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Energy System Transition in the Context of NDC and Mitigation Strategies in Tunisia

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Abstract: The evolution of the Tunisian energy system in the next few decades will highly depend on the implementation of its Nationally Determined Contribution by 2030 and its potential long-term low-emission strategies. This study analyses the technology, emissions, energy systems and economic impacts of meeting Tunisia's NDC targets (conditional and unconditional) and long-term transition pathways compatible with the Paris Agreement. Different climate policy targets and settings are explored using a detailed energy system model (MENA-EDS) that integrates detailed representations of energy demand and supply and their complex linkages through energy pricing. The analysis shows that in order to meet its NDC targets for 2030, current climate policies in Tunisia need substantial strengthening, based on the massive uptake of renewable energy technologies (especially solar PV and wind) and a reduction of oil and gas use. Long-term low-emission transitions leading to emission reductions of about 80% from baseline levels in 2050 is based on the further expansion of renewable energy within and beyond the electricity sector; the increased electrification of energy end-uses (especially through the uptake of electric vehicles in transport); accelerated energy efficiency improvements in transport, industries and buildings; and the emergence of low-carbon fuels. The study provides insights into the challenges to achieve the deep decarbonization of the Tunisian economy but also into the opportunities from energy sector-restructuring, including reduced energy import dependence and increased low-carbon investment.

Keywords: MENA-EDS model; fossil fuel reduction; Paris-compatible pathways; Tunisian energy system; low-emission strategies; renewable energy uptake

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1. Introduction

Climate change is the great global policy challenge of our time. It is increasingly recognized that unabated climate change can lead to large impacts on the environment and human societies [1]. Limiting climate change has been the subject of international negotiations fsor more than 25 years. Within this process, long-term goals have been suggested by the different parties to the UNFCCC, especially under the Paris Agreement, aiming to keep global temperature rise at well below 2 °C compared to pre-industrial times and pursue efforts to limit it to 1.5 °C [2]. The Paris Agreement has established a platform to facilitate the monitoring of countries' progress towards the long-term mitigation target. Following the Paris Agreement (PA), a large majority of countries representing more than 90–95% of global greenhouse gas (GHG) emissions have submitted climate pledges labeled as Nationally Determined Contributions (NDCs). However, countries' NDCs when aggregated have been found to be insufficient for paving the way towards meeting the PA temperature goals [3]. As part of its updated Nationally Determined Contribution (NDC) in 2021 [4], Tunisia has decided to strengthen its climate change mitigation strategy by adopting more ambitious targets and committing to reducing its national emissions intensity (emissions per unit of gross domestic product-GDP) by 2030 to 45% below the 2010 level if international financial support is provided, while in its initial NDC, the reduction goal was only a reduction of 41%. In addition, in its Unconditional NDC target, Tunisia committed to reducing its emissions intensity by 28% by 2030 compared to 2010 levels, while in its first NDC, the reduction goal was only 13% [4].

These updated NDC targets requires the mobilization of all major pollution-emitting sectors, such as industry, agriculture, energy, forestry and waste. Emission reductions compared to the BAU trajectory are projected to amount to 87.5 Mt CO_2 from 2020–2030 [3]. These emission reductions come principally from the energy sector, accounting for 72% of the overall effort; agriculture, forestry and other land uses (AFOLU) accounting for 13%; and industrial processes for 9%; while the remaining 6% of the mitigation results stem from the low-carbon policies of the waste sector [4]. The NDC strategy covers all economic sectors and relies chiefly on the transformation of the energy sector towards the use of sustainable energy sources, including sectoral targets for renewable energy capacities and energy efficiency improvements in the demand sectors.

In Tunisia, although there is support for climate policy at the middle management level [4], high political commitment is missing due to frequent changes in government and generic post-revolutionary challenges. Between 2015 and 2019, only three mitigation projects were carried out but information regarding their mitigation potential is limited [5]. The state-owned Tunisian Company of Electricity and Gas (STEG) hinders the development of renewable energy projects by the private sector. Although Tunisia has prepared and drafted various Nationally Appropriate Mitigation Actions (NAMAs), the dearth of financing does not allow clean energy projects to be implemented. The recent low rates of economic growth, the financial shortages and the monopolistic market structure in the electricity market are the main reasons for the limited climate action progress in Tunisia [5].

Tunisia has a power production capacity of 5547 MW installed in 25 power plants, which produced 19,252 gigawatt hours in 2018 [6]. The Tunisian power sector is relatively well developed as the entire population enjoys access to national electricity grid. Most electricity is generated from fossil fuels, primarily natural gas, which is mostly imported (mainly from Algeria). Local gas production comes from the concessions of the country's national exploration company and foreign companies' concessions [7]. Electricity generated from renewables covered only about 3% of the total power production in 2018. Primary energy demand in Tunisia has been steadily increasing in last decades [8]. While Tunisia has planned to increase its renewable energy production, the current policy settings, infrastructure and investment plans do not ensue these goals.

Despite its increasing energy consumption needed to meet growing mobility, industrial and residential requirements, Tunisia is promoting the diversification of its energy supply through the deployment of renewable energies based on the exploitation of domestic hydro, wind and solar resources [8]. Tunisia's government has committed to building institutional and technical capacities in the energy sector as a response to climate change issues. The implementation of the revised NDC targets will lead to a reduction in national emissions intensity to 28–45% below 2010 levels (depending on international financial support). This heightened ambition relative to its first NDC demonstrates Tunisia's willingness to deploy more domestic efforts towards the attainment of its increased commitment to mitigate climate change.

According to the revised Tunisian NDC, over the period of 2021–2030, the implementation of energy conservation programs will result in an average of 3.6% reduction in primary energy intensity and a 12% share of renewable energy in primary energy consumption until 2030 [8]. Over the same period, as a result of the implementation of measures related to the rational use of energy, the industrial sector will improve its energy efficiency [9]. The transport sector, through organized urban travel and the gradual introduction of electric vehicles, is expected to contribute about 37% to the overall mitigation effort; the contribution of the building sector to emission reduction included in the Tunisian NDC accounts for about 25%, triggered mostly by energy efficiency improvements.

There have been some previous efforts to quantify the impacts and requirements for the low-carbon transition in Tunisia, but the research is fragmented and does not cover all sectors of the energy system. For example, all previous decarbonization studies focused on the transformation of the Tunisian electricity sector [4,10], neglecting the potential for emission reduction from energy demand transitions, e.g., in the transport and industrial sectors. Other studies focused on specific topics, e.g., on the integration of North Africa and EU electricity systems [11], while others developed only stylized projections for the decarbonization pathways in African countries without considering national energy and climate policies and NDCs and the links between electricity generation and demand sectors [8]. Lastly, so far there has been limited research on developing pathways for Tunisia by exploring deep decarbonization goals, while covering all energy-related emission sources. These are the main research gaps that we aim to cover in the current study.

This paper provides a quantitative model-based analysis of energy system restructuring and clean technology uptake in the case of Tunisia in order to meet its NDC targets for 2030 and then engage in the transition to low emissions by 2050. Using a comprehensive energy system model (MENA-EDS) [12], the study covers in detail the interactions between energy demand and supply and estimates the required investment in low-carbon technologies in order to meet the Tunisian emission reduction targets. The study shows that NDC implementation largely relies on the transformation of the electricity sector with the rapid up-scaling of renewable technologies combined with the reduction of fossil-based power generation by 2030. Implementing the Tunisian NDCs can set the path towards the structural transformations required to ensure a low-emission development strategy compatible with the Paris Agreement goals [7]. Tunisia has large renewable energy resources that can be exploited to replace fossil fuel use in and beyond the power sector. Enhanced climate policy ambition can increase renewable energy expansion and accelerate energy efficiency improvements and the electrification of end-uses. As Tunisia's economy relies heavily on hydrocarbon imports, numerous opportunities exist in reducing its energy import bill through developing domestic renewable energy and reducing fossil fuel imports [8].

This article investigates, discusses and analyses all options of reducing emissions related to both energy supply and demand—as well as their complex interlinkages—aiming to provide a holistic assessment of energy transition strategies in Tunisia by 2030 and 2050, which is currently lacking in the scientific literature. As the modelling methodology is based on the analysis of integrated energy systems, it provides new, innovative insights on the synergies and trade-offs between demand and supply-side mitigation options in Tunisia, with a focus on the interlinkages between renewable energy expansion, the electrification of end-uses and energy efficiency improvements. Our study assesses the interplay between (Conditional and Unconditional) NDC targets for 2030 and the way these can become a roadmap toward long-term, low-emission development strategies. The article also explores the link between national decarbonization efforts and the global cost-optimal Paris-compatible pathways, as included in the IPCC Special Report on 1.5 °C [13,14], paving the way for innovative research on synergies between national strategies and the aspirational long-term global Paris goals. This article emphasizes key challenges and opportunities for Tunisia's energy transition, provides policy recommendations on how to implement its NDC targets for 2030 and even raises its climate ambition towards a low-emission, sustainable and climate resilient development by 2050 compatible with the Paris goals.

The energy system modelling and the scenarios examined in the study are described in Section 2. The model-based projections related to the implementation of NDCs and low-emission long-term targets are included in Section 3, while Section 4 discusses the main results and policy implications, and Section 5 describes future work and concludes the article.

2. Materials and Methods

This section presents a detailed description of MENA Energy Demand and Supply (EDS) model and the alternative policy scenarios examined. The article focuses on Tunisia, which is the northernmost country in Africa. Tunisia (Figure 1) is a part of the Maghreb region of North Africa and is bordered by Algeria to the west and southwest, Libya to the southeast and the Mediterranean Sea to the north and east. It covers 163,610 km^2 (63,170 sq mi) and had a population of 12.1 million in 2020. It contains the eastern end of the Atlas Mountains and the northern reaches of the Sahara desert; much of its remaining territory is arable land. Its 1300 km (810 mi) of coastline include the African conjunction of the western and eastern parts of the Mediterranean Basin.

Figure 1. Map of Tunisia and neighbors. The image was taken from https://www.freepik.com/free-photos-vectors/Tunisia-map under open license (accessed on 23 September 2022).

2.1. MENA-EDS Model Description

The MENA-EDS model is a country-scale model that provides detailed projections of energy demand, supply, power generation mix, carbon emissions, energy prices and investments in the future. This fully developed energy demand and supply simulation model includes relations covering all main variables concerning the energy-economy system and energy system analysis. The model includes demographic and economic activity indicators, energy consumption (primary and final), fuel mix by sector, fuel resources, fuel prices, CO_2 emissions and technology dynamics for key energy- and power-producing technologies. It also provides electricity system planning, energy system analysis and assesses climate and emission reduction policies by sector for the Middle East and North Africa (MENA) countries, including Tunisia [15]. The MENA-EDS uses various sources of data, including the IEA database [16] (for energy consumption by sector and detailed energy balances), Enerdata [17] (for energy prices and power generation capacities), EDGAR [18] (for CO_2 emissions), the World Bank [19] (for economic indicators and transport activity), UN population prospects [20] (for data and projections for population), BGR [21] (for hydrocarbon resources), OICA [22] (for vehicle and car stocks) and the European Commission [23] (for technology costs). The model uses actual data until the year 2020.

MENA-EDS represents the entire chain of energy supply through primary fuel extraction, energy transformation (power generation, refineries) and supply to final consumers covering the main energy end-use sectors, including industries, transport, agriculture and buildings. The interactions between energy demand and supply are governed by market-derived prices to balance energy demand and supply. The fuel mix used in each demand and supply sector and the investment required and the impacts of various policy instruments, such as carbon prices, energy taxes or subsidies, technology standards and policies promoting the uptake of energy efficiency, renewable energy and other low-carbon technologies are determined by the MENA-EDS model endogenously.

MENA-EDS is a recursive dynamic energy system simulation model. Endogenous model variables (e.g., energy consumption) are calculated based on the evolution of explanatory variables (e.g., economic activity, energy prices) through econometrically estimated elasticities and other parameters (e.g., Heating or Cooling Degree Days) and policy-related variables (e.g., carbon price). The economic decisions regarding the investment and operation of the energy system and related technologies are based on the myopic anticipation of future technology costs and system or climate constraints. The model uses myopic anticipation, while some foresight can be forced in the electricity production sector. The core operating principle of the MENA-EDS model is that of market equilibrium [12]. The representative agents included in the modelling framework (e.g., energy consumers, power suppliers) use information on energy commodity prices and decide on the allocation of resources [12]. These representative agents interact with each other through the energy markets, simulated in MENA-EDS [24]. The model utilizes a set of market prices so that supplies and demands are balanced in all energy markets [25]; in other words, market equilibrium is assumed to take place in each of the energy markets (partial equilibrium). The demand and supply modules interact with each other in the solution process based on market prices until the demand–supply equilibrium is reached.

In each demand sector, the model examines substitutions among fuels and technologies and the possibility for energy efficiency improvements. It also incorporates sector-specific energy technologies and emulates the cost-driven competition between different energy forms, such as oil products, coal, electricity, gas, traditional biomass, biofuels and hydrogen. The total cost of alternative, competing options includes fuel costs, carbon costs, capital expenditures as well as operation and maintenance (O&M) costs. Many factors, such as income growth, activity evolution, climate policies, energy prices and efficiency improvements determine the energy demand by sector, while other factors, such as behavioral changes, energy prices and stock turnover, can influence the development of vehicle markets. Specific technologies are represented in the transport sector, including conventional vehicles, plug-in hybrids, electric and hydrogen fuel-cell vehicles, while their competition is driven by relative costs, commercial maturity and supportive policies.

A detailed representation of power generation is included in MENA-EDS [24,26], based on the bottom-up modelling of several power-producing technologies (coal, oil, gas, nuclear, hydro, biomass, wind onshore and offshore, solar PV and CSP, Carbon Capture and Storage (CCS)), sectoral load profiles, own-consumption of power plants, electricity trade between countries, transmission and distribution losses [25,26]. Under technical and operational constraints, the model minimizes the total electricity generation costs, including both capital expenditures and O&M and variable fuel costs.

In terms of simulating the substitutions of fossil fuels with zero or low carbon technologies, the MENA-EDS model has the capability to explore ambitious mitigation scenarios through various technological configurations and policy measures, both market-oriented and regulatory. Thus, MENA-EDS can simulate the evolution of both energy demand, covering several energy end-uses, and energy supply, with a focus on the electricity system operation and the dynamics of capacity expansion. In this study, the model is used to investigate Tunisia's energy transition pathways for achieving its NDC targets by 2030 and its longer-term, low-emission, climate-resilient strategies.

2.2. Scenario Design

This study considers a business-as-usual (BAU/Reference) scenario that contains only already implemented energy and climate policies (without the mitigation actions included in the Tunisian NDC). Our BAU/Reference scenario is fully consistent with the BAU scenario included in the Tunisian NDC [27]. In BAU, the Tunisian energy system is based on the continuation of already legislated policies, current trends, existing plans and cost improvements in low-carbon technologies, without considering additional climate targets, with fossil fuels remaining the prime forms of energy until 2050 (Table 1).

In NDC scenarios, Tunisia is assumed to achieve the emission reduction targets included in its Unconditional and Conditional NDC goals, i.e., a reduction of emissions intensity by 28% and 45% over 2010–2030, respectively. These targets are met by a mixture of mitigation actions, as included in the Tunisian NDC (e.g., 12% share of renewable energy in primary energy consumption in 2030, 34% energy savings from BAU [27], reduced upstream waste generation, and a 35% emission reduction in the AFOLU sector). This study assesses the potential energy system transformations to achieve the Tunisian NDC targets, considering that the electricity and transport sectors are the major carbon-emitting sectors in Tunisia [27,28].

Table 1. Summary of key assumptions used in policy scenarios, source of data [27].

Scenario	Policy Targets and Instruments
Reference (BAU)	Current trends and already implemented energy and climate policies
Unconditional NDC	Emission intensity of GDP declines by 28% over 2010–2030, implementation of Unconditional mitigation actions included in Tunisia's updated NDC across all energy demand and supply sectors
Conditional NDC	Emission intensity of GDP declines by 45% over 2010–2030, the implementation of conditional mitigation actions included in Tunisia's updated NDC across all energy demand and supply sectors
2 °C Compatible	Based on climate change mitigation pathways of MENA region compatible with 2 °C (IPCC SR1.5 database): 2% CO_2 emissions reduction over 2010–2050 based on Conditional NDC actions combined with carbon pricing
1.5 °C Compatible	Based on climate change mitigation pathways of MENA region compatible with 1.5 °C (IPCC SR1.5 database): 35% CO_2 emissions reduction over 2010–2050 based on Conditional NDC actions combined with carbon pricing

The establishment of national and international market-based mechanisms based on an economy-wide carbon price can be exploited to achieve the emission reduction goals of Tunisia's NDC. In this paper we explore different scenarios which ensure that Tunisian development is compatible with the Paris goals of keeping the global temperature increase to "well-below 2 °C" and further limit any increase to 1.5 °C. According to the IPCC Special Report [14], this requires net-zero carbon emissions by 2050–2070, depending on the total transformation of the energy supply, as well as the decarbonisation of transport, buildings and industrial sectors. However, global warming is a global challenge, leading to increased temperatures, frequent wildfires and droughts, shifting rainfall patterns and rising sea levels. In this context, energy transition is vital to mitigate climate change impacts based on the transformation of the global energy sector from fossil-based to zero-carbon by 2050. Each country's mitigation effort is highly dependent on the current status of national energy-economy systems, its capacity and capability to perform climate actions (according to the "common but differentiated effort principle" included in the Paris Agreement) by implementing various policies and equity considerations, while high-income countries should provide financial and technical support to developing ones [29].

To avoid severe climate change impacts, the global warming must stay well below 2 °C (or even 1.5 °C). Until now, a comprehensive and widely accepted methodology to assess whether national emission pathways are compatible with these Paris goals has not existed. Here, we use the comprehensive IPCC SR1.5 database (https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/, accessed on 22 September 2022), including many model-based mitigation and climate stabilization scenarios, and we assess what the global targets of "well-below 2 °C" or "1.5 °C" imply for emission pathways in the Middle East and Africa region (R5MAF), combined with a recent study on low-emission transition pathways in African countries [8]. Based on the methodology described above, Tunisia should reduce its CO_2 emissions by 2% over 2010–2050 to ensure compatibility with the well-below 2 °C goal, while the 1.5 °C target requires even larger reductions (of about 35% in 2010–2050 period) in Tunisian CO_2 emissions. These targets are achieved by combining the sectoral mitigation actions and plans as included in the Tunisian NDC with the imposition of an economy-wide carbon price to reduce fossil fuel consumption up to the level that ensures the specific emission reduction targets are met by 2050.

The overall study design and modelling methodology is displayed in the schematic flow below (Figure 2).

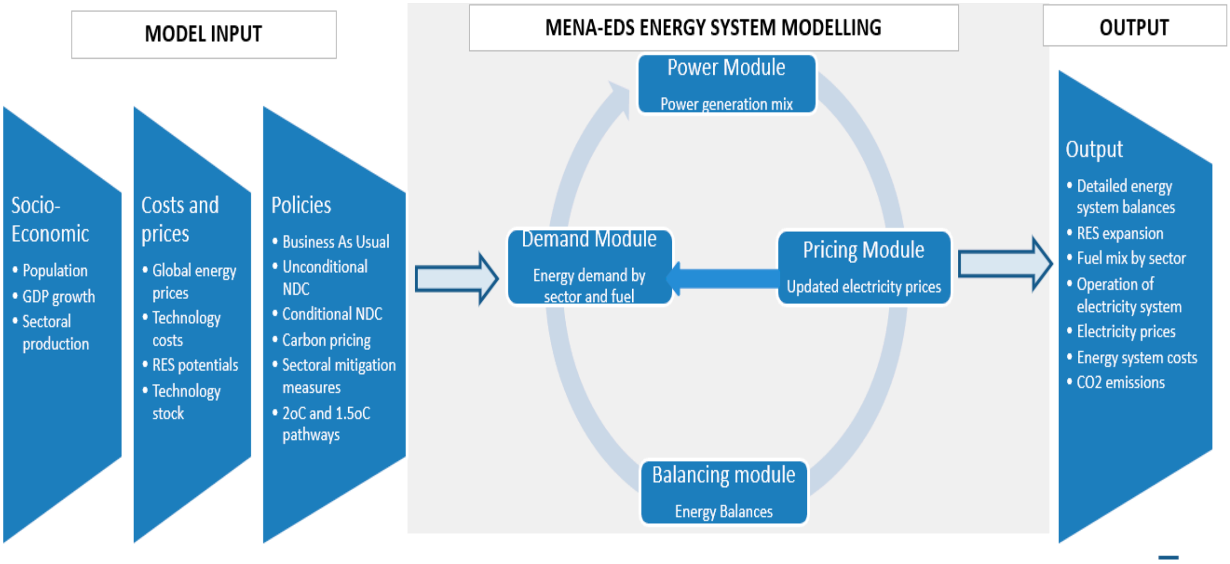

Figure 2. Schematic flow of the study design.

3. Model-Based Results

The current section describes the model-based projections for the period until 2050 under the alternative climate policy scenarios described above.

3.1. Energy and Emissions Development in BAU Scenario

Tunisia's energy situation is characterized by its high fuel import dependence; its high use of fossil fuels in the transport, electricity and industrial sectors; and its fiscal deficit. Tunisia's energy consumption has been increasing in the last decades; specifically, between 2000–2010 there was an increase of 3.5%/year, while the growth rate amounted to 1.7%/year in the period 2011–2019, and in 2020, energy consumption dropped by 6% as a result of COVID-19 restrictions and lockdowns [29]. Electricity production is dominated by gas-fired power plants, despite the recent policy developments and NDCs. In the business-as-usual (BAU) scenario, where there is a lack of strong climate policies, the energy consumption is projected to increase following GDP and population growth and the rising standards of living (Figure 3). Some efficiency improvements and structural changes result in a reduction of energy intensity per unit of GDP, following the relative slowdown of energy demand growth after 2010 because of energy market reforms and the gradual uptake of more efficient technologies. Despite the gradual deployment of renewable energy in the electricity sector (especially wind and PV) following technology cost improvements and existing policies, fossil fuels-oil and natural gas-will continue to dominate the Tunisian energy mix (Figure 3), accounting for 86% of primary energy consumption in 2050 [13].

