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# Long-term Bottom-up Modeling of Renewable Energy Development in Morocco

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ABSTRACT

*Renewable energy is an essential source of green growth for countries facing a shortage of fossil fuels. They offer a sustainable, inexhaustible, carbon-free solution to the future energy dependency of nations. Morocco, which has no traditional energy resources, depends entirely on the international primary energy market to meet its growing demand. For this reason, Morocco launched the National Energy Strategy in 2009 to reach 42% renewable production by 2020. This strategy has been renewed to 52% by 2050. Thanks to this policy, the country has been able to address most of its energy challenges. This study analyzes the energy mix of Morocco from 2010 to 2050. The methodology adopted is to simulate Morocco's electricity mix for this period. We assumed we were at the beginning of deploying the country's energy policy to assess the adopted strategic decisions. The analysis shows that the different technological solutions for electricity production chosen at the beginning of Morocco's energy transition could be better. Indeed, the decision to develop concentrated solar power as the leading renewable source and coal as a backup option, for example, appears to be contested. However, according to the third scenario of our study, renewables have the potential to become the main source of energy for the Moroccan power grid.*

## 1 Introduction

This paper is an extension of work initially reported in the "2021 International Conference on Electrical, Computer and Energy Technologies (ICECET)" [1].

The Kingdom of Morocco relied primarily on foreign supplies to meet its growing energy needs during the first decade of the 21st century [2]. Forecasts for 2008 suggested that the country's high rates of population growth and urbanization, as well as its economic prosperity, would contribute to higher energy consumption and a greater mismatch between supply and demand [3]. This dependence on imported fossil fuels has widened the country's trade and financial deficits [4]. On the other hand, Morocco has significant potential to meet its energy needs through renewable sources such as hydroelectricity, solar energy, and wind power [5].

Considering the country's greatest renewable energy potential and the significant scarcity of fossil-fuel reserves, the kingdom initiated a new national energy policy in 2009 [6]. This strategy prioritized supply security, energy mix diversity, low cost, safety, efficiency, and environmental cleanliness [7]. This strategy intended to raise renewable energy's installed capacity share to 42% in 2020 and 52% in 2030 [8].

Although it has a percentage of renewable energy (RE) that is around 36.8%, Morocco has not yet accomplished the goal it set for itself in the energy transformation field. The target was to achieve a share of renewable energy in the power sector equal to 42 percent by the end of 2020 [9]. Despite this, the renewable energy targets specified have been increased to exceed the current goal of 52% of the national power mix by 2030 [10, 11].

The most significant delay was in the implementation of the Solar Plan [12]. This enormous project, with a significant capacity for electric energy production, has provided Morocco with a valid

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energy alternative and a tool for socioeconomic growth, allowing it to become a "reference" in Africa for renewable energy production! In addition, the accomplishments in the hydroelectricity field follow the goals. Towards the wind side, we expect to surpass the goals barely. Despite this, the cumulative impact of the two, whose targets will be surpassed in 2021, will not be sufficient to compensate for the delay in the solar plan [13]. Because of this circumstance, we began to wonder whether the decisions and approaches suggested in the Moroccan solar plan, developed after the energy strategy implementation, were especially relevant. In addition, we questioned the reliability of the guidance of the subject-matter experts who supported these choices.

In light of this, this article provides a historical and projected assessment of Morocco's electricity system. The plan is to simulate the power mix in Morocco from 2010 to 2050 as though we were at the beginning of the country's energy policy rollout. The analysis is based on OSeMOSYS (Open-Source Energy Modeling System), a long-term planning model that allows us to compute the energy supply mix that best fulfills the energy service demands in each year and a time step of the investigated scenario while reducing total discounted costs.

The remainder of this work will be organized as follows: First, we will go through the OSeMOSYS model and the applied analytical approach. In this section, we will go over the changes made to the model code's initial version. These changes provided a more accurate picture of Moroccan energy policy. Section 03 then presents our model's various input data and assumptions. We also recall the scenarios' assumptions and attributes. Then, in Section 04, we will present and debate the key findings of the simulated scenarios, and ultimately, we will give the study's primary conclusions. The final purpose of our analysis is to evaluate Morocco's judgments made between 2010 and 2020, as well as the best solutions that should be chosen. Furthermore, would it be possible to speed the shift away from fossil fuels between 2020 and 2050, and what would the costs be?

## 2 Material and Methods

### 2.1 Tool: Open-Source energy Modelling System

Bottom-up modeling approaches are applied to optimize power systems in developing nations with suitable technology and supply resources [14]. One example of a model that fits this description is the bottom-up, dynamic, linear optimization model known as the Open-Source Energy Modelling System (OSeMOSