve the environment. One of the strategy's orientations toward large-scale development of RE is the ambition to achieve a share of 42% by 2020, 52% by 2030, and 70% by 2040 in the national electrical capacity mix [23].

The first objective has not yet been achieved, as the share of RE capacity installed and connected to the grid by the end of 2021 stood at 37.08% of the country's total electricity mix, which is 5% below the target set [24]. This was due to the impact of COVID-19 on Morocco's energy sector, as well as on the rest of the world. Confinement and curtailment of industrial and tourist activities led to disruption of supply chains. Rising prices of fossil fuels and energy equipment contributed to inflation and the stagnation in investments and RE project deployment. As a consequence, the demand for electricity in 2020 fell by 8.5% compared with 2019. However, the installed capacity remained almost the same (10.6 GW), distributed as follows: 1430 MW of wind capacity, 751 MW of solar capacity, 464 MW of pumped hydro capacity, 6974 MW of thermal capacity, and 1306 MW of hydroelectric capacity. In addition to the pandemic, the geopolitical crisis (the war in Ukraine) has highlighted the risk of fossil-fuel supply, which underlined the importance of accelerating the transition to RE [25].

The Moroccan energy sector began to show signs of recovery in 2021, with electricity production increasing by 6.5% after a 3.9% decline in 2020. Moreover, there was a 19.6% decrease in the volume of imports alongside a 36.5% increase in exported volume [24]. Additionally, it should be noted that the share of RE in the national electricity mix reached 38% in 2022 and surpassed 40% in 2023. By the end of 2023, the total installed capacity reached 11.47 GW, representing an increase of approximately 400 MW compared with 2022 [26]. This increase included the commissioning of 500 MW of wind energy, of which 300 MW was from the Boujdour wind farm (as part of the integrated wind energy program of 850 MW) and 200 MW from the "Aftissat 2" project (under Law 13-09).

Overall, it can be observed that the MES led to an 80.9% increase in the total installed capacity in 2023, compared with 2010, and a 7.97% increase compared with 2020. The maxi-

mum power demand reached 7400 MW in 2023, marking a 2% increase over the year. The total electricity production amounted to 42.409 TWh, with 9.2 TWh originating from ONEE facilities. RE accounted for 20.9% of the national demand satisfaction, which is equivalent to nearly 8863 GWh. Figure 5 summarizes the development of the Moroccan electricity sector in terms of installed capacity in GW, total electricity production in TWh, and the share of RE in the total installed capacity, spanning from 2010 to the last three years after the global energy crisis. In addition, this figure illustrates the main projects contributing to the progress of each year.

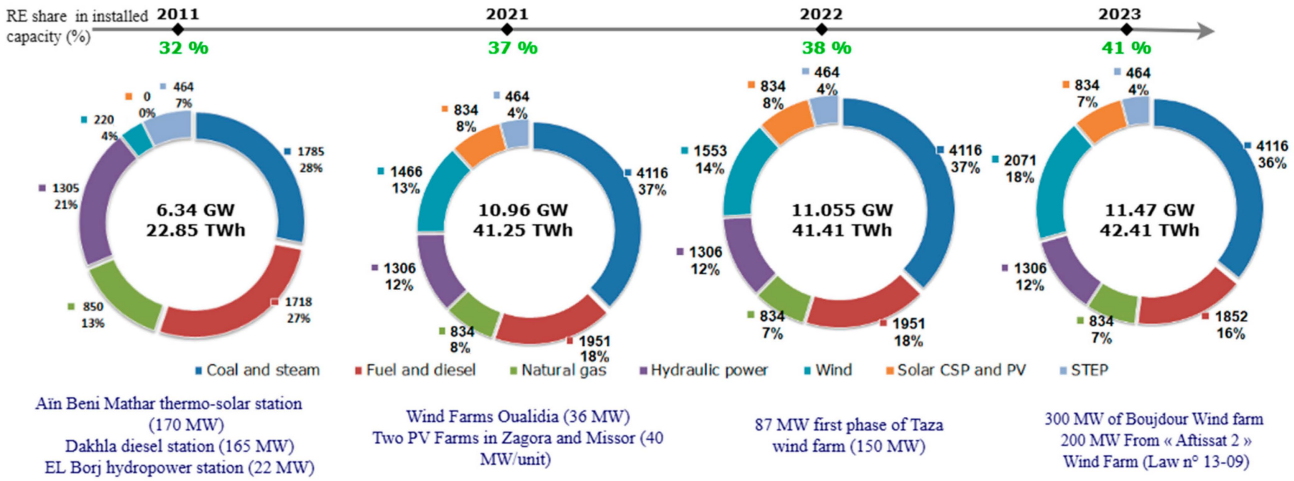


Figure 5. Evolution of the installed energy capacity by source between 2011 and 2023.

The National Electricity Regulatory Authority (ANRE) has examined the evolution of the national production by energy sources between 2010 and 2022, as depicted in Figure 6. The use of coal has experienced a continuous rise, with an annual growth rate of 8.5%. Conversely, electricity production from natural gas has seen a decline of 11.5% on average annually over the same period, with a sharp and significant drop of 80.3% noted between 2021 and 2022. This is attributed to the end of the Maghreb Europe gas pipeline contract at the end of 2021 and the global crisis that affected the natural gas sector. To address the resulting security of supply in the electricity sector, the use of fuel oil and diesel in electricity production was intensified.

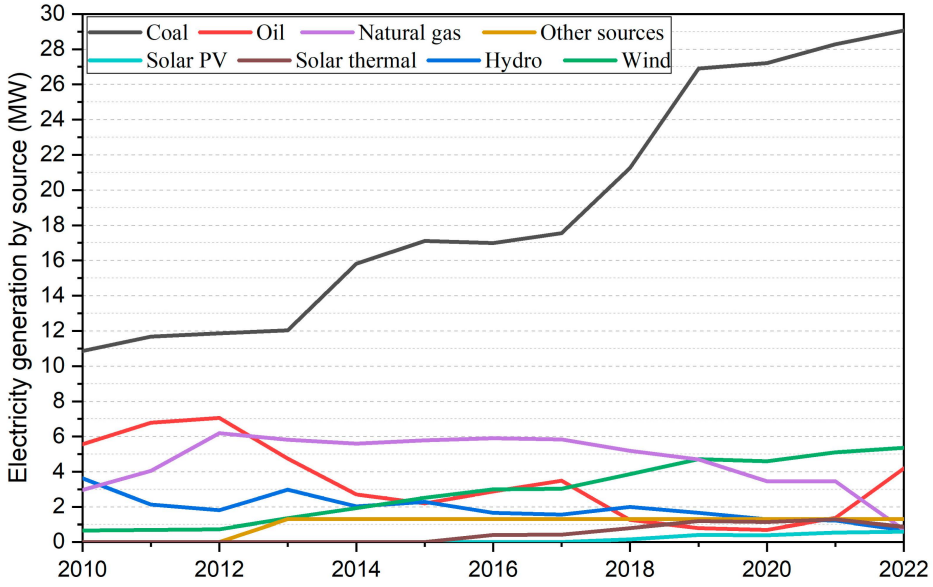


Figure 6. Evolution of national electricity production by energy source in GWh (2010–2022). Data from [8].

Figure 6 demonstrates that Morocco's dependence on coal for electricity production increased by approximately 6.5% between 2010 and 2022. The use of fuel oil and natural gas showed a gradual decline, while renewable energy sources gradually took a larger share. Wind power contributed 5.3 MW in 2022, followed by solar energy with 1.45 MW, and hydroelectric power with around 0.7 MW. According to the ANRE report [8], solar energy achieved an impressive compound annual growth rate (CAGR or TCAM, taux de croissance annuel moyen) of 63.4% in terms of the amount of solar electricity injected into the grid between 2010 and 2022. Similarly, wind energy registered a CAGR of 19.1%, while pumped storage (STEP) recorded a growth rate of 6% during the same period. This is attributed to the success of the MES in harnessing the country's solar and wind potential through the development of many projects (detailed in Section 3). The country hosts one of the largest solar complexes, NOOR, spanning an area of 6000 hectares, which required investments exceeding MAD 24 billion (equivalent to approximately USD 2.4 billion). It is divided into four stations where large-scale photovoltaic (PV) and concentrated solar power (CSP) technologies are used, with a total installed capacity of 580 MW. The first plant of this series (NOOR 1) was launched in 2016, followed by the others two years later. Regarding wind energy, several projects were implemented, particularly in the southern regions, where the largest wind farm in Africa (300 MW) is located in Tarfaya and became operational in 2014. Currently, wind power is considered the champion in RE, surpassing solar energy. Both sectors foresee continuous advancements, particularly with the development of other scheduled projects such as the 1600 MW Nour Midelt solar project with storage, the six plants under the Noor Atlas solar program (300 MW), and the completion of the Nassim Koudia Al Baida wind farm (100 MW). With these considerations, significant efforts have yet to be deployed to achieve the government's target of raising the share of RE to 52% by 2030. It is noteworthy that solar and wind projects are distributed across various regions of the country. This ensures sustainable regional development, leading to increased electrification rates and a fair distribution of socio-economic impacts. The report from ONEE indicates the success of the overall Rural Electrification Program (PERG), which electrified 99.88% of rural areas by the end of 2023 [26]. The program used individual photovoltaic kits to electrify approximately 51,599 households in villages far from the electrical grid.

Furthermore, the building sector stands out as the largest consumer of energy, followed by the industrial sector and then agriculture. It consumes approximately 36% of the total energy, with the residential sector alone accounting for 25% [27]. Consequently, Morocco has shown its commitment to energy efficiency as a cornerstone of its adopted energy strategy. It targets a 20% energy saving by 2030, including action plans to reduce energy consumption in the transportation (−24%), building (−14%), industrial (−22%), agricultural, and public lighting (−13%) sectors [28].

The electricity sector is the leading emitter of greenhouse gases in Morocco [29]. These emissions are primarily due to the significant dependence of the electricity sector on thermal power plants (coal, natural gas, fuel oil, and diesel). However, the rapid transition from fossil fuels to RE is an imperative that Morocco has already begun, along with the development of de-carbonization strategies for its industry. As a result, the kingdom has secured first place in Africa and ninth in the European Union countries in the 19th Climate Change Performance Index 2024 (CCPI). This report allows for the visualization and comparison of the climate protection efforts and progress made by the countries. It is based on scores in greenhouse gas emissions, RE, energy consumption, and climate policy [30].

The country's determination to ensure its energy security by promoting the development of RE and energy efficiency is reflected in the implementation of several energy plans and strategies [31]. Alongside this, the government is pursuing a continuous evolution of the regulatory and institutional framework of the energy sector (particularly laws and regulations related to RE integration) in order to facilitate the integration into the national grid and improve private-sector investments in RE projects in a secure and viable manner (the main RE laws and amendments are detailed in Section 4.1) [32]. Morocco has stepped

up its efforts as part of its national energy strategy by planning to invest MAD 54 billion (≈USD 5.4 billion) in RE projects by 2030 [11]. Furthermore, the launch of the National Investment Pact, aimed at boosting the private sector's contribution to investment to MAD 550 billion (≈USD 55 billion) by 2026 was also launched [8].

2.3. Moroccan Green Hydrogen Strategy

Due to its strategic geographical position and abundant resources in RE, Morocco also has the potential to become a regional key player in the development of the green hydrogen sector and could capture up to 4% of the global demand for green molecules [33]. The objective is to position Morocco as a green hydrogen technological hub. The establishment of economic and industrial sectors around green molecules, particularly hydrogen, ammonia, and methanol, will contribute to reducing greenhouse gas emissions (up to 20%) and support the de-carbonization efforts of the country and other partner countries. In the reference scenario, domestic demand for green hydrogen and its derivatives is estimated to reach 4 TWh in 2030, 22 TWh in 2040, and 40 TWh in 2050 [34]. Export demand is estimated at 10 TWh in 2030, 46 TWh in 2040, and 115 TWh in 2050 [35]. The RE capacity required to meet these demands is estimated at 8 GW for 2030, 36.7 for 2040, and 78.2 for 2050. This will require a cumulative investment of MAD 90 billion (USD 9 billion) by 2030 and MAD 762 billion (USD 76.2 billion) by 2050. This roadmap presents significant prospects for industrialization across the entire value chain, including desalination, RE (photovoltaic and wind), electrolysis, and green chemistry. A National Hydrogen Commission involving all stakeholders will coordinate the implementation of this roadmap through technological development, investments, infrastructure, and markets. The Commission will also contribute to structuring the optimal deployment of the hydrogen sector within the country by facilitating investment inflows and the development of PtX (power-to-X) projects through the establishment of favorable regulatory, legislative, and fiscal measures.

As Morocco is one of the largest importers of ammonia, the country also endeavors to become a leader in the production of green ammonia to fulfill the long-term demands of its domestic and foreign fertilizer markets. To this end, OCP (Office Chérifienne des Phosphates), which is in charge of the phosphate industry, has set up the new green investment plan with two targets: (a) green ammonia, aiming for the production of 1 million tons by 2027 and 3 million tons by 2032; (b) green energy, targeting 5 GW of clean energy by 2027 and no less than 13 GW by 2032.

Furthermore, exporting methanol and other synthetic fuels will meet the demand of several European partner countries. In the long term, sectors such as heavy and maritime transportation and aviation can also be decarbonized through the utilization of green hydrogen. Other applications such as urban mobility, industrial heat, energy storage, and methane substitution for cooking can be decarbonized in the medium term through the use of synthetic fuels. A capacity-building program, research, and innovation in the field of green hydrogen will accompany industrial integration and enhance the competitiveness of national enterprises through the formation of qualified human capital, the preparation of local subcontracting, and the development of national champions. Power-to-X and cross-sector coupling will, therefore, play a major role in the massive deployment of intermittent RE sources into the electricity grid.

The action plan of the hydrogen roadmap includes the following eight measures: (a) cost reduction throughout the value chain of green hydrogen and its derivatives; (b) creation of a Moroccan and regional research and innovation hub; (c) promoting measures to ensure local industrial integration; (d) establishment of an industrial cluster and development of a master plan for corresponding infrastructure; (e) ensuring financing for the hydrogen sector; (f) creation of favorable conditions for the export of green molecules; (g) development of a storage plan; (h) development of domestic markets [MEM].

2.4. Electricity Sector Organization

Morocco's electricity sector has been progressively liberalized since the 1990s. This liberalization laid the foundations for investment by independent power producers in accordance with Decree-Law 2-94-503. Subsequently, Law 16-03 introduced self-generation, thus enabling large industrial users to generate their own electricity for internal consumption, notably for power plants with a capacity of less than 50 MW, and to sell a limited surplus of electricity to the National Office of Electricity and Drinking Water (ONEE). In 2009, the government launched the process of creating a competitive market for RE, now open to private investors under Law 13-09. This law authorizes electricity transactions between private individuals for RE projects and requires third-party access to ONEE's transmission network. In addition, the self-generation was extended with the removal of the 50 MW limit, thus integrating this sector into the new open market. Law 13-09 also allows small-scale renewable projects to sell their surplus electricity to ONEE and large industrial customers, either through a consortium of consumers with access to extra-high voltage (EHV) and high voltage (HV) transmission lines, or through public distribution utilities [36].

The Moroccan government has prioritized the growth of the RE sector by strengthening the role of the Moroccan National Agency for Solar Energy (MASEN) (now the National Agency for Sustainable Energy) in developing and implementing RE projects, as well as streamlining the authorization process for these projects. MASEN, created under Law 57-09 in 2010, operates as a public limited company with a Board of Directors and a Supervisory Board and is placed under the administrative and technical supervision of the Ministry of Energy Transition and Sustainable Development. It provides a "one-stop shop" for private project developers, covering all aspects of permitting, land acquisition, and financing, as well as a state guarantee for the investment [37].

Nowadays, Morocco's electricity market has a hybrid structure, combining a regulated market dominated by ONEE, independent power producers (IPPs), and MASEN's public–private partnerships, with an open market welcoming RE producers and self-generators. The various public and private players are involved in activities such as generation, transmission, and distribution to meet electricity needs, as illustrated in Figure 7 [36].

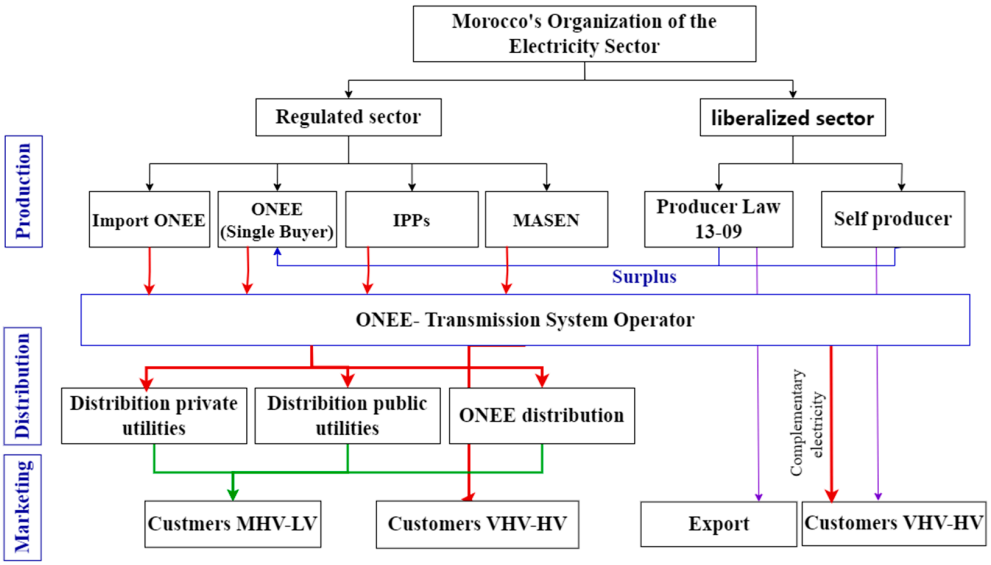


Figure 7. Current organization of Morocco's electricity sector, divided into a regulated sector and a liberalized sector. Arrows indicate the flow of electricity and responsibilities. Red arrows show the path of electricity received or output directly (to distributors or consumers) by ONEE as a single transport system. Green arrows: Indicate the paths for distributing electricity to customers in the medium-voltage (MV) and high-voltage (HV) segments, highlighting the distinction between private and public companies. Blue arrows: Represent the flow of electricity between the private producer and the various receivers. Source: [36].

ONEE is the central player in Morocco's electricity sector. It is the only authorized wholesale buyer and the only authorized reseller to distribution companies. ONEE is also responsible for grid management, planning, and maintenance of the Moroccan electricity system, ensuring that electrical energy is transported from production plants to consumption centers under the best conditions of safety and efficiency.

Independent power producers (IPPs) can also sell RE electricity to a consumer or consortium of consumers through access to extra-high voltage (EHV), high voltage (HV), and, under certain conditions, medium voltage (MV). IPPs are linked to ONEE through long-term power-purchase agreements. The concessionary power producers include Jorf Lasfar Energy Company (JLEC) with a capacity of 2080 MW, Compagnie Eolienne du Détroit (CED) with 54 MW, and SAFI Energy Company (SAFIEC) with 1386 MW.

A list of the various players in the development of the energy sector in Morocco is presented in Appendix A.

3. Solar Resources Potential in Morocco

The performance of a solar system is closely linked to the characteristics of solar radiation in a specific location. These are obtained from the solar resources, which are influenced by factors such as latitude, climatic conditions, topography, season, and time of day [38]. Typically, a horizontal surface will receive two main components of solar irradiance: the direct component and the diffuse component. The direct component, particularly the DNI (direct normal irradiance), comes directly from the sun. This component is particularly useful in concentrated solar power (CSP) or concentrated photovoltaic systems, where it can be focused to maximize energy production. The diffuse component, known as DHI (diffuse horizontal irradiance), corresponds to the irradiance received on the horizontal plane from all other directions in the sky. Global horizontal irradiance (GHI) is the sum of the direct and diffuse components of solar radiation. A thorough understanding of these components is crucial to the efficient design and optimal management of solar systems [38].

Morocco is located in a high-solar-potential region. Its territory benefits from an average of 3000 h of sunshine per year, with up to 3600 h in the desert. The daily sunshine duration ranges between 5 and 6 h in winter and 11 and 12 h in summer. It should be noted that sunrise and sunset times vary from one city to another, depending on their distance from the equator. Figure 8 shows the sunrise times and the monthly average duration of sunshine for Marrakech, Morocco [39]. This city is located at a latitude of 31.63 degrees north and has a semi-arid Mediterranean climate characterized by hot, dry summers and mild winters.

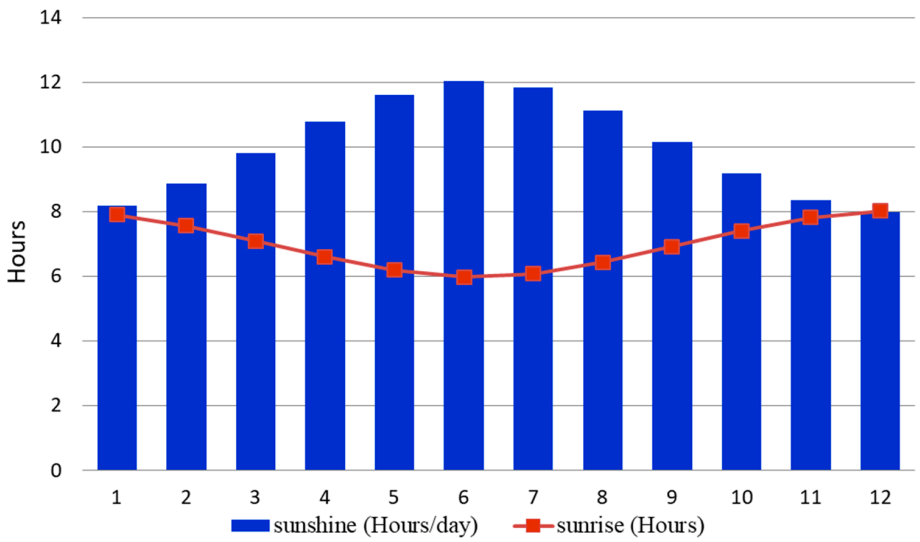


Figure 8. Approximate average monthly sunshine duration and sunrise times in the case of Marrakech, Morocco. Source: [39].

The global horizontal irradiance (GHI) shows a daily average of 5.8 kWh/m^2/day, with an annual global irradiance between 1800 and 2500 kWh/m^2 [40] (Figure 9). The lowest values are found in some coastal areas, while the highest values are found in the south of the country. From Figure 8, seven zones can be distinguished; each zone is characterized by approximately the same amount of irradiation, the same altitude, and other performance indicators [41]. Bouhal el al. [41] mapped Morocco in accordance with climate zoning in order to compare the energy generated by concentrated solar power (CSP) systems, particularly parabolic trough systems. The results confirmed the cost-effectiveness of this technology on a large scale (less expensive and more productive). The best results were obtained in the zone with GHI levels of over 5.57 kWh/m^2/day, which includes Errachidia, Taroudant, Ouarzazate, Smara, and Bouarfa [41]. In addition, these regions offer a high direct solar irradiation (DNI), making them attractive for concentrated solar power (CSP) technologies, such as those employed in Ouarzazate. Figure 10 shows the DNI solar map of Morocco. The values range from 1800 to 3000 kWh/m^2/year [42], while commercially viable CSP plants should maintain a DNI of at least 2000–2800 kWh/m^2/year [15]. Morocco ranks among the top countries in the world in terms of the highest DNI.

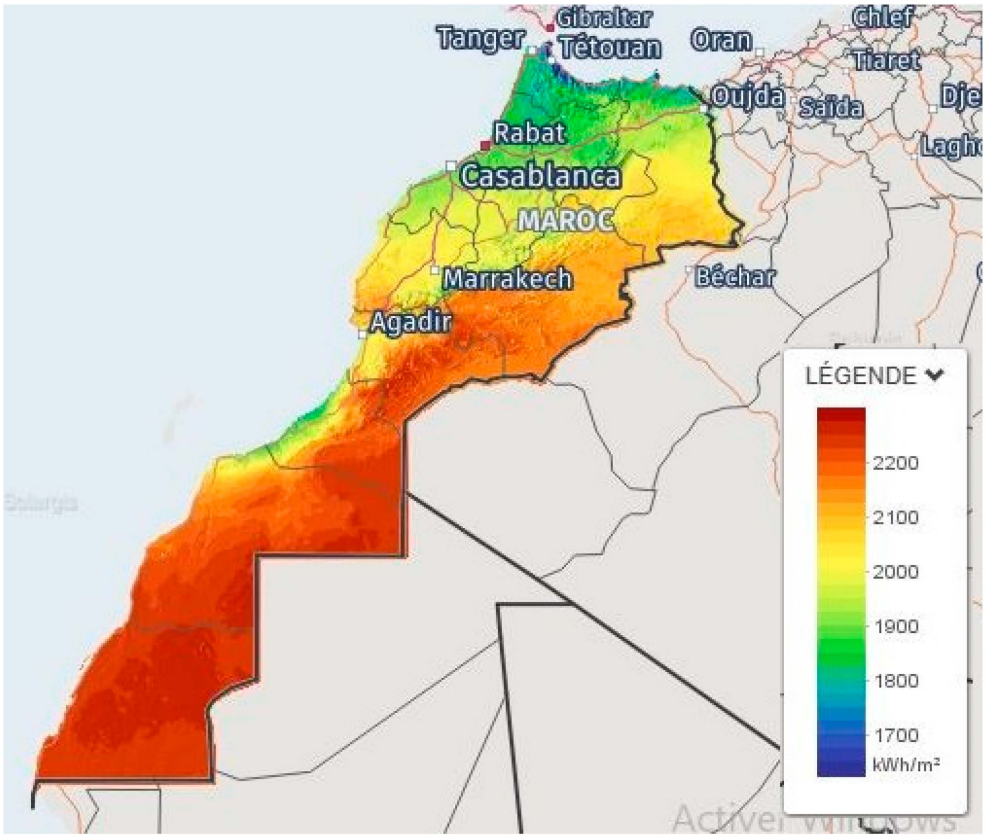


Figure 9. Map of yearly global horizontal irradiation in Morocco (kWh/m^2/day). Source: [43] https://solaratlas.masen.ma/.

Figure 11 shows the potential for photovoltaic energy in most regions of Morocco. PVOUT (photovoltaic Output) is an indicator (kWh/kWp/year) that evaluates the potential solar energy production per unit of solar panel capacity installed over a long period. The average annual PVOUT in Morocco ranges from 1600 to 1900 kWh/kWp/yr depending on the location.

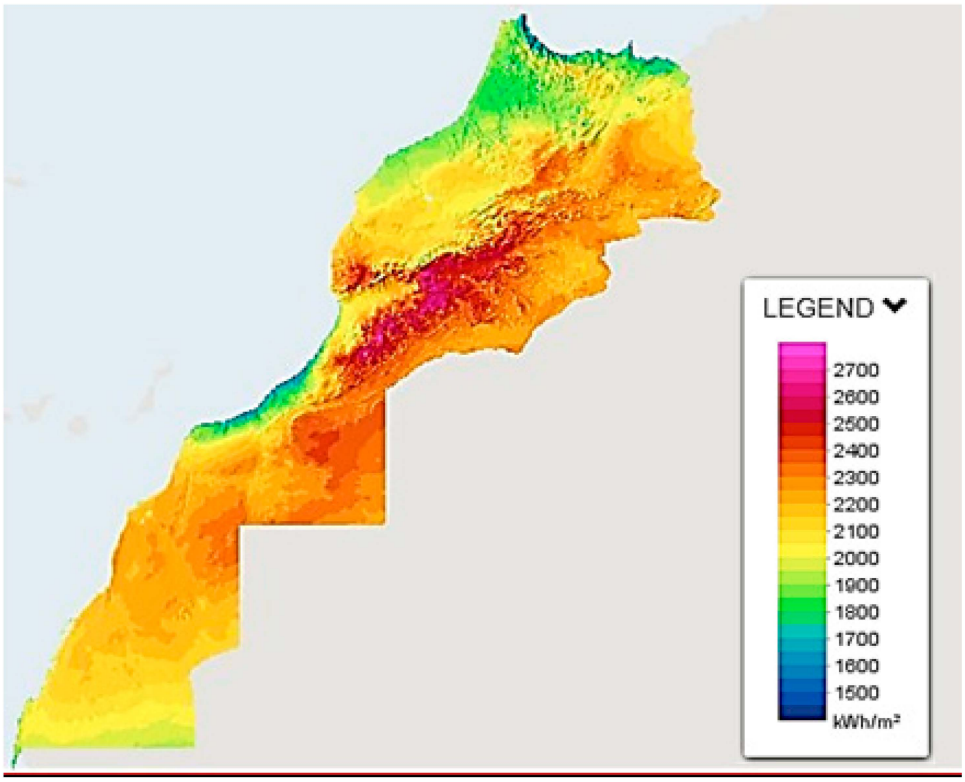


Figure 10. Map of yearly direct normal irradiation in Morocco (kWh/m^2/year) Source: [43] https://solaratlas.masen.ma/.

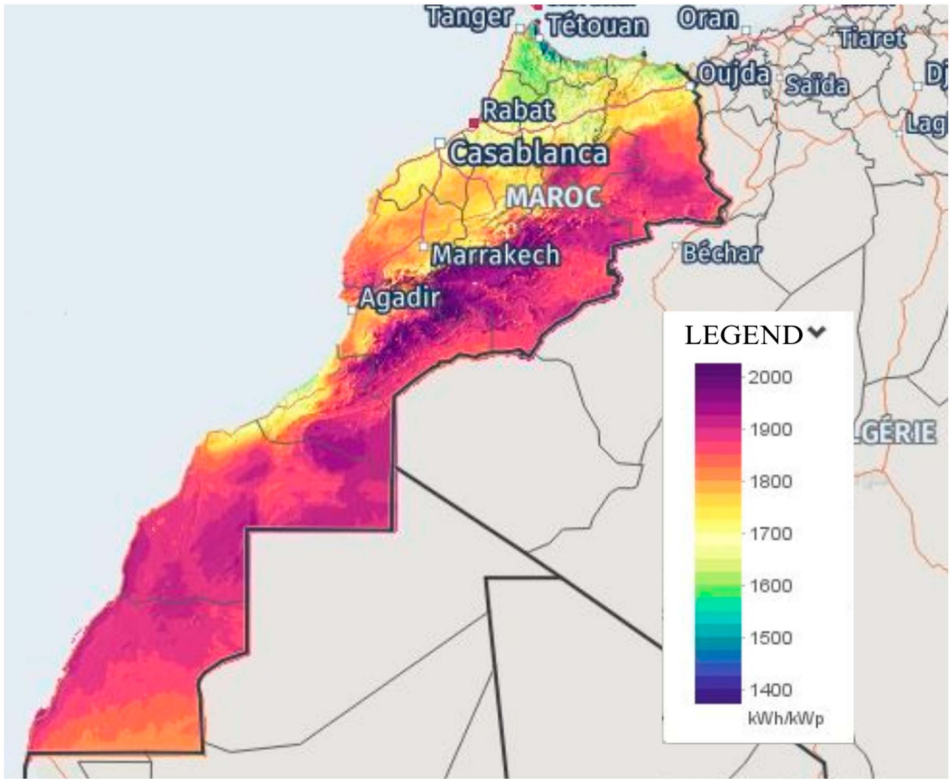


Figure 11. Map of yearly photovoltaic output in Morocco (kWh/kWp/year). Source: [43] https://solaratlas.masen.ma/.

Other factors can influence the productivity of photovoltaic (PV) systems. Global tilted irradiation (GTI), which refers to the amount of solar energy available on an inclined surface, plays a significant role in determining the potential productivity of a PV system. Similar to the previously mentioned parameters, GTI varies across different regions, with maximum values observed in arid and desert areas (1800 to 2600 kWh/m^2/year) [43]. Additionally, the performance ratio (PR) represents the ratio between the actual energy output and the theoretical maximum energy that a PV system could generate. This metric is crucial for assessing the overall efficiency of the PV system by accounting for various losses (capture losses, cable losses, and inverter inefficiencies). Figure 12 illustrates the monthly average variation of PVOUT, GTI, and PR for the case of Marrakech, Morocco. Consequently, an annual average of 1779 kWh/kWp, 2276 kWh/m^2, and 78% is recorded for PVOUT, GTI, and PR, respectively.

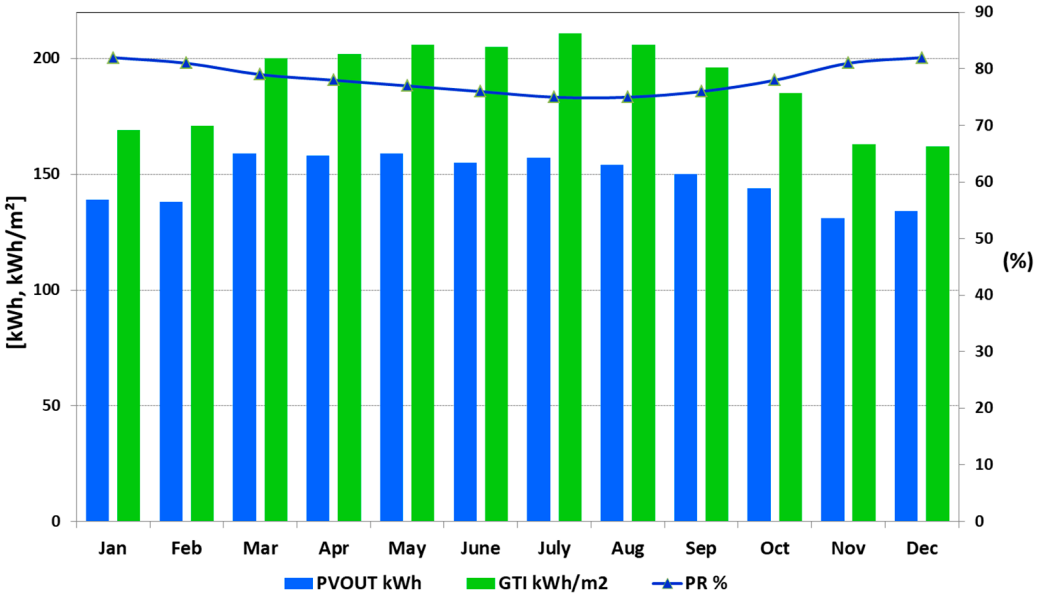


Figure 12. Average monthly variations in PVOUT, GTI, and PR in the case of Marrakech, Morocco.

Therefore, it can be seen that Morocco has the resources for sustainable energy options that can address the two challenging issues that the country faces: electricity availability and global warming mitigation. Indeed, the country has a huge technical capacity in sustainable resources, primarily solar and wind, with generation potential varying from 20 to 25 GW. On a worldwide scale, MASEN indicated that the country ranks ninth in terms of solar radiation and 31st in terms of wind energy potential [44]. The 3500-km Atlantic coastline records wind speeds between 7.5 and 11 m/s, representing an estimated technical potential of 25,000 MW [44]. Figure 13 illustrates the wind-power potential in Morocco [45]. Jordan, on the other hand, boasts a strong solar potential, closely rivaling that of Morocco, with an average solar irradiation of 2000 to 2300 kWh/m^2/year in its most favorable regions and approximately 3200 h of sunshine per year. However, the geographic and climatic variations between the two countries result in differences in solar intensity and utilization. Morocco, particularly in its southern desert regions, enjoys even higher solar radiation, giving it a slight edge in terms of overall solar potential and exploitation [46].

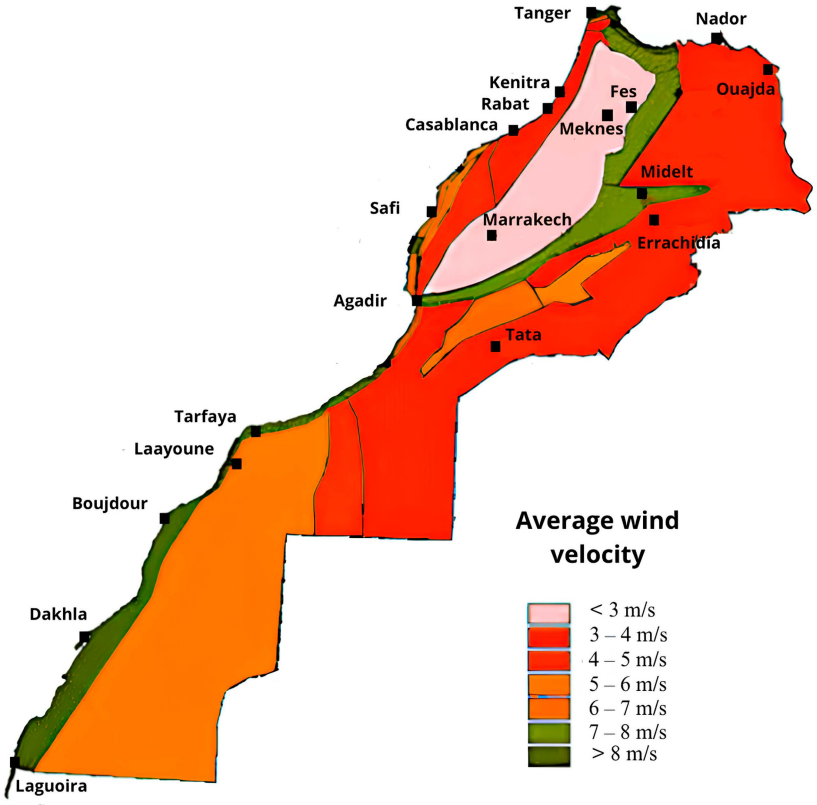


Figure 13. Map of yearly wind potential in Morocco. Source: [45] https://solaratlas.masen.ma/.

4. Current State of Solar Energy in Morocco

4.1. Policies and Regulations

The electricity sector in Morocco has undergone a remarkable transformation, transitioning from a vertically integrated monopoly to a more open and competitive market. During the first phase of the monopoly from 1963 to 1994, the National Office of Electricity (ONE), which was established in 1963, was in charge of electricity production, transmission, and distribution, thereby laying a solid foundation for the country's electricity system [47]. The second phase, which started in 1994, marked a shift toward liberalization by encouraging private operators to take part in electricity production as independent power producers (IPPs). Since then, there have been consistent efforts to foster private-sector involvement in electricity generation and distribution while promoting investment in the energy sector and ensuring the stability of the electricity grid [47].

Institutional and legislative measures have continuously evolved since the inception of the energy strategy in 2009, aiming to create an environment conducive to sustainable growth and innovation in the energy sector. These are based mainly on three framework laws: Law 13-09 on RE (amended and supplemented by Law 58-15); Law 47-09 on energy efficiency; and Law 54-14 on producers to supply medium voltage to end-users. Table 1 summarizes the main laws related to the RE sector, as well as the texts defining the dedicated institutions, in particular AMEE, MASEN, and ANRE.

For further details, the laws and regulation texts are available for download from the website of the Ministry for Energy Transition and Sustainable Development, and on the AMEE Website.

Table 1. Main laws related to the RE sector in Morocco and the texts creating the dedicated institutions.

Law	Main Points
Law 13-09 relating to RE. Promulgated by Dahir (Royal Decree) 1-10-16, dated on 26 Safar AH 1431, corresponding to 11 February 2010 (B.O. No. 5822 of 18 March 2010)	- Promotion of RE by exploiting renewable sources. - Enhancing the competitiveness of the national economy and developing a clean national industry capable of seizing the opportunities offered by the energy transition, both nationally and internationally. - Outlines implementation procedures such as providing licenses for RE production facilities and granting private investors the right to generate electricity from renewable energy sources and sell it to consumers connected to the national electricity grid. - Defines the general principles and legal system required to implement and operate power plants from RE sources by individual or legal entities, whether public or private.
Decree 2-10-578 of 7 Jumada I, 1432 (11 April 2011), adopted in the application of Law 13-09 on RE	- Defines and establishes the regulations and overall procedures governing the application of Articles 5, 8, 17, 18, 28, and 29 of Law 13.09 on RE, such as: - Application files/forms submitted to request licenses. - Rules for extending the validity of the final license. - Conditions of access and grid connection for renewable electricity production facilities. - Technical and financial details of grid connection and execution of commercial supply contracts. - Determination and review of annual exploitation rights, and schedules, rates and rules of annual operating rights for RE production plants.
Law 57-09 (14 January 2010)	- Creation of the Moroccan Agency for Solar Energy (MASEN), responsible for implementing the Moroccan solar plan. - Realization and setting out a specific framework for solar energy projects.
Law 37-16, modifying and completing Law 57-09, creating MASEN	- The extension of MASEN's competencies in the field of RE (except hydropower). - Transformation of MASEN into a limited company with a supervisory board, granting exclusive rights to develop RE projects and reinforcing its financial autonomy.
Law 16-09 (13 January 2010) and its amended Law 39-16 (25 August 2016).	- Law 16-09: Creation of the National Agency for the Promotion of Renewable Energies and Energy Efficiency (ADEREE) (mainly active in the energy-efficiency program). - Law 39-16: Strengthens ADEREE's mandate, and increases its powers to promote and regulate RE and EE initiatives.
Law 47-09 on energy efficiency (29 September 2011)	- Lays out measures to increase energy efficiency in the industrial, transportation, and building sectors - Sets thresholds for mandatory energy audits. - Sets minimum energy performance standards for appliances.
Law 48-15 relative to regulation of the electricity sector (24 May 2015)	- Regulation of the electricity sector and creation of ANRE (the National Electricity Regulatory Authority). - Missions and obligations of transmission system operators and distribution system operators. - Accords ANRE the power and procedures to carry out its regulatory missions in the national electricity sector.
Law 58-15 amending and supplementing Law 13-09 relating to RE (published in Official Bulletin 6436 of 4 February 2016)	- Increases the threshold for operators from 12 (upper limit imposed by Law 13-09) to 30 MW for hydropower. - Access to the high-voltage grid and the sale of excess energy up to a limit of 20% of the production. - Access to the low voltage, which was not provided by the RE Law 13-09. - Mandates the opinions of basin agencies for granting authorization to hydroelectric projects. In Law 13-09, authorization was granted based only on the technical opinion of the electricity transmission agency (ONEE).

Table 1. *Cont.*

Law	Main Points
"Dahir" (Royal Decree) 1-16-60 of 17 Shaaban 1437 (24 May 2016)	- Enacting Law 48-15 related to regulation of the electricity sector and creation of the national electricity regulation authority.
Order 927-20 of Official Bulletin 6870 (2 April 2020)	- Photovoltaic products and solar thermal systems must be regulated by Moroccan norms, officially published in the Official Bulletin in April, 2020. - The standardized framework for products makes it easier to regulate and monitor their compliance with quality and safety standards, thereby guaranteeing consumer protection.
Act 40-19 supplementing and amending Act 13-09 on RE sources and Act 48-15 on regulation of the electricity sector	- Adopted in May 2022. - Amendments and additions to remedy the difficulties encountered by private sector operators and the adoption of solutions aimed at boosting the return on RE projects and accelerating the energy transition.
Law 82.21 on the auto production of electrical energy (December 2022)	- This law aims to expedite the energy transition and foster sustainable development by governing the self-generation of electrical energy (particularly from RE) for self-consumption, regardless of the production source, network characteristics, voltage level, or installation capacity used. - It prioritizes the safety and reliability of the national electricity grid while upholding the principles of transparency and nondiscrimination among all stakeholders.
By-Law 3851-21, published in January 2022	- Establishes the trajectory for the next decade (2022–2031), made up of allocations for injecting electrical energy produced from RE sources into the medium-voltage electrical grid.
By-Law 2138-22, published in September 2022	- Defining the areas in which private developers can carry out solar projects to serve private customers under Law 13-09. - Texts will help to secure national supply and energy sovereignty, facilitate management of the balance between supply and demand, and make the RE sector more attractive to investment, as well as enhancing the country's entrepreneurial infrastructure.

4.2. Installed Capacity

Solar energy can be harvested through three main technologies. Firstly, photovoltaic (PV) systems directly convert solar radiation into electricity through solar cells made of semiconductor materials. These systems are widely used due to their simplicity of operation and efficiency, especially for small- and medium-scale applications. Their continued advancement has led to reasonable costs in the market. The second technology involves solar thermal systems, where solar energy is used to heat water or air for residential, commercial, or industrial applications. The third technology is concentrated solar power (CSP) systems. They employ mirrors to reflect solar rays toward a focal point (solar towers and Dish–Stirling systems) or focal line (as in the case of Fresnel mirrors or parabolic trough systems), thereby heating a heat-transfer fluid to elevated temperatures. This fluid is subsequently used in the power block of the power plant to produce steam, which powers turbines that generate electricity. CSP systems allow the storage of heat by passing part of the heated fluid into a large tank filled with molten salts or other storage media. This is one of the major advantages of this technology since it has a storage capacity greater than that of batteries. Storage allows the stabilization of electricity production, thus limiting the intermittency of solar energy and facilitating its integration into the grid. However, the levelized cost of CSP-derived electricity is generally higher than that of PV systems. Despite this, their higher efficiency, ease of storage of heat, and reduced intermittency make them well-suited for large-scale power generation.

Development of manufacturing and technologies has led to a significant drop in the LCOE of solar electricity. Over the 2010 to 2022 period, the LCOE dropped from 0.445 to 0.049 USD/kWh for PV and from 0.380 to 0.118 USD/kWh for CSP [48]. At the national scale, a lower LCOE of 0.05 USD/kWh was obtained for the photovoltaic plant NOOR IV, while an LCOE of 0.14 USD/kWh was obtained for CSP plant NOOR I [36]. We should highlight that the cost of PV electricity becomes higher than that of CSP when batteries are used for energy storage (discussed in Section 5). For international and national scales, detailed analyses of the cost of electricity production, installation, and maintenance for different renewable energy sources (solar, wind, geothermal, hydropower, etc.), are available in the IRENA reports [48–50] and another reference [14,36,51].

All these technologies are making a major contribution to the exploitation of solar energy and the development of RE on various scales in Morocco's private and public sectors. Concentrated photovoltaic (CPV) offers a conventionally higher efficiency than any other technology (around 39%) [52]. Its operating principle involves the use of optical devices (mirrors or Fresnel lenses) to concentrate radiation on PV cells. This makes it possible to reduce the surface area occupied by a project, as well as the number of cells and thereby the quantity of semiconductor materials used, which is one of the most expensive elements in a photovoltaic cell. Due to the significant intensity of direct normal irradiation (DNI) in Morocco, CPV is potentially attractive as it offers higher efficiency compared with other PV technologies [53]. However, this technology presents additional investments for optical devices, solar tracking systems, and cooling systems to evacuate the heat that could affect solar-cell efficiency [54]. These constraints explain the limitations of this technology to an experimental scale, with a few pilot projects led primarily by research institutions and technology companies such as IRESEN, MASEN, and AMEE. For example, MASEN adopted the world's first CPV pilot plant (Sumitomo Electric) in 2016, with an installed capacity of 1 MWe and the ability to generate over 1 GWh of electricity, enabling large-scale testing of CPV systems [36]. In addition, pilot systems were installed at various universities, such as the AL Akhawayn University in Ifrane, which has installed a 30-kW CPV system (with three two-axis sun trackers) [52], and the Mohamed V University in Rabat, which installed a CPV system (Beghelli HCPV technology) with state-of-the-art, two-axis tracking systems with azimuthal rotation and zenithal elevation [53].

The Moroccan solar energy plan (MSP), which is one of the pillars in the implementation of the MES, aims to increase the share of solar energy in electricity production [54,55]. The main expected outcomes of the MES are as follows.

- RE will account for 52% of total installed electrical capacity before 2030, and 70% by 2040.
- By 2030, solar, wind, and hydro power are expected to account for 20%, 20%, and 12%, respectively, in the energy mix. Accordingly, 10 GW of RE must be added between 2018 and 2030, 4560 MW of solar, 4200 MW of wind, and 1330 MW of hydro power [36], including those to be carried by the private sector within the framework of Law 13-09.
- Investment: USD 9 billion for solar projects.
- Reduction in greenhouse gas emissions by 42% in 2030.
- Creation of an industrial base for solar technologies.
- Promotion of capacity building and applied research in PV and CSP technologies (particularly parabolic trough and solar tower) and related disciplines.

In addition, for the year 2030, energy savings by sector would be 17% for industry, 24.5% for transport, 14% for buildings, and 13.5% for agriculture and sea fishing, which will amount to 1 million toe.

In the framework of the MSP, Morocco has completed one of the largest solar complexes in the world, aiming to contribute to meeting domestic and European green energy demands. The Noor Ouarzazate complex extends over 6000 acres and consists of four power plants, each using different technologies. Noor I (160 MW) and Noor II (200 MW) use parabolic trough mirrors, while Noor III (150 MW) uses heliostat technology, which directs the sun to a tower. Each of these power plants uses a thermal storage system to store

the heat obtained by the concentrated radiation in a large tank filled with molten salt. The storage capacities in the three plants are different: Noor I has a three-hour storage capacity, while Noor II and Noor III each have a seven-hour storage capacity [56]. Meanwhile, the Noor IV plant (72 MW) employs polycrystalline photovoltaic modules with a tracking system. Noor I was commissioned in 2016, and the other plants in 2018 [36]. MASEN is leading the complex, while construction, operation, and maintenance were awarded to a consortium led by the Saudi company ACWA Power. The project was co-financed by the World Bank and the European Investment Bank.

At the present date, CSP technology is predominant in Morocco, with 510 MWe installed at the Nour Ouarzazate complex and 20 MWe (parabolic trough) at the Ain Beni Mathar plant. Ain Beni Mathar consists of a 470 MWe hybrid plant-integrated solar combined-cycle (ISCC) [57].

Other utility-scale solar projects are still in the pipeline or under testing, such as Noor Midelt (800 MWe) and Noor Tata (800 MWe), in addition to the ONEE Noor projects (Noor Atlas, Noor Tafilalt, Noor Argana) totaling 400 MW. The Noor Midelt project involves a hybrid technology combining CSP (600 MWe) and PV (1000 MWe), which will be realized in two phases (Noor Midelt I and Noor Midelt II). Midelt I combines 300 MWe of parabolic trough CSP and 500 MWe of PV systems, taking advantage of a storage option offered by CSP technology with a much lower cost per kWh for photovoltaic technology. As a result, this project will supply electricity 5 h after sunset, with a cost of 0.068 USD/kWh. Morocco is among the first countries to adopt such a hybrid solution.

According to IRENA's "Renewable Capacity Statistics" report, the global installed capacity of concentrated solar power (CSP) systems by the end of 2023 reached approximately 6876 MW, with Morocco accounting for nearly 20% of this total. Morocco is the leading country in Africa in terms of CSP capacity, followed by South Africa with 500 MW. Notable CSP installations are also present in other regions, including China (570 MW), the United States (1480 MW), the European Union (2321 MW), and Spain (2304 MW). However, CSP technology remains concentrated in a limited number of countries, whereas photovoltaic (PV) technology is far more widespread globally. This disparity is reflected in the total global PV capacity reported by IRENA, which stands at an impressive 1412 GW. Of this, 12.4 GW is installed across Africa, underscoring the dominant role of PV technology in global renewable energy development compared with CSP [49].

Table 2 summarizes all solar projects in operation and under construction as part of Morocco's large-scale solar strategy. In addition, other solar projects are implanted by self-producers and according to Law 13-09 and Law 16-08 related to auto production (Table 3).

Several other small-scale solar energy projects and/or sub-projects were implemented in the framework of the MSP by ONEE:

- Small PV plant in Tit Mellil: 46 kW.
- Small PV plant in Ouarzazate: 120 kW.
- PV plant in Assa: 800 kW.
- PV plant in Kénitra: 2 MW.

Two photovoltaic solar power plants are being built under Law 13-09 related to RE. "Maroc Photovoltaïque", which consists of implementing a PV system with a capacity of 10 MW in the province of Jerada, is scheduled for commissioning in 2024. In addition, "Green Power Morocco", with a capacity of 30 MW, is being developed by the company Green Power. The electricity generated will be used exclusively by the delegated operator Amendis-Tanger to meet its ancillary service needs. Furthermore, other projects are being developed within the framework of Law 16-08, where the electrical energy produced by the power stations is intended entirely for the producer's own use.

Table 2. Characteristic of solar projects in operation and under construction as part of Morocco's large-scale solar strategy [http://www.mem.gov.ma/] accessed on 5 May 2024.

Project Name	Installed Capacity/Annual Production/LCOE	Location	Technology/ Storage Technology	CO_2 Avoided TCO_2/Year	Project Framework	Investment Cost (Million MAD)	Planned Start-Up Date
Ain Beni Mathar	20 MW/55 GWh/yr/2.4 MAD/kWh	Beni Mathar	ISCC + parabolic trough	-	ONEE	-	2018
Noor Ouarzazate I	160 MW/618 GWh/yr/1.62 MAD/kWh	Ouarzazate	CSP (parabolic trough) 3 h of storage molten salt with two tanks	280,000	Managed by MASEN, and the construction, operation, and maintenance have been awarded to the consortium led by ACWA Power	7000	2016
Noor Ouarzazate II	200 MW/ 600 GWh/yr 1.36 MAD/kWh	Ouarzazate	parabolic trough + dry cooling 7 h of storage molten salt with two tanks	300,000		9218	2018
Noor Ouarzazate III	150 MW/ 500 GWh/yr 1.42 MAD/kWh	Ouarzazate	CSP power tower + dry cooling 7 h of storage molten salt with two tanks	222,000		7180	2018
Noor Ouarzazate IV	72 MW/120 GWh/yr 0.46 MAD/kWh	Ouarzazate	polycrystalline PV with tracking -	86,539		775	2018
Noor Laayoune I	85 MW/200 GWh/yr 0.46 MAD/kWh	Laayoune	polycrystalline PV with tracking	104,300		968	2018
Noor Boujdour I	20 MW/45 GWh/yr 0.46 MAD/kWh	Boujdour	polycrystalline PV with tracking	23,855		302	2018
Noor Boujdour II	350 MW		polycrystalline PV	-		-	Will be operational by 2027)
Noor Tafilalt	120 MW/220 GWh/yr	Erfoud	polycrystalline PV	102,045	ONEE, developed within the concessional and contractual framework	1200	Late 2020
		Missour					2021
		Zagora					2021
Noor Midelt I	800 MW ≈0.68 MAD/kWh	Midelt	hybrid system CSP parabolic trough (300 MW)/PV (500 MW) 5 h of storage	675,360	Consortium EDF/MASDAR(EAU)/Green of Africa (Morocco)	7572	Planned for 2024
Noor Midelt II	400 to 800 MW			-			Plan on the horizon for 2030
Noor Atlas	200 MW distributed over eight power plants of 30 to 40 MW. 320 GWh/yr.	Boudnib, Bouanane, Outat El Haj, Enjil, Ain Beni Mathar, Tata, and Tan Tan.	polycrystalline PV	204,090	ONEE, developed within the concessional and contractual framework	2000	Constructed in 2021 Planned for 2024
Solar Program Noor PV II	750 MW (distributed over seven power plants)	Ain Beni Mathar, El Hajeb, Bajaad, Sidi Bennour, Kalaa Sraghna, Taroudant, Guersif	polycrystalline PV	-	400 MW will be developed within the framework of Law 13-09	-	From 2023

Table 3. Photovoltaic power plants are implemented by self-producers, [http://www.mem.gov.ma/] accessed on 5 May 2024.

Solar Energy Power Plant: Sub-Projects
Solar photovoltaic plant (10 MW): "Maroc Photovoltaïque"
Solar photovoltaic plant (30 MW): "Green Power Morocco"
Photovoltaic solar power plant in self-production (1 MW): "Golden Logistics"
Photovoltaic solar power plant in self-production (1 MW): "OCP Holding"
Photovoltaic solar power plant in self-production (1 MW)
Photovoltaic solar power plant in self-production (1.69 MW): "Safran Nacelles"
Photovoltaic solar power plant in self-production (2.5 MW): "Nexans Maroc"
Photovoltaic solar power plant in self-production (18 MW)

The geographical locations of the installed and planned solar energy plants are shown in Figure 14 (source MASEN).

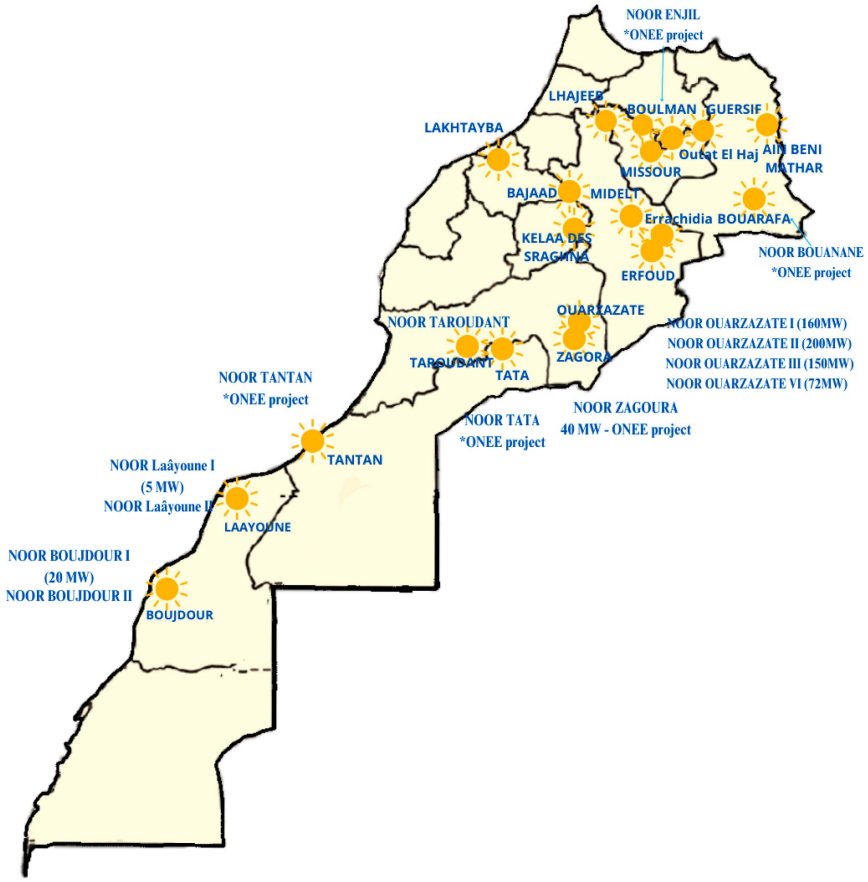


Figure 14. Geographical locations of the installed and planned solar plants (Source MASEN, https://www.masen.ma/en).

These projects, combined with other planned wind and hydro projects, will greatly contribute to the attainment of the national RE target of 52% of installed capacity by 2030.

In addition, there has been a significant increase in the use of PV in solar water pumping (SWP), either for the supply of drinking water or for irrigation. These systems are widely used in the agricultural sector as a means to promote RE and energy efficiency in this vital sector. The first program, "The Moroccan National Solar Pumping program", was launched in 2013 under the responsibility of The Ministry of Energy, Mines, Water,

and Environment and the Ministry of Agriculture. The government aimed to install 3000 SWPs with an approximate capacity of 15 MW [58]. Given the limited results achieved by this program, an additional one was launched in 2016 under the title "The United Nations Development Program: Promotion of the development of photovoltaic pumping systems for irrigation" [59]. In collaboration with the Agricultural Development Fund (FDA), an envelope of MAD 2.5 billion was divided between subsidizing photovoltaic systems and subsidizing irrigation and is intended to support 4450 SWPs for small- and medium-scale farmers. Statistically, 10,000 SWP systems were installed in the agricultural sector between 2019 and 2020. SWP led to a competitive cost of pumped water of 0.44 MAD/m^3 compared with 0.76 and MAD 1.67 for butane and diesel, respectively [60].

The use of solar water-heating systems (SWHs) has also noticeably increased. Morocco promotes the use of these systems in administrative and tourist buildings, schools, and collective and individual housing. To this end, it has developed various programs such as the PROMOSOL (programme de développement du marché marocain des chauffe-eau solaires) program carried out by the Ministry of Energy, Mines, and the Environment (MEMEE) in two phases (2000–2008), with the aim of promoting the use of solar water heaters and improving their quality. In addition, the SHEMSI program set up by AMEE was designed to encourage the development of SWHs. It aimed to install 1.7 million m^2 of SWHs by 2020 and 3 million m^2 by 2030, which will save 920,000 tons of CO2 per year [61]. The first launched project aimed at promoting the Moroccan solar thermal market, although it failed to produce a significant result. The second one was launched to present a new Moroccan SWH with an accessible price and a technology adapted to the economic and climatic conditions of the country [62].

The Moroccan SWH market is based on imports of over 120,000 solar water heaters annually. In addition, 40,000 units of solar water heaters are expected to be produced locally, thanks to the construction of a large unit in Tafilalet, "MySol CES", scheduled to come on stream in the second half of 2023. In addition, a scientific and technological partnership with universities was included to support process development, ensure continuous innovation in solar water heaters, and guarantee better quality and competitiveness in the long term [63].

Furthermore, the private sector is also increasingly using PV technologies to offset some of its conventional electricity consumption. However, the official statistics of the overall installed power in these cases are yet to be determined, as mentioned in Section 2, and the installed capacity of RE connected to the grid in 2023 increased by 500 MW, reaching a total capacity of 4672 MW by the end of 2023, compared with 4154 MW at the end of 2022. This increase is attributed to the commissioning of the 300 MW Boujdour wind farm (as part of the 850 MW wind farm project) and 200 MW of the "Aftissat2" wind farm under the provisions of Law 13-09. The share of RE in the electrical capacity mix rose from 4% in 2010 to 41% in 2023. The remarkable achievements during this period are attributed to the development of solar and wind energies, as illustrated in Figure 15. The installed capacity of hydroelectric and pumped hydro storage plants connected to the transmission grid has remained stagnant over the past two years at 1306 MW and 464 MW, respectively [26]. The pumped hydro storage (PHS or STEP) power plants consist of a pump–turbine system for energy storage and generation and two water reservoirs located at different altitudes. Energy is stored by pumping water from the lower reservoir to the upper reservoir when demand is low, which is then released from the upper reservoir through the hydraulic turbines to supply the electricity grid when demand is high. This process allows for storage and regulation of energy production while preserving the environment (no CO_2 emissions and no pollution). The first PHS plant commissioned in Morocco in 2011 was the Afourer plant, with an installed capacity of 464 MWe [64]. STEP plants have become a strategic priority for Morocco to achieve its ambitious renewable energy (RE) targets. As such, several other STEP plants (El Menzel 300 MW, Abdelmoumen 350 MW, IFAHSA 300 MW) and many small hydroelectric power plant projects [65] are under construction, with the aim of adding 1330 MW of installed capacity by 2030 [64]. Benefiting from a 3500 km coastline, Morocco is also exploring solutions for marine PSH plants, with an artificial

waterfall between an elevated reservoir and sea level. This approach, combined with wind power, would represent a promising solution to smooth load curves and make the national power system independent of fossil-fuel plants [56].

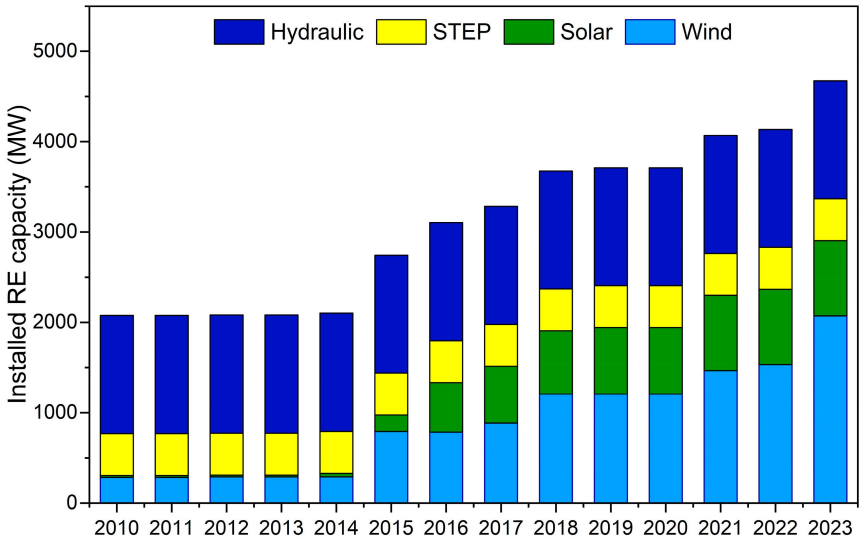


Figure 15. Evolution of installed RE capacity (2010–2023). Data From http://www.one.org.ma/ and [8].

Solar energy has transitioned from an installed capacity of 20 MW originating from the Ain Beni Mathar CSP project in 2010 to 831 MW from both solar thermal and photovoltaic sources. According to statistics from 2022 and 2023, the installed capacity of solar energy was 7.5% and 7.2% of the total national capacity, respectively, and 20% and 18% of the installed capacity in the RE mix. In addition, it contributed 3.5% to national electrical energy production. This breakdown includes 13.3% from concentrated solar power and 7.2% from photovoltaic sources, with 85% supplied by MASEN production and 15% by ONEE plants. However, no solar projects connected to the grid were developed under Law 13.09 due to delays in the publication of the decree specifying the areas suitable for hosting solar power plants. This decree was published in the Official Gazette on 25 September 2022. Figures 16 and 17 illustrate the evolution of installed solar capacity and solar energy fed into the grid in Morocco between 2010 and 2023, respectively.

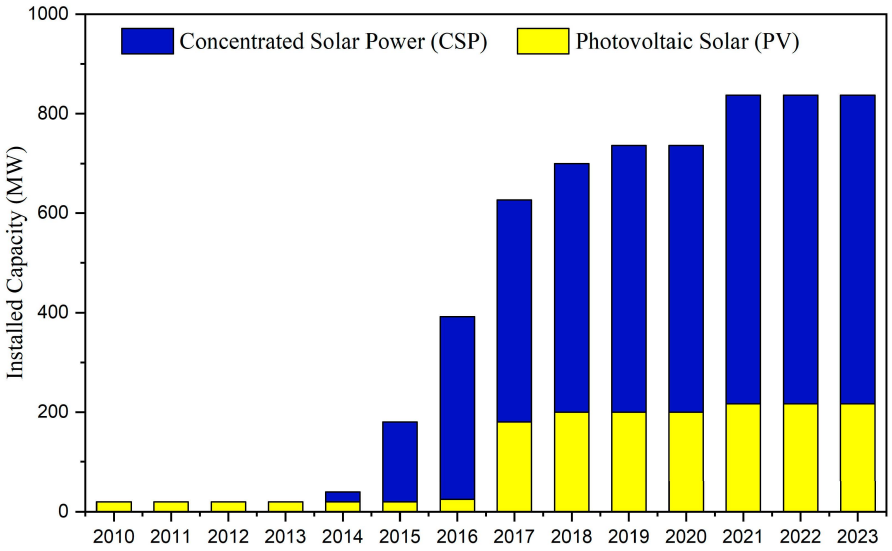


Figure 16. Evolution of the installed capacity of solar energy plants by technology (CSP and PV) in Morocco between 2010 and 2023. Source: (ANRE Annual Report 2021) https://anre.ma/en/publicationdocs/rapport-annuel-2021-version-anglaise/ (Accessed on 5 August 2024).

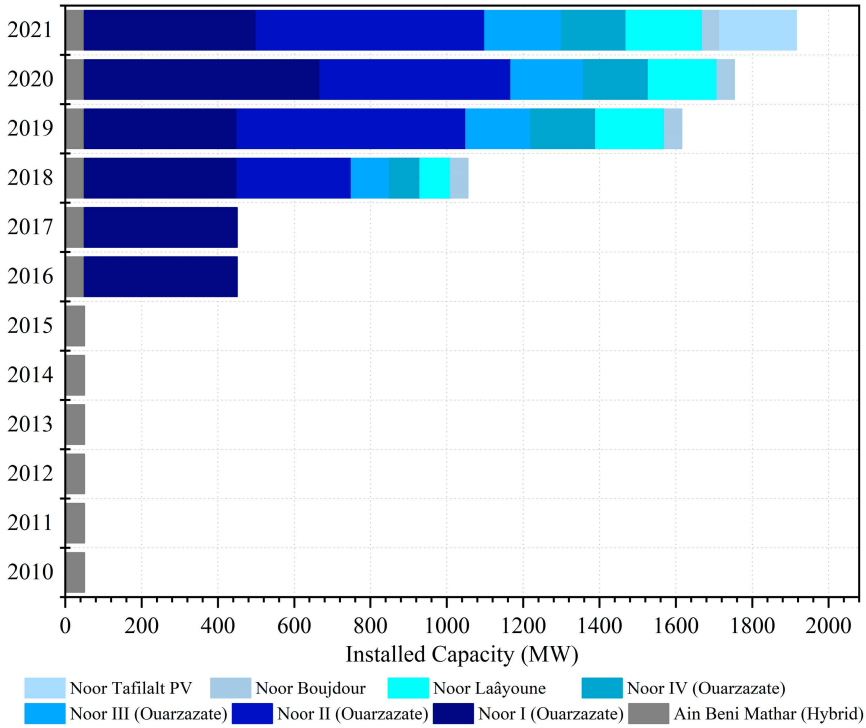


Figure 17. Evolution of the solar energy fed to the grid by plant in Morocco between 2010 and 2021 (ANRE Annual Report 2021. https://anre.ma/en/publicationdocs/rapport-annuel-2021-version-anglaise/ (Accessed on 5 August 2024)).

In addition, the installed wind-energy capacity increased significantly during this period, from 222 MW in 2010 to an installed capacity of 2071 MW in 2023. Figure 18 illustrates the evolution of installed wind-energy capacity in the country between 2010 and 2023.

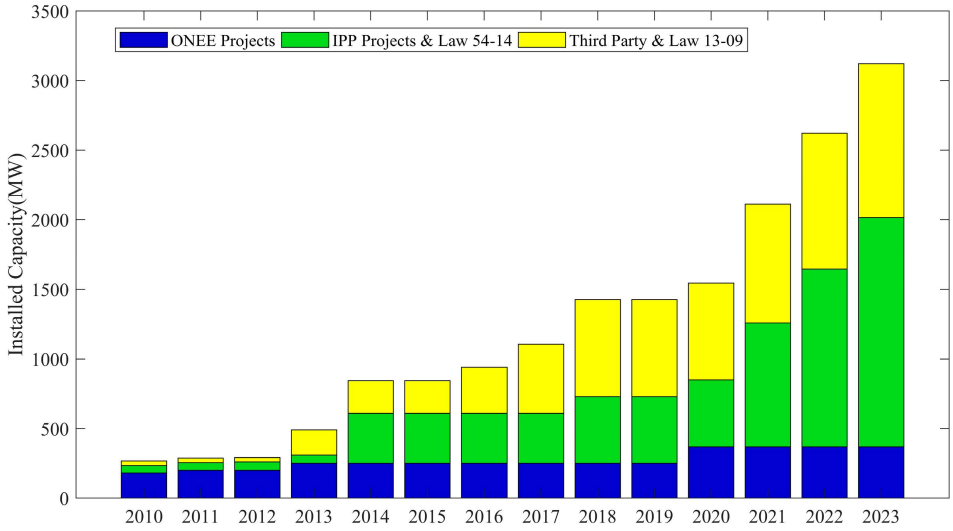


Figure 18. Evolution of installed wind-energy capacity by framework (2010–2023). Data from https://www.mem.gov.ma/.

In terms of energy, electricity generated from RE sources and fed into the national transmission grid in 2022 amounted to 7421 GWh compared with 7972.8 GWh in 2021 (Figure 19). This represents a −7.8% annual variation compared with 2021. This decrease can be attributed to a reduction in hydroelectric, pumped hydro storage, and solar production, which account for −57.2%, −16.5%, and −20.3% of the decrease, respectively [8].

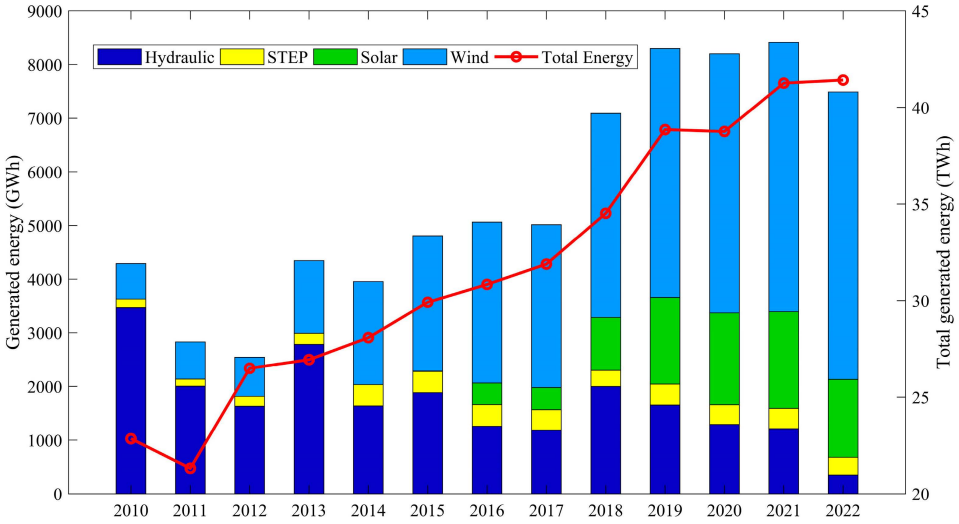


Figure 19. Evolution of the total energy generated and the energy generated from renewable sources (2010–2022). Data from: http://www.one.org.ma/.

To assess the status of renewable energy in Morocco, it is crucial to consider its impact on CO_2 emissions. As in all countries, CO_2 emissions are steadily increasing despite all efforts. The vast majority of CO_2 emissions in the energy sector originate from the combustion of fossil fuels such as coal, oil, and natural gas. In 2022, 66.665 Mt of CO_2 was emitted from fuel combustion, reflecting a 126% increase compared with emissions 22 years ago. As a result, Morocco is considered the fifth-largest emitter of CO_2 from fuel combustion in Africa. According to Figure 20, the electricity and heat sectors are the largest contributors to CO_2 emissions (45%), followed by transportation (28%) and industrial fuel consumption. Furthermore, using RE may have a significant impact on reducing CO_2 emissions in the electricity and heat sectors, as presented in the IRENA report [66].

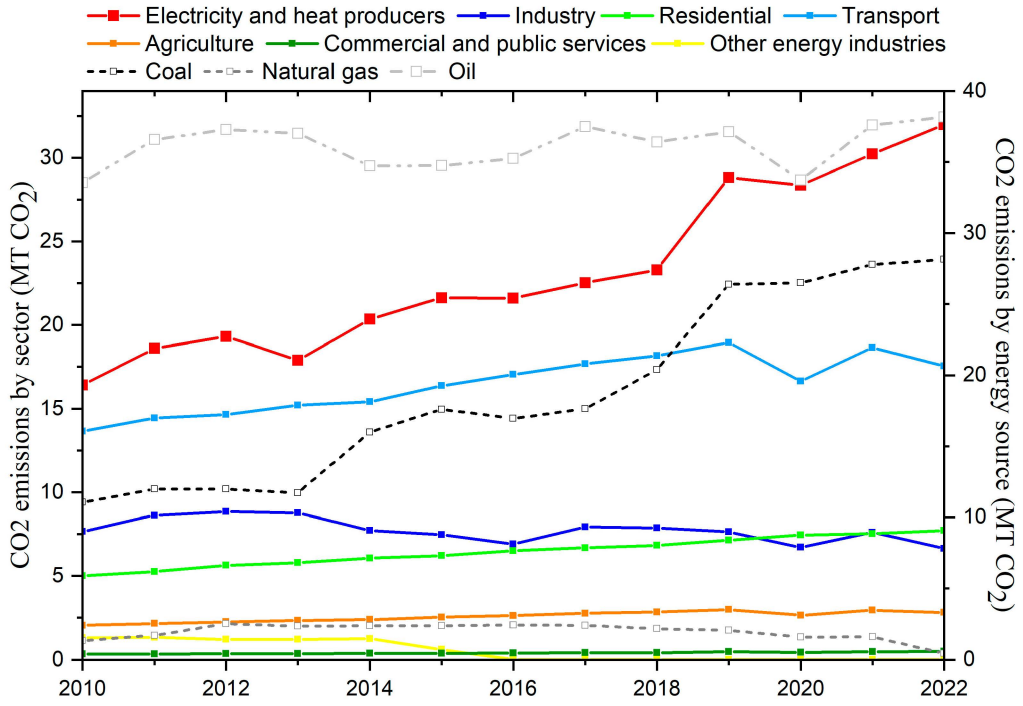


Figure 20. CO_2 emissions by sector and energy source in Morocco (2010–2022). Data from: IRENA [65] and https://www.iea.org/countries/morocco/electricity (Accessed on 5 August 2024).

4.3. Investment and Funding

Morocco stands out among the MENA countries for its steadfast commitment to developing RE, aimed at enhancing energy security through the reduction of its dependency on imported fossil fuels and curbing greenhouse gas emissions. Leveraging its abundant solar and wind energy potential, Morocco has successfully implemented many projects. Furthermore, the country's enhanced regulatory and institutional framework concerning RE makes it an attractive destination for both national and international investments.

To meet the objectives outlined in its energy plan and programs, the Moroccan government estimated a minimum investment of USD 8 and 6 billion for the implementation of solar and wind energy projects, respectively. Moreover, it anticipated a total investment of USD 45 billion to implement strategies aimed at reducing greenhouse gas emissions by 32% from 2015 to 2030 [31]. Additionally, an investment of USD 2.3 billion is planned between 2023 and 2027 for the green hydrogen project [67]. Consequently, the funding and realization of RE projects rely on various factors, including government political and financial backing, involvement of national public–private institutions, collaboration with international organizations and foreign governments, and engagement of the private sector.

MASEN was established specifically to implement RE projects, particularly solar energy initiatives. Its mandate encompasses the entire project lifecycle, including coordination and supervision of related activities. Members of the agency include the Hassan II Fund for Economic and Social Development, the Energy Investment Company, and the National Office of Electricity (ONEE). The solar plan received support from Germany, with funding provided by the German Federal Ministry for the Environment (BMU) and KfW Development Bank, while GIZ was engaged in enhancing industry skills and capabilities. For instance, the first project executed under the Moroccan solar plan, the Noor Ouarzazate Complex, required an investment of USD 3.9 billion, including USD 1 billion from the German investment bank KfW, USD 596 million from the European Investment Bank, and USD 400 million from the World Bank [68].

Furthermore, the acceleration of MES orientations and the encouragement of Moroccan companies can be further promoted through the mobilization of funds within the framework of the green financing concept. This concept gained momentum in Morocco in 2016 during the COP22 held in Marrakech [69]. Green finance relies on various instruments and mechanisms, such as green bonds, ISR labels, green or environmental funds, regulations, and monetary and financial policies. In collaboration with the Solar Cluster, AMEE (the Moroccan Agency for Energy Efficiency) developed a financing and support guide for Moroccan businesses [70]. These financing instruments revolve around two main axes. The first axis focuses on financing and supporting green investments by businesses, including financial support from national organizations (such as Tatwir Croissance Vert and subsidies for resource protection in agriculture), co-financing offers like Green Invest in partnership with Moroccan banks, and offers in partnership with international financial institutions (such as Cap Blue, Green Economy Financing Facility (GEFF), Green Value Chain, and Istidama). The second axis concerns investment funds (such as AZUR, Maroc Numeric Fund II, and SEAF) and programs for the development of green entrepreneurship.

On the other hand, there are other financing options available to businesses, including the following:

- MORSEFF, a financing line for energy-efficiency and RE projects, which allows Moroccan companies to access loans (or leasing) for the acquisition of equipment or the realization of major sustainable energy projects of up to EUR 4.5 million in finance, an investment subsidy of 10% of the credit, and a free energy audit for the evaluation, implementation, and verification of the project. MORSEFF's services are accessible locally thanks to distribution through partner banks such as Banque Populaire with Eco Energy Invest credit, BMCE with Cap Énergie, or Maghrebail with Energy Lease. For example, a loan of MAD 75 million was granted to Moroccan companies to improve their energy efficiency, thanks to the BMCE and BCP banks.

- Standard credits from local banks such as BMCI's Green Credit or Attijariwafa Bank's Effinergie.
- Imtiaz-Croissance aims to strengthen the support system for SMEs, VSEs, and auto-entrepreneurs. It targets SMEs operating in industry and activities integrated into industry that meet the following criteria. (i) Turnover in the last financial year between MAD 10 million and MAD 200 million. (ii) Having a development project promoting growth, creation of added value, and creation of jobs likely to accelerate the change in scale and emergence of new business models.
- The Moussanada program aims to support 700 companies per year in the process of modernization and improvement of their productivity to (i) strengthen their competitiveness in terms of reducing costs and lead times and improving quality; (ii) improve their performance and productivity; and (iii) support them to access new markets.
- FODEP aims to encourage industries to invest in depollution or save resources and introduce an environmental dimension into their activities to deal with the regulatory framework in preparation for the globalization of trade.
- The Small Business Support (SBS) program was launched by the European Bank for Reconstruction and Development (EBRD) and financed by a grant from the European Union and other donors to support Moroccan SMEs through appropriate advice and international industrial expertise coupled with grant mechanisms.
- The establishment of energy performance contracts with an Energy Service Company (ESCO), which allows the financing of investment and maintenance costs, and the guarantee of savings. An explanatory brochure of a typical green electricity supply and energy-efficiency improvement project can be downloaded.
- Companies can also finance their green energy projects through funds dedicated to improving the competitiveness of companies in general as part of Morocco SME programs, for example.

4.4. Challenges and Barriers

The urgent need to mitigate the impacts of climate change, ensure energy security, and comply with international objectives highlights the pressing demand to accelerate the energy transition in Morocco and the Middle East and North Africa (MENA) region in general. These include financial, technological, institutional, and legal barriers. M. Wael et al. [71] highlighted several barriers, among which the complex interaction between formal institutions, legal and policy frameworks, and informal institutions is the most significant. In addition, the gap between national and international goals and the practical implementation of projects and regulations, as well as resistance to changing governance structures and adopting new technologies, restrict the development and transition to renewable energy. G. Vidican et al. [58] suggested that the deployment of RE in the MENA region faces difficulties due to reluctance to invest in such projects, primarily because of lower profitability and higher risks. RE projects are often more costly and involve longer payback periods than traditional energy sources [57]. Additionally, low electricity prices and high subsidies for fossil fuels in the region exacerbate profitability issues. Furthermore, RE projects require significant initial investments and are subject to various risks, including political and regulatory uncertainties. As a result, commercial banks and private investors hesitate to finance these projects. Despite these challenges, Morocco has implemented measures to attract private investments and ensure adequate financing for RE projects [58]. However, investors still express concerns, especially regarding the uncertainty surrounding investments in solar energy. Similarly, A. Šimelytė [11] conducted detailed research on persistent obstacles in the Moroccan energy sector in 2019, highlighting the challenges in terms of financing, institutional coordination, technical capacity, and social acceptance. She identified various barriers influencing decision-making to invest in the renewable energy sector. For example, the uncertainty of regional or country-level market development and prospects and the lack of international financial resources for new financing are some of

the factors. The unclear energy policy and the high level of taxation were also mentioned among these barriers.

Moreover, the 2020 diagnostic of the Moroccan economic model carried out by the government states that the challenges facing the Moroccan energy sector are key factors that could accelerate the Moroccan energy transition. Resolving these issues could provide pathways that will stimulate the resilient and sustainable growth of the country. One of the challenges is that in the electricity sector, Morocco still relies heavily on coal despite the increase in the installed RE capacity. Indeed, in 2020, about 68% of electricity was generated using imported coal. RE sources only represented 19% of the overall electricity production. The barriers to the development of solar energy in Morocco can be overcome by improving institutional and regulatory frameworks, including those related to low-voltage grid access, and completing the liberalization of the renewable electricity sector. In addition, enacting the National Electricity Regulatory Authority and effective coordination between the different players in this field (ONEE, MASEN, and the Ministry of Energy and Mines) will accelerate the implementation of the transition. Furthermore, a recent study showed that the de-carbonization pathways of Morocco call for an attractive policy framework to encourage private investments and promote private–public partnerships to scale up investments in this sector [72].

Given the country's efforts and the progress mentioned above, Table 4 below groups together the main barriers to accelerating the energy transition.

Table 4. Barriers that may influence the acceleration of promotion of the renewable energy sector.

Financial barriers
• High capital of the systems (PV or water heaters) especially for public. The initial cost of purchasing a solar system is still fairly high, especially with the existence of subsidies for butane (water heating, pumping, etc.)
Technological and Industrial barriers
• Weak industrial base in Morocco for solar energy systems (PV modules, BOS, solar water heaters, concentrators, monitoring systems, etc.) • Energy storage, especially for PV electricity. Development of large-scale storage (pumped hydro) and/or fast-response-time power plants (e.g., natural gas) is required for the large-scale integration of solar energy. • Absence of additional sources of flexibility in the national electric power system: supply- and demand-side management, smart grids, cross-sector coupling through the development of power-to-X. • Grid instability, especially when low-voltage (LV) grid access is granted. • Absence of national standards and certified installers and OM operators (for small scale systems) • Land usage, which is required to further increase the efficiency of the systems (promote R&D).
Political barriers
• Lack of government incentives and subsidies for RE systems (PV, water heating, etc.) • Slow implementation of regulations. • Absence of regulations for small/medium-scale RE, particularly solar energy (e.g., access to low-voltage public grids).

These challenges require concerted action to accelerate the energy transition toward renewable sources, in particular solar, to meet the growing energy demand. M. Said Hidane et al. [39] proposed several recommendations regarding the photovoltaic (PV) and wind sectors to address challenges and strengthen the emergence of a competitive industrial ecosystem. In addition to being eco-friendly, solar energy and its applications (electricity generation, water pumping, desalination, green hydrogen, green fuel production, and integration in buildings) can stimulate economic growth, create new jobs, and become a pillar for the growth of manufacturing and service industries.

5. Future Outlook of Solar Energy in Morocco

Morocco is steadily working on increasing the share of renewables in its electricity mix and has set up very ambitious targets of reaching an RE share in the installed capacity of 52% by 2030, 70% by 2040, and 80% by 2050 (Figures 21 and 22). These targets will be achieved thanks to the technological advances in energy storage and green hydrogen production, as well as the decreasing costs. The country is actively engaged in its 2030 renewable capacity target and will reduce its dependence on fossil-fuel-based power plants (oil and coal). The share of coal in the installed capacity is expected to decrease from 38.8% in 2020 to 22% by 2030, and that of oil will drop to 9.2% by 2030 from 16.2% in 2020.

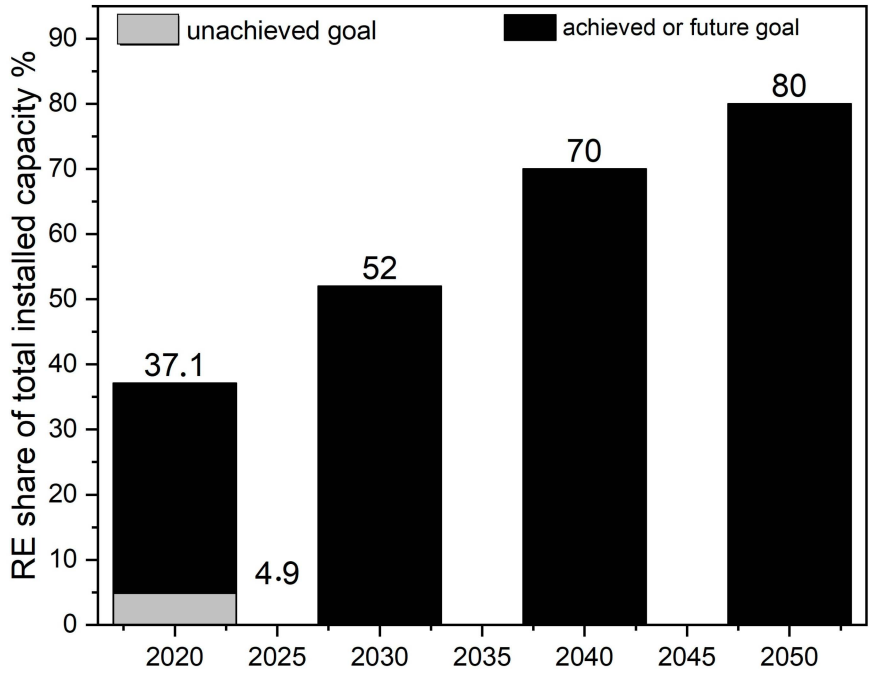


Figure 21. Morocco's 2020–2050 RE capacity targets (%). Source: Global Data https://w3.windfair.net/wind-energy/news/39797-globaldata-morocco-renewable-energy-renewables-wind-wind-power-solar-tender-target-aim-progress-energy-transtion (Accessed on: 5 August 2024).

Morocco's renewable installed capacity is expected to increase at an average rate of 9.3% between 2020 and 2030. Wind power is expected to surpass hydroelectricity. The installed capacity for wind will increase from 1.4 GW in 2020 to 4.3 GW in 2030 at an average growth rate of 11.5%. On the other hand, solar power capacity (both PV and CSP) will increase from 734 MW in 2020 to 2.1 GW in 2030 at a rate of 11%, while hydropower capacity (including PHS) will go from 1.8 GW in 2020 to 3.3 GW in 2030 [48]. An actionable plan determining the share of various sources in the energy mix was proposed by MASEN, as illustrated in Figure 23. Compared with the initial orientations of the National Energy Strategy (NES), which focused on large-scale projects considering CSP systems as the first choice, the new forecasts express the kingdom's orientation toward more PV (15% by 2030) against CSP (9% by 2030) through projects at various scales.

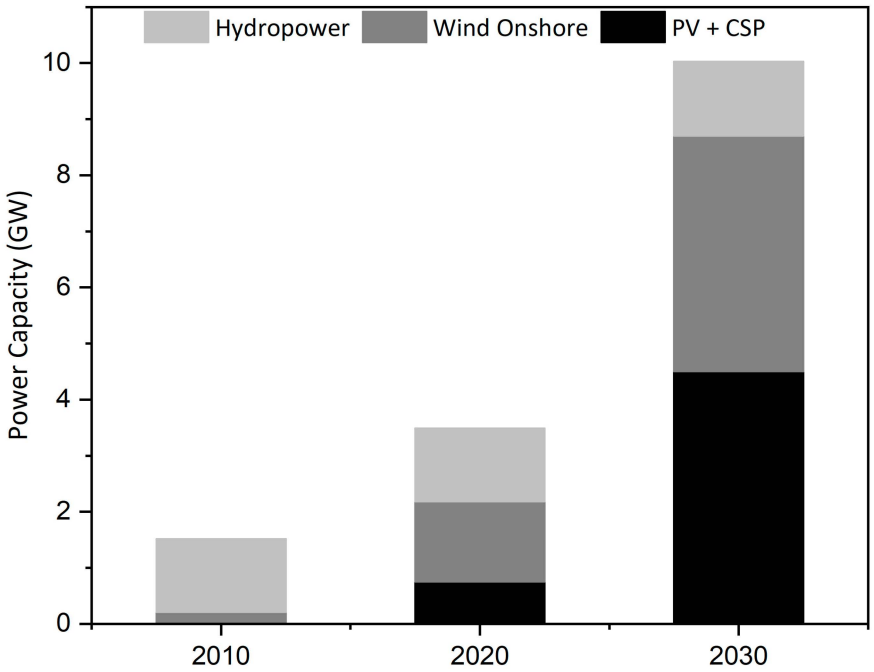


Figure 22. Cumulative capacity of Morocco's renewable power market in 2010–2030. Source: Global Data https://w3.windfair.net/wind-energy/pr/40252-globaldata-morocco-capacity-installation-investment-thermal-power-renewable-power-wind-energy-program-wind-farm (Accessed on: 5 August 2024).

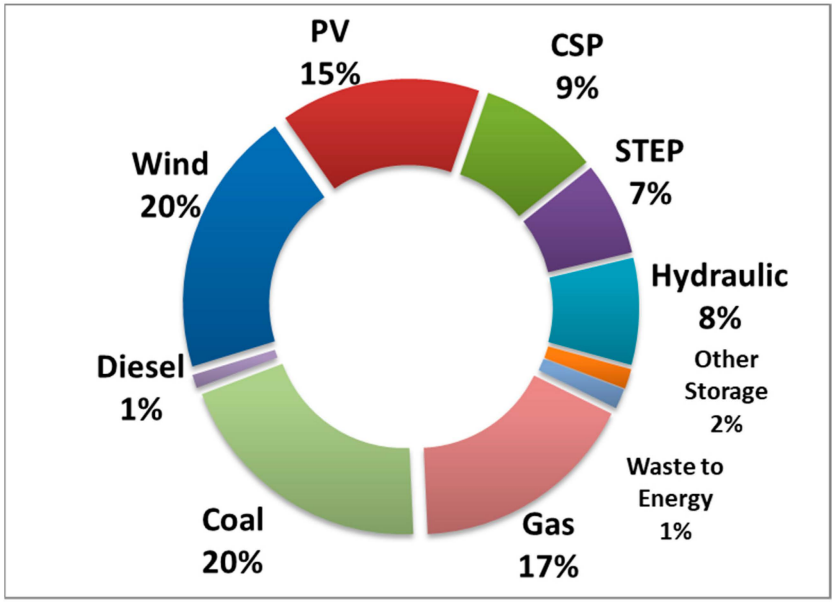


Figure 23. MASEN's plan to reach 52% by 2030. Source: [56].

The choice to develop PV technology can be explained by its continuous advancement in terms of efficiency and durability, alongside low installation costs and a low levelized cost of energy (LCOE). PV module prices have dropped by over 80% globally or less since 2010 [73]. It is worth noting that PV technology requires the use of storage systems (often batteries), which significantly increase the LCOE. Conversely, CSP technology allows for storage (latent or sensible), justifying its efficiency in large-scale projects connected to the national electrical grid. Estimates conducted by NREL suggest that a PV system with six hours of storage will produce a projected LCOE lower than CSP by 2030 (Figure 24). Ad-

ditionally, MASEN has demonstrated through a comparative study of various technologies that a CSP/PV hybrid system is the optimal solution for a predefined production profile.

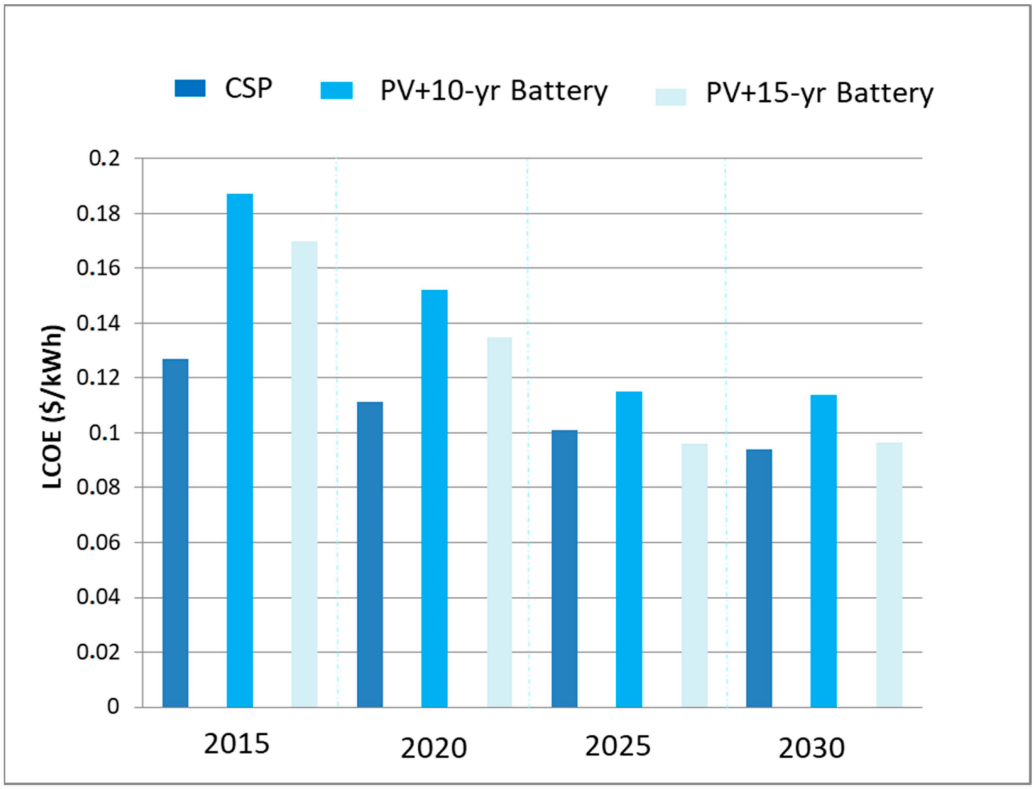


Figure 24. Variation of the LCOE cost projection of CSP versus PV (six hours of storage), 2015–2030. Source: [74].