Final energy consumption is projected to increase in all end-use sectors triggered by rapid GDP and population growth, urbanization trends and rising standards of living and comfort (Figure 4). Energy consumption is distributed among different economic sectors with the transport sector (public transport, private cars, trucks, logistics) having the highest energy consumption in 2050 (Figure 4) with a share of about 40% in total consumption. As incomes grow, rapid motorization and increasing rates of car ownership are expected to push transport consumption upwards. Energy consumption in freight transport is closely linked to economic activity and thus is projected to increase steadily. Industrial activities require enormous amounts of energy despite some efficiency improvements. Oil products, biomass, electricity and natural gas are used for cooking and water heating purposes. In the BAU scenario, increasing energy requirements are mostly covered with imported fossil fuels while the share of electricity in energy demand is projected to gradually increase. In order to meet the increasing demand for electricity, Tunisia allows private SMEs and the households to produce green electricity utilizing co-generation and other renewable energy technologies, generating electricity for their own consumption, while the electricity surplus can be sold to STEG at a fixed price [10,30]. The rapidly growing energy demand and the decline of Tunisian fossil fuel deposits implies that the use of domestic renewable energy sources, such as hydro, solar and wind, has the potential to offer multiple benefits in Tunisia, including enhanced energy security, reduced fossil fuel import bill, lower electricity costs and enhanced resilience to fuel import prices.

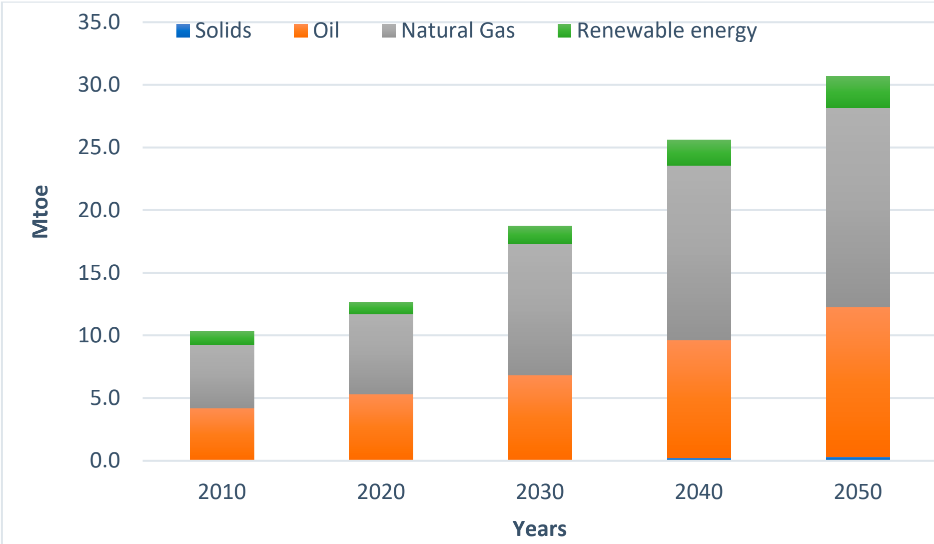

Figure 3. Gross inland energy consumption by source in Mtoe over 2010–2050 in Tunisia (BAU scenario). Source: MENA-EDS Model (BAU scenario).

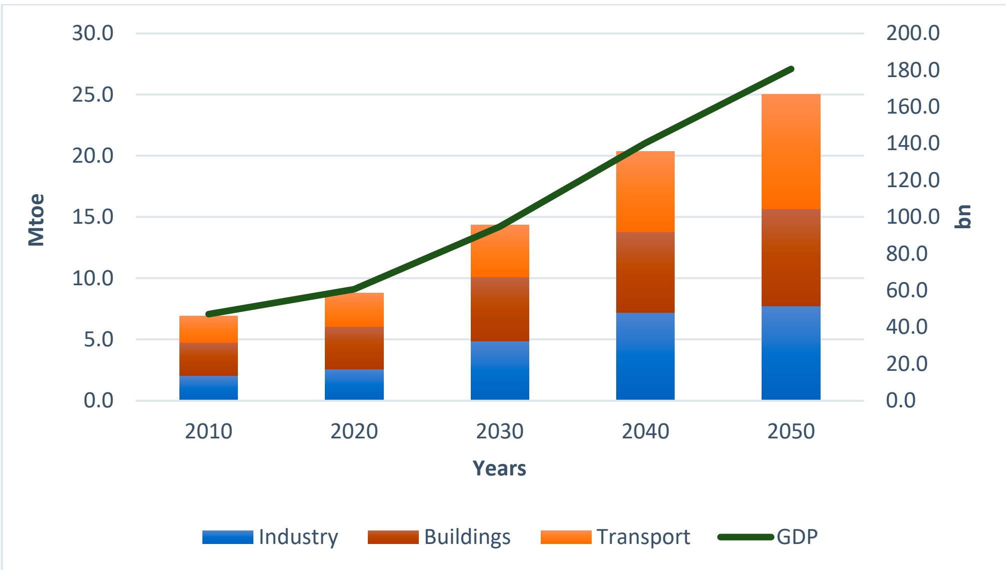

Figure 4. Sectoral split of final energy consumption (Mtoe) in Tunisia (left axis) and GDP (bn) evolution (right axis), over 2010–2050 (BAU scenario). Source: MENA-EDS Model (BAU scenario).

The Tunisian government, in order to meet growing electricity demand and increase country's energy security, is highly interested in diversifying its energy mix into renewable energy technologies (especially wind and solar). The new Tunisia Solar Plan (TSP) aims at raising the generation from renewable energy resources to 30% of total electricity production by 2030 [31]. In recent years, only a few companies have invested in fossil fuel extraction because the Tunisian government has discontinued research licenses, and companies have oriented themselves toward alternative energies and biofuels [32].

In March 2022, the Tunisian government announced the approval of solar energy projects in the south of the country (Tataouine, Tozeur, Sidi Bouzid, Kairouan and Gafsa), designed to service Tunisia's domestic energy needs [29]. The 2030 target of the 30% share of renewable energy in the power mix will be translated into an additional renewables-installed capacity of 3815 megawatts (MW) by 2030, compared to the 2017 installed levels [32]. In our BAU scenario, Tunisia's solar energy capacity in 2030 will reach 1.2 GW, falling short of the Tunisian Solar Plan goals. However, these renewable capacity goals are achieved in the Unconditional and Conditional NDC scenarios, where the solar capacity is projected to reach 1.7 GW and 2.8 GW, respectively, making the Tunisian Solar Plan strategy possible, especially in case of international financial support.

Tunisia enjoys a vast solar potential, with an average of 3000 h of sun/year [33], implying that the country can become a centre of renewable energies. Tunisia can be turned into a low-carbon model where modern, clean technologies can benefit local communities through providing reliable energy sources and cheap, low-emission electricity, boosting job creation and further enhancing economic development (Figure 5).

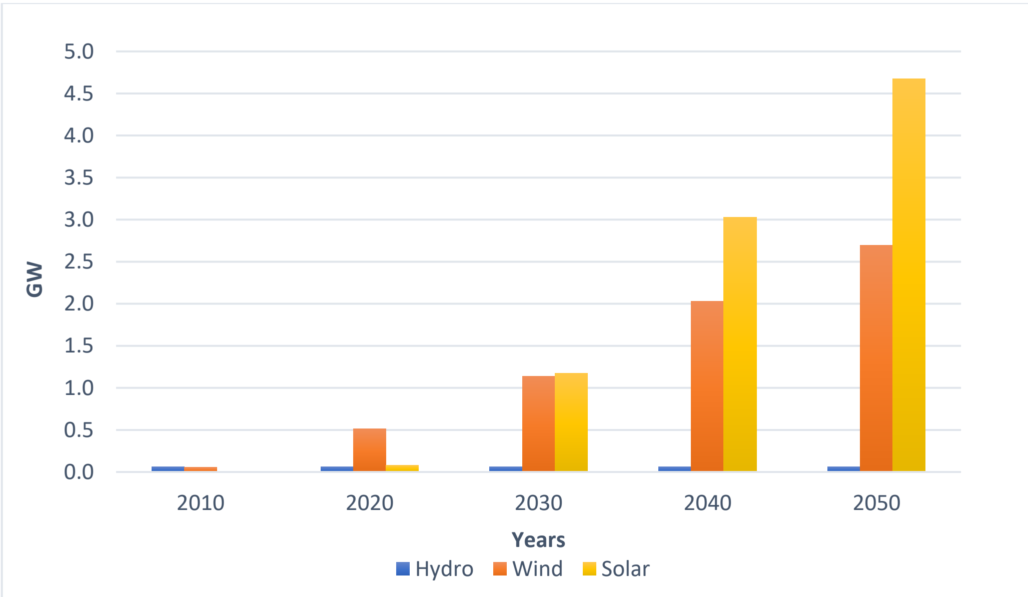

Figure 5. Renewable technology capacity (GW), over 2010–2050 in Tunisia (BAU scenario). Source: MENA-EDS Model [25].

3.2. How can Tunisia's NDC Targets Be Achieved?

With currently implemented policies and measures, Tunisian CO_2 emissions from energy use in the BAU scenario are projected to increase by 2050, due to the high GDP and energy demand growth, rising standards of living and limited climate action [34,35]. Tunisia's CO_2 energy-related emissions are projected to increase from 23.2 Mt CO_2 in 2010 to 72 Mt in 2050, i.e., a growth of 3% annually in line with historical trends and the BAU of the Tunisian NDC [4]. Carbon emissions are increasing in all sectors, but transport and electricity production will remain the highest emitting sectors by 2050 (Figure 6).

With its revised NDC, Tunisia's domestic climate effort will result in a reduction of emissions intensity of 28% below 2010 levels by 2030 and with international financial support the target could increase by an additional 17%, i.e., increasing the emission intensity reduction target to 45% in the 2010–2030 period.

The implementation of Tunisia's mitigation targets included in its NDC requires the mobilization of significant financial resources estimated at around USD 19.3 billion [36] to cover the investment needs of the NDC pathway over the period 2021–2030 [36]. Current policies and plans as included in BAU fall short of meeting Tunisia's NDC Conditional and

Unconditional targets and need further strengthening to ensure that the country achieves its emission pledges by 2030.

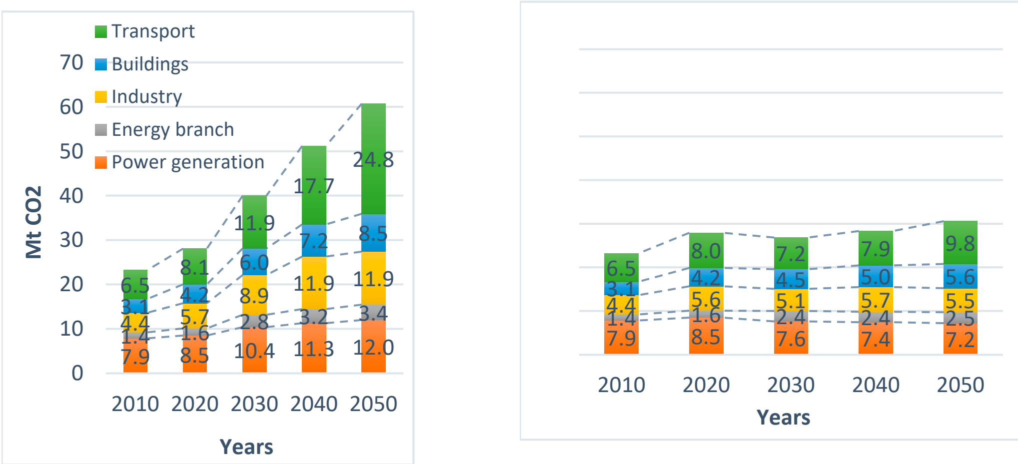

Figure 6. Tunisia's CO_2 energy-related emissions by sector (Mt CO_2), over 2010–2050 (**Left**: Unconditional scenario, **Right**: Conditional scenario), Source: MENA-EDS Model (Unconditional and Conditional NDC Scenarios).

The implementation of Tunisian NDC targets heavily relies on the transformation of the country's energy sector aiming at reducing dependence on fossil fuel imports and increasing the share of renewable energy, while meeting growing energy demand to ensure the socio-economic and industrial development and well-being of its citizens [34]. The most important sectoral plans and targets under the Tunisian NDC are as follows: the share of renewable energy in power generation should increase to 30% by 2030; the energy consumption should decline by 13% relative to BAU levels by 2030; inefficient fossil fuel subsidies should be eliminated; the use of gas-instead of oil-through infrastructure projects should be increased, allowing liquefied natural gas import plants; market-based emission reduction mechanisms should be established; and renewable energy programs based on the facilitation of renewable energy investment should be implemented. The emission reduction effort to achieve the Unconditional NDC target relative to the BAU scenario (or the "emission gap", as often mentioned in policy debates [37]) is estimated at 8 Mt CO_2 in 2030, while the "gap" with the Conditional NDC target amounts to 16 Mt CO_2 in 2030.

Based on comprehensive energy system modelling with MENA-EDS, covering energy demand and supply sectors, cost-effective pathways for the implementation of Tunisian NDCs are derived. The model-based assessment shows that the "gap" between the BAU scenario and NDC targets for 2030 can close with ambitious climate action largely based on the expansion of renewable energy, efficiency improvements and the reduction of fossil fuel-based power generation. The electricity sector is a major contributor to achieving the Tunisian NDC targets by 2030, through the large-scale uptake of wind and solar plants can replace fossil fuel-based generation. Gas-fired combined cycles can support the large-scale deployment of variable renewables and provide an important flexibility option.

Efficiency improvements result directly in lower emissions in transport, buildings and industrial sectors. Efficiency is facilitated by the removal of fossil fuel subsidies, increased electrification, the uptake of efficient appliances, improved equipment and vehicles and energy management in industries. It is estimated that about 50% of Tunisian emissions occur in urban areas through the building sector (residential and tertiary), industrial activities and intercommunal transport. Therefore, there is high potential to reduce energy consumption by implementing energy efficiency projects and installing efficient appliances in buildings and scaling up industrial energy efficiency [29].

As the ambition increases in the Conditional NDC, the transport sector plays an increasingly significant role in reducing CO_2 emissions through the uptake of cleaner fuels (mostly electricity) to replace oil products, accelerated efficiency of vehicles, gradual shifts from individual traffic to public mass transport and additional mobility plans included in the NDC. The increased electrification of energy end-uses combined with the decarbonized electricity generation is a cost-effective way to meet Tunisia's NDC goals.

The electricity sector transformation with large-scale increase in solar and wind power is a major pillar for Tunisia's transition, as the country has large renewable energy potential that can be efficiently exploited [7]. Gas-based generation will provide flexibility to the large-scale growth of variable renewable energy sources [38]. In MENA-EDS projections, the share of renewable energy in electricity generation will increase from 3% in 2015 to 43% in 2050 in the Unconditional scenario and further to 65% in the Conditional NDC scenario, driven by the high uptake of solar PV, CSP and wind turbines (Figure 7).