Furthermore, the solar sector has seen considerable development. Table 2 summarizes the various projects constructed and scheduled for commissioning by 2030. Particularly, the Noor ATLAS project led by ONEE involves installing 200 MW of PV distributed across eight plants. MASEN has launched various projects, including the multi-site solar program "Noor PV II" with a capacity of 800 MW, the Noor Midelt I project (800 MW) using a hybrid system (CSP/PV), and the Noor Midelt II project designed to provide a total grid-fed power of around 230 MW (190 MW during peak hours) by allowing private developers to propose optimal configurations combining PV, CSP, thermal storage, or battery storage. Moreover, other projects are programmed under the framework of private very-high-voltage (VHV) and high-voltage (HV) production, as well as projects of photovoltaic solar power plants intended for consumers connected to medium voltage (Table 3). However, self-production projects can only contribute 20% of their annual production to the grid.

Alongside the development of these projects, solar energy will contribute to several of the country's sustainable strategies to strengthen the energy transition, reduce electricity consumption by improving energy efficiency, and preserve the environment.

Indeed, the residential sector is a major consumer of energy. Projections indicate an interesting increase in the next decade, surpassing 30% to 70% by 2030 [16]. This trend presents a compelling opportunity for self-production using photovoltaic (PV) systems to supply households. Studies suggest that the residential sector could reach capacities ranging from 100 MW to 250 MW by 2030 [75]. This translates to a potential generation of 0.2 to 0.4 TWh of solar energy. In a high-case scenario, this would equip 160,000 households with an average system size of 1.5 kWp, representing roughly 2% of all households by 2030. Looking toward 2040, the high-case scenario suggests installations could even surpass 1 GW. However, the adoption of PV systems in the residential sector is facing some challenges. These include variations in household energy consumption and equipment

levels and the complexity of adapting the current tariff structure implemented by ONEE and other utilities [15]

Furthermore, PV systems are recommended to ensure self-production for public administrations and companies while maximizing energy-efficiency measures. With the support of the AMEE and the investment company (SIE), the total installed capacity on residential, public, and industrial rooftops is estimated at 210 MW. Thus, PV technology development has been addressed in the national public lighting program (2020–2040), with the aim of reducing electricity consumption in the public lighting network [56].

According to the World Resources Institute (WRI), Morocco is facing a major water deficit, with an extremely high level estimated by 2040 [76]. According to 2022 statistics, irrigation consumes 89.26% of the available water volume [77]. In this regard, the country has prepared a National Program for Drinking Water Supply and Irrigation 2020–2027 (PNAEPI 2020–2027) presenting various solutions aimed at irrigation water management, wastewater reuse, and desalination. In particular, PV and CSP technologies hold promising potential in the desalination strategy. The cost of desalinated water as a function of different energy sources between 2017 and 2030 has been studied by [78]. This analysis demonstrates that solar energy is a competitive option for large-scale reverse osmosis desalination plants. Prospective results until 2030 suggest that CSP + storage + grid and PV + storage + grid solutions offer potential benefits, but PV + grid remains the most competitive solution. This research demonstrated the capacity of photovoltaic (PV) and concentrated solar power (CSP) technologies to be rapidly integrated into the reverse osmosis desalination process. Moreover, the capacity of CSP to store heat at low cost offers significant flexibility, thereby considerably reducing dependence on the electrical grid, if necessary. Consequently, this work advocates for the integration of PV and CSP technologies to meet the energy needs of desalination. Within 10 years, desalination in Morocco could require between 40 MW and 200 MW of installed solar capacity. By 2040, this demand could significantly increase, surpassing 500 MW, to meet government objectives of desalinating several million cubic meters per day. Achieving this goal would require energy production on the order of terawatt hours (TWh) [16].

Building experience from the last two decades, Morocco is committed to giving new impetus to the energy transition and playing a vital role in the fight against global warming and the resulting climate changes in Africa. The country revised and submitted its Nationally Determined Contribution (NDC) to the United Nations Framework Convention on Climate Change in June 2021. In its new NDC, Morocco revised its emissions reduction targets to 45.5% from a value of 42% by 2030 in the business-as-usual scenario [35].

Morocco has the potential to be a role model in decarbonized energy production and, as such, expand its experience to neighboring markets. In addition, Morocco aspires to become a world leader in new clean technologies, including green hydrogen. Despite encouraging prospects and ambitious roadmaps being developed, technical limitations such as production technologies, transport/storage infrastructures, loss of ecological value, and cost reduction need to be overcome before Morocco will be able to export green hydrogen. Further, the large-scale integration of intermittent RE energies required for the decarbonization of the economy is compounded by uncertainty in the demand for greater flexibility in the power system. Supply-side flexibility, transmission/distribution reinforcement, energy storage at both large and small scales (e.g., Electric vehicles), demand-side management, advanced grid management (smart grid), and sector coupling through power-to-X should be promoted for proper balancing of the grid at different timescales.

A strong focus should also be put on improving existing laws relative to the development of small-scale grid-connected renewable systems. Legislation and incentive mechanisms promoting investments in rooftop PV and small-scale grid-connected renewable systems other than those for self-generation should be developed. These distributed systems will play a significant role in future grids as they reduce transmission and distribution losses, improve grid stability and security, and reduce GHG emissions.

6. Conclusions

The development of RE in Morocco is a national priority to ensure energy security and preserve the environment by reducing dependence on fossil fuels. Consequently, the energy sector has made significant progress since 2009, following the implementation of the Moroccan Energy Strategy. This strategy aims to strengthen supply security and energy availability by promoting the participation of RE in the national electricity mix to reach 42% by 2020 and 52% by 2030. Despite missing the first target because of the pandemic and the energy crisis, Morocco has accelerated its progress to achieve subsequent aims.

Positive trends are observed, as the share of RE in the electricity mix increased from 24% in 2009 to 41% in 2023 as of 2022, wind energy reached an installed capacity of 1553 MW, representing 12.9% of the total national electricity production capacity. Solar energy ranks second with a capacity of 831 MW, contributing 3.5% to the national production capacity. Overall, Morocco has successfully overcome the challenges of the pandemic and the energy crisis and continues to pursue its energy strategy goals. It can even be said that the country's RE development is in line with international objectives. The array of planned RE projects, energy-efficiency strategy, and development efforts are improving Morocco's standing in terms of renewable energy (especially solar) within the MENA region and globally. By maintaining this trend, Morocco will contribute to international objectives. Recent IRENA data indicate that 2023 set a new benchmark in renewable energy deployment, adding 473 GW to the global energy mix, with solar energy accounting for 73% of this growth.

Morocco has fully invested in concentrated solar power (CSP) systems, which require substantial investment for large-scale project realization. Consequently, Morocco hosts the largest solar complex in the world, Noor Ouarzazate, which was fully commissioned in 2018. A new hybrid project (CSP/PV) is planned for 2024, while the government is increasingly inclined toward photovoltaic solutions in other projects. PV technologies have been instrumental in rural electrification efforts, achieving a 99.87% electrification rate, and are commonly employed in residences for power supply, as well as in pumping systems.

The continued development of this sector remains dependent on the formulation of guiding policies and government decisions to strengthen the sector, facilitate investment, and integrate companies and research centers. The liberalization of the electricity sector and the continuous improvement of the regulatory framework for RE encourage private-sector participation and financing in various projects. Legally, Morocco has established a robust framework through Law 13-09, which facilitates private-sector involvement in the renewable energy sector. Regulatory bodies such as MASEN and the National Electricity Regulatory Authority play a crucial role in implementing these policies. Given Morocco's abundant solar and wind potential, remarkable geographical position, and expertise in multi-technology solar projects, the country offers a favorable environment for national and international investments.

Recently, Morocco has emphasized accelerating the energy transition toward RE through the development of green hydrogen production, desalination, and the decarbonization of the economy. Consequently, Morocco has attracted increased attention for international investments and collaborations. Notably, Morocco signed a memorandum of understanding with France, Germany, Portugal, and Spain to facilitate cross-border electricity sales during the COP27 climate conference in Sharm El-Sheikh.

RE development has faced certain obstacles and barriers, particularly in terms of financing, institutional coordination, technical capacity, and social acceptance. There is enormous global potential for using solar energy to meet the rising critical demands (electricity generation, water pumping, desalination, green hydrogen production). This can stimulate economic growth, create new jobs, and become a pillar for the growth of manufacturing and service industries. More efforts should be directed toward the ease and speed of implementing regulations. In addition, the development of scientific research and cooperation with various RE stakeholders will be beneficial to improve the energy sector by opening up to other technologies and developing expertise. In this regard, INNOMED (Boosting Innovative Solar Energy Technologies and Applications

in Mediterranean Countries Education), an Erasmus Plus project, is exemplary since it conjugates the efforts of universities from Jordan, Cyprus, Morocco, Austria, Greece, and Italy to promote innovation, capacity building, networking, and stakeholder involvements in the field of solar energy.

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Appendix A. Main Actors Involved in the Development of the Energy Sector in Morocco

- Ministry for Energy Transition and Sustainable Development (MTEDD), Rabat, Morocco, Site Web: www.mem.gov.ma
- Direction Générale des Collectivités Territoriales (Directorate-General for Local Authorities), Rabat, Morocco, Site Web: https://www.collectivites-territoriales.gov.ma/
- Moroccan Agency for Energy Efficiency (AMEE),Rabat, Morocco, Site Web: http://www.amee.ma/index.php/en/ (Accessed on: 5 August 2024).
- Office National de l'électricité et de l'Eau Potable (Water Branch/Electricity Branch), Morocco, Site Web: http://www.one.org.ma
- National Office for Hydrocarbons and Mines (ONHYM), Rabat, Morocco, Site Web: https://www.onhym.com/en
- ANRE—l'Autorité Nationale de Régulation de l'Électricité, Rabat, Morocco, Site Web: https://anre.ma/en/
- Moroccan National Agency for Sustainable Energy (MASEN), Rabat, Morocco, Site Web: http://www.masen.ma/fr/masen/ (Accessed on: 5 August 2024).
- National Inventory Commission (CNI), a Moroccan government agency responsible for overseeing the preparation and updating of Morocco's national greenhouse gas inventory. CC National Data | 4C Maroc. https://www.4c.ma/donnees-nationales-cc?lang=en (accessed on: 5 August 2024)
- Moroccan Energy Observatory (OME), a Moroccan government agency responsible for collecting, analyzing, and disseminating data on Morocco's energy sector. Mise en service du Portail de l'Observatoire Marocain de l'Energie (mem.gov.ma). https://www.mem.gov.ma/Pages/actualite.aspx?act=25 (accessed on 5 August 2024)
- Moroccan Agency for Nuclear and Radiological Safety and Security (AMSSNur), https://www.iaea.org/newscenter/news/moroccan-agency-for-nuclear-and-radiological-safety-and-security-designated-as-first-iaea-collaborating-centre-in-the-field-of-nuclear-security-in-africa (accessed on: 5 August 2024)
- National Centre for Nuclear Energy, Science, and Technology (CNESTEN), Rabat, Morocco, Site Web: https://www.cnesten.org.ma/
- Energy Investment Company (SIE), Rabat, Morocco, Site Web: https://www.siem.ma/. It offers consultancy services and assists in project development (energy efficiency, RE) through several actions such as identification of needs, choice of appropriate

technologies, financing options, project implementation arrangements, and assessment of project profitability.

- Société Chérifienne des Pétroles (SCP), Morocco.
- Institute for Research in Solar Energy and New Energies (IRESEN), for research and innovation, Rabat, Morocco, Site Web: http://www.iresen.org/. The missions of IRESEN include the development and financing of nationwide research projects (fundraising agency) and the development of international collaborations in the sector of solar energy and new energies. Since its creation, IRESEN has financed hundreds of projects and established other research instances (e.g., Green Energy Park, Green and Smart Building Institute) in Morocco and Africa.
- Rabat School of Mines National ('École nationale supérieure des mines de Rabat—ENSMR), Morocco, site web: https://www.enim.ac.ma/.
- Moroccan Institute for Standardization (IMANOR), Rabat, Morocco, site web: https://www.imanor.gov.ma/.
- Public Testing and Research Laboratory (LPEE), Morocco, site web: http://www.lpee.ma/en.
- Economic, Social, and Environmental Council (CESE), Rabat, Morocco, site web: https://www.cese.ma/en/.
- 4C Morocco (Platform for dialogue and capacity building on climate issues).
- Concessionary electricity producers. Since 1994, private companies have been authorized to produce electricity solely to meet ONEE's needs. They are connected to ONEE through long-term power-purchase agreements (PPAs). At present, the concessionary electricity producers are Jorf Lasfar Energy Company, JLEC (2080 MW); Compagnie Éolienne du Détroit, CED (54 MW); Société Energie Électrique de Tahaddart, EET (384 MW); Tarfaya Energy Company, TEC (300 MW); and SAFI Energy Company, SAFIEC (1386 MW).
- Auto-producers. Self-generators may produce electrical energy in one of the following cases, mainly for their own use, and the surplus is sold exclusively to ONEE: the generating capacity to be installed by the producer must not exceed 50 MW; the generating capacity must exceed 300 MW, with a right of access to the national electricity grid to ensure transmission of the electrical energy.
- Société d'Investissement Énergétique (SIE), Rabat, Morocco, site web: https://www.siem.ma/.
- SIE, founded in 2009, is the government's financial arm for achieving the planned energy mix. The organization develops projects in the energy sector with the help of partners, investors, and developers. SIE has a capacity of MAD 1 billion (around EUR 100 million) available through the Fonds de Développement de l'Électrification (FDE). A quarter of their capacity is allocated to energy efficiency and three quarters to RE.

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