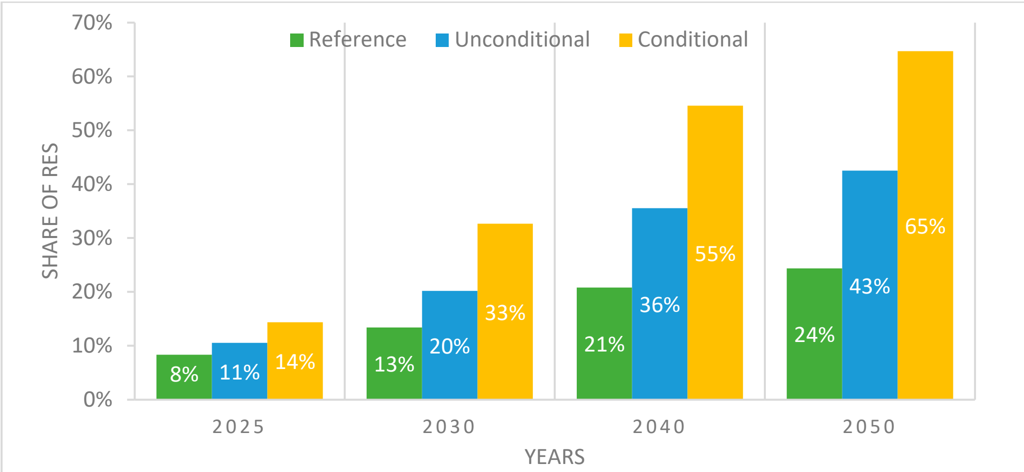

Figure 7. Share of RES (%) in electricity generation across different scenarios over 2025–2050. Source: MENA-EDS Model (Reference, Unconditional and Conditional NDC Scenarios).

The deployment of renewable energy will lead to a drop in fossil fuel-based power generation from BAU levels. Despite lower electricity requirements than BAU (due to energy efficiency measures in buildings and industries), the uptake of solar and wind power requires increased investment in electricity capacities [39]. Investment is also required for the implementation of energy efficiency measures in end-use sectors. The model-based estimates on investment are consistent with those included in the Tunisian NDC. As Tunisia relies heavily on fossil fuel imports, the development of domestic renewable energy to meet NDC targets combined with increased energy efficiency will lead to a large reduction of energy imports, especially in oil and natural gas. The energy import dependence of Tunisia would decline from 51% in the BAU scenario in 2030 to 44% in the "Unconditional NDC" and further to 31% in "Conditional NDC" scenario (Figure 8). The improvement in security of energy supply is even more profound in 2050, with Tunisian import dependence declining from 64% in BAU to 30% in the Conditional NDC, implying that energy imports are reduced by 15 Mtoe, through energy savings and the expansion of renewable energy.

If it was to meet its NDC targets, the Tunisian economy would use its domestic energy resources more efficiently than in BAU. NDC implementation would lead to large reductions both in the energy intensity of the economy but also in the carbon intensity of energy consumption, driven by the shift away from fossils and the uptake of renewable energy, especially in the electricity sector (Figure 9).

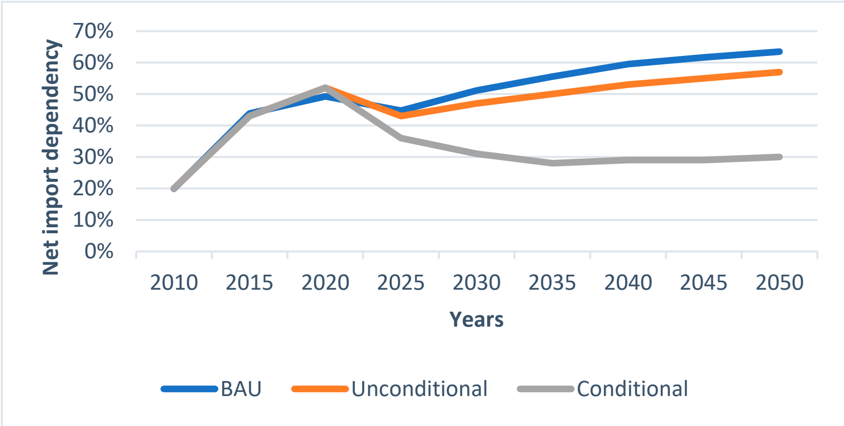

Figure 8. Tunisia's net import dependency in different scenarios until 2050 (in %). Source: MENA-EDS Model (Scenario: BAU, Conditional, Unconditional).

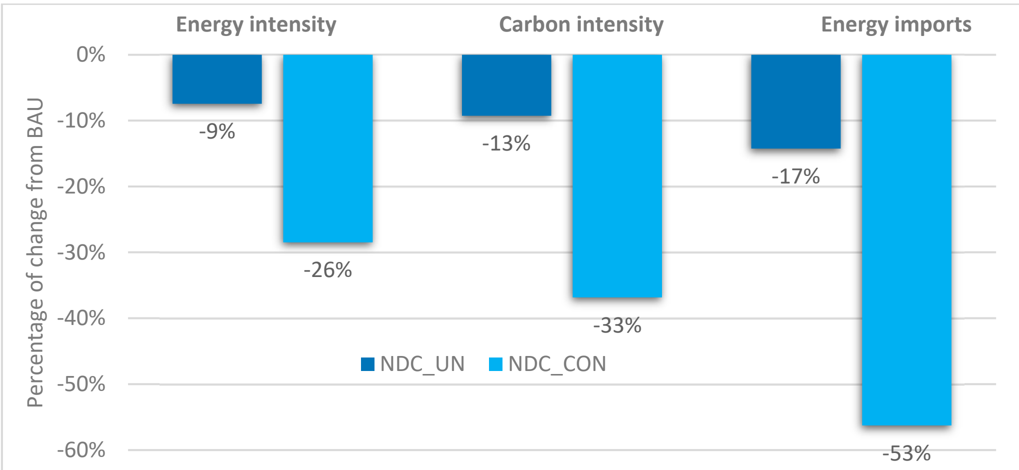

Figure 9. Key energy systems and emission indicators of Tunisia in 2030. Source: MENA-EDS Model.

3.3. Tunisia's Long-Term Paris-Compatible Pathways

This section assesses whether Tunisian NDC targets are adequate to ensure compatibility with the Paris goals, using data from the IPCC SR1.5 database. Figure 8 shows Tunisia's emission pathways in different scenarios, where the NDC effort is extrapolated after 2030 by assuming that carbon prices are increasing with the GDP growth rate, as in [30], indicating constant climate policy intensity. The Conditional NDC leads to a relative stabilization of CO_2 emissions in Tunisia in the 2015–2030 period, aligned with the effort for MENA region considered compatible with the 2 °C goal [5]. However, after 2030, an increased climate policy effort is required to ensure that Tunisia remains on track for Paris-compatible paths (Figure 8). In 2050, the emissions "gap" of the NDC scenarios with pathways towards the well-below 2 °C and 1.5 °C goals is estimated at 25–50 Mt CO_2 for the Unconditional NDC scenario, declining to 13–20 Mt CO_2 in the Conditional case; but in any case, the emission reduction effort included in the Tunisian NDC should accelerate considerably after 2030 to ensure consistency with Paris-compatible pathways in the long-term.

Using the MENA-EDS model we explore the low-carbon development pathways for Tunisia based on energy system transformation to ensure deep emission reductions. This is achieved through increased climate policy ambition combined with transformative sectoral strategies, high carbon pricing, and other policy measures from 2025 onwards on top of those already included in NDC scenarios. Although carbon dioxide removal (CDR) solutions are required for the transition towards 1.5 °C, the recent literature predicates that these solutions are not a substitute for emissions reductions. There are important limitations in the deployment of CDR, including risks related to land use, high costs and uncertainties regarding the potential of CO_2 storage capacity combined with little societal support [34]. Therefore, we assume that CDR technologies will not be deployed in Tunisia by 2050 [27]. Based on scenario projections with MENA-EDS model, Figure 10 shows Tunisia's carbon emissions pathways compatible with the Paris goal of keeping global temperature at 1.5 °C and well below 2 °C. Cost-effective national decarbonisation pathways need a higher climate policy effort than the NDCs. In Tunisia, scaling up international finance and developing robust strategies towards net-zero are necessary to support decarbonization and compatibility with Paris goals.

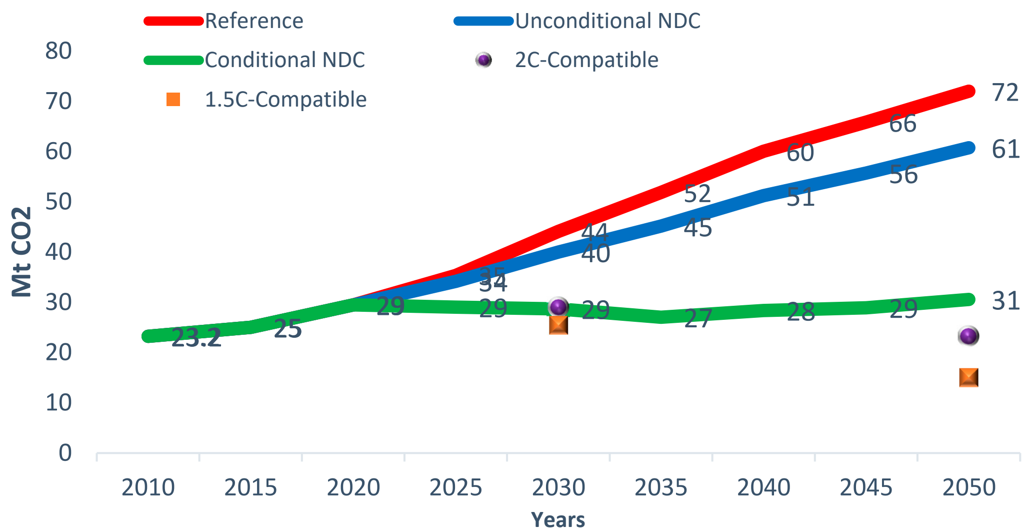

Figure 10. CO_2 emission pathways in Tunisia under NDC and Paris-compatible scenarios in 2010–2050. Source: MENA-EDS Model, Author estimates.

The model-based analysis shows that even low carbon prices (of about USD 20–30/tn CO_2) may lead to a large-scale exploitation of available emissions reduction opportunities with uptake of cost-efficient technologies, especially low-cost renewable energy that can be exploited at low cost (Figure 11). However, additional abatement opportunities are diminishing [28], and thus, to ensure compatibility with the Paris 1.5 °C goal, the carbon price should massively increase to about USD 80/tn CO_2 in 2030. Moving towards 2050, with emission reduction effort will constantly increase and the required carbon price will increase steeply to about USD 400/tn CO_2 as low-cost mitigation options have already been exploited and currently immature and expensive low-emission technologies and fuels need to be widely deployed to decarbonize hard-to-abate sectors, such as industry and specific transport segments [40,41].

Ambitious climate policies would induce deep transformations in Tunisia's energy system, based on four inter-connected pillars: uptake of renewable energy, electrification of end-uses, energy efficiency improvements and the reduced carbon intensity of the fuel mix. The electricity sector should be restructured with large investments in renewable energy, while strengthening as well as expanding the transmission and distribution grids so that it can integrate larger shares of renewable technologies in the long term. The share of renewable energy is projected to increase rapidly from 3% in 2015 to 33% in 2030 and further to about 65% in 2050 in the NDC conditional scenario and to about 75% in the 1.5 °C compatible scenario. The vast Tunisian renewable energy resources could dominate the power generation mix by 2050 through the massive uptake of solar and wind power [42], combined with their large technology cost reductions and limitations in hydroelectric and bioenergy potential and difficulties in implementing nuclear plants.

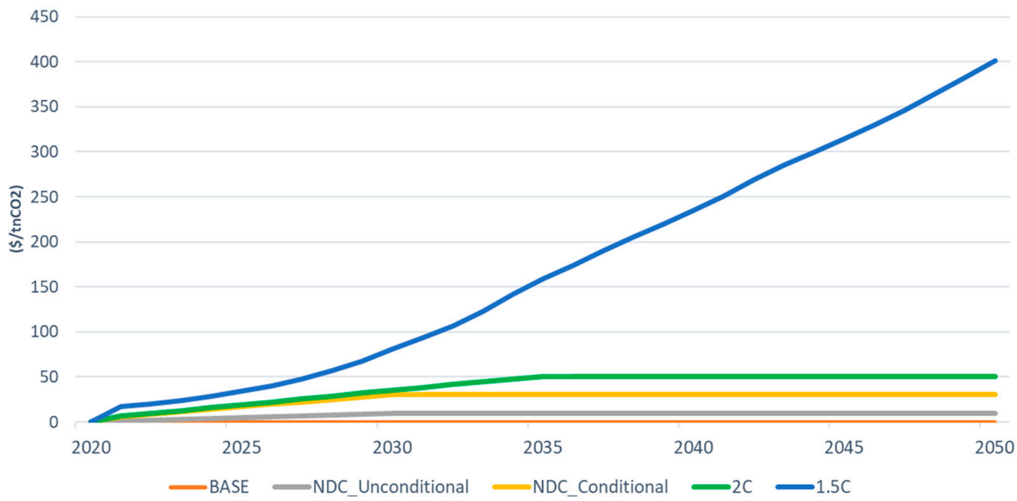

Figure 11. Tunisia's carbon price projections from 2020–2050 (in USD/tnCO_2), Source: MENA-EDS Model.

As power generation decarbonizes before 2050, the electrification of end-uses becomes an important strategy to reduce emissions, e.g., through uptake of electric cars. Electrification has been established in stationary energy uses, as appliances, lighting, air conditioning and other services are already powered by electricity. This trend accelerates ambitious mitigation scenarios with renewable-based electricity increasingly used in the buildings, transport and industrial sectors. The uptake of plug-in hybrid and electric cars is driven by technological progress, cost reductions, carbon pricing and transport policies. The electrification of end-uses is a prominent strategy to reduce emissions from sectors with limited mitigation potentials [43].

Reducing energy needs while delivering the required energy services could be implemented by accelerated efficiency improvements [44]. This is driven by: (i) the high uptake of energy-efficient energy forms, technologies, equipment and appliances; (ii) the investment in building envelopes and energy-saving policies; and (iii) the price-driven behaviour changes of consumers. Energy savings in turn imply reduced requirements for energy supply investments, thus further saving emissions [45].

In Tunisia, additional promising emission reduction options include: (1) the uptake of advanced biofuels in transport; (2) gas substituting for oil products; and (3) biomass and solar water heaters in buildings. The use of green hydrogen produced with renewable-based electricity in transport systems and industrial processes that cannot be electrified will also play a role in Paris-compatible pathways in the long term [46]. However, this requires a robust, ambitious and easily predictable policy framework to overcome technical, market and regulatory challenges and resolve relevant technology and cost uncertainties.

The implementation of Paris-compatible pathways will lead to the lower consumption and imports of fossil fuels in Tunisia. Energy import dependence will improve considerably by 2030, declining from 51% in the Reference scenario to 31% in the Conditional NDC and further to less than 30% in low-emission pathways in 2050. This leads to 15 Mtoe lower fossil fuel imports in the 1.5 °C compatible scenario than in BAU, indicating a significant reduction in energy import bill. As Tunisia heavily depends on hydrocarbon imports, opportunities abound to improve its energy supply security by developing domestic renewable energy plants. Tunisia may profit from the transition as it can be a key supplier of low carbon products, including renewable electricity and electric vehicles [42]. The rapid upscaling of mature, market-ready technologies (i.e., solar PV, wind) combined with the deployment of new, emerging options (i.e., batteries, electric vehicles, advanced biofuels) could significantly reduce Tunisian emissions to close to net zero by 2050.

4. Discussion

The NDCs highlight each country's effort to reduce domestic emissions and adapt to the effects of climate change. Tunisia, aware of climate challenges and its high environmental and socio-economic vulnerability to climate change, has set ambitious climate pledges in its updated NDC, aiming to reduce emission intensity by up to 45% below 2010 levels in 2030 in the case of international financial support (Conditional NDC target), while pledging to an Unconditional target of 28% reduction of emission intensity over 2010–2030 based only on domestic efforts.

Tunisia aims to prepare for the transition towards climate resilience with its actions primarily focusing on the sectoral level. Over the last few years, Tunisia's government has focused on the implementation of its NDC targets, largely based on clean energy transition. The country has made visible efforts to support the deployment of renewable energy and energy efficiency projects, pursuing a secure and low-emission energy future. Relevant legislations are also in place, combined with specific policy instruments on major emitting sectors.

Despite recent policy developments, Tunisia's energy consumption has been rapidly increasing in the last few decades and is still dominated by fossil fuels, while the plans for expansion of gas-powered electricity plants raise significant concerns. Political tensions may raise barriers for the implementation of the ambitious Tunisian NDC targets, delaying the installation of renewable energy projects [27].

To explore the impacts of policy developments, NDC strategies and potential Paris-compatible pathways, we used the MENA-EDS model to simulate a series of scenarios with different climate policy ambitions to explore energy sector transformation strategies. It is the first study to analyze mitigation options for Tunisia both in energy supply and demand sectors, including transport, buildings and industries, also capturing their complex interlinkages, e.g., through the electrification of energy end-uses. We also examined ambitious deep decarbonization scenarios for Tunisia, reaching about 80% emission reduction from baseline levels in 2050, requiring the fundamental transformations of the energy, industrial and transport systems of Tunisia. The analysis shows that Tunisia can explore its large renewable energy potential to decarbonize its economy, diversify its energy mix, eliminate inefficient energy subsidies and plan towards a cost-effective transformation, ensuring compatibility with Paris goals. Our analysis showed that the further development of renewable energy resources in Tunisia requires a supportive and well-established legal framework to overcome persistent structural challenges, which are the main reason for the limited expansion of renewables so far. Given that fossil fuels-oil and natural gas-dominate the Tunisian energy sector and its whole economy, the roadmap to an energy system based on renewable technology requires strong government support at all levels to be successful.

The benefits and opportunities of renewable energy should be comprehensible by decision makers and public authorities in order to gain further political support. If new investment is exploited, the vast renewable energy potential of Tunisia can meet its domestic energy needs and offer opportunities to export clean electricity or green hydrogen to European markets. This path can eliminate the current large dependence of Tunisia on energy imports and increase the energy security and boost domestic employment and sustainable economic development.

The implementation of Tunisian NDC is based on the electricity sector transformation with the rapid upscaling of renewable energy technologies (solar PV, CSP and wind) combined with the minimization of gas-powered energy generation by 2030-with the exception of those providing flexibility to a system dominated by variable renewables. Tunisia has recognized that energy efficiency plays an important role in implementing NDC targets for 2030 and has launched many energy efficiency projects targeting all sectors and consumer types, such as research and investment incentives, laws, taxes and awareness campaigns. Our model-based analysis showed that to meet its NDC targets, Tunisia should considerably increase its climate policy ambitions, with the implementation of strategies for the electricity sector transformation, the expansion of renewable energy and energy efficiency projects.

5. Conclusions and Future Work

The implementation of Tunisian NDC can pave the way towards structural systemic transformations required to ensure compatibility with Paris goals by 2050. The complete electricity sector restructuring with the large-scale expansion of renewable energy and accelerated energy efficiency improvements in all end-use sectors are key ingredients for a low-carbon transition. The transition towards renewable energy affects policy makers, stakeholders, industry and citizens as well; in order to be successful, it is crucial to involve the participation of citizens. Tunisian society seems to have limited information and knowledge about the positive socio-economic effects of renewable energy uptake. As the electricity sector is projected to decarbonize well before 2050, the increased electrification of energy services becomes a growing necessity to reduce emissions in end-use sectors. The rapid upscaling of mature renewable technologies (solar, PV, wind) combined with the deployment of newly emerging options (storage, biofuels, electric vehicles) can significantly reduce Tunisia's emissions close to net zero by 2050.

Tunisia has many opportunities to reduce its energy import dependence and import bill through a shift to clean energy technologies. Switching to renewable energy can improve the energy import bill and the balance of payments by strengthening energy security and limiting vulnerability to the fluctuations of oil and gas import prices. The development and uptake of renewable energy may contribute to economic growth, attract foreign investment and create new, high-quality jobs.

Tunisia can attract international green finance and become a major climate policy partner in the Mediterranean region and in Africa. The development of a committed low-emission energy strategy for the medium and long term will be based on renewable energy expansion, electrification and energy efficiency. The required investment for a decarbonized, renewable-based power generation may be high, as solar and wind technologies are more capital intensive than fossil-based options. However, this leads to large reduction in energy imports as well as in the fuel purchasing costs, while ensuring the diversification of Tunisia's energy mix.

Tunisia is making strong progress towards reliable and sustainable energy, although progress in reducing the energy intensity of its economy is more difficult to achieve, as demonstrated by the constantly increasing energy consumption. By developing renewable energy capacities to cut its dependency on imported gas, Tunisia may consider setting specific targets for the use of modern renewables, not only in the electricity sector (as is already underway), but also in the residential, industrial and transport sectors. The clean energy expansion targets in sectors beyond electricity provide large emission reduction potential that should be included in national policy plans. This will strongly promote the reduction of fossil fuel use across the economy, which comes with several co-benefits in terms of reduced air pollution, lower energy imports and stimulating green investment and jobs.

This study can be expanded in various directions that were not fully captured in this paper and could be the basis of future research. The current study does not analyze the broad socio-economic and industrial impacts of NDCs and low-emission strategies for Tunisia. These aspects should be covered in future works as well as the analysis of possible policy measures to boost the economy and create jobs. The deep decarbonization of sectors with hard-to-abate emissions (e.g., heavy industry, aviation) should also be explored. The model-based projections crucially depend on the assumptions made, especially on the values of specific elasticities, including the income and price elasticities determining the evolution of energy consumption by sector. A comprehensive sensitivity analysis on the values of these elasticities or on technology costs is required to consistently evaluate the impacts of NDCs and other climate policies. Finally, the addition of other modelling tools towards a multi-model scenario comparison study, as carried out in [46], can help us derive more robust policy recommendations.

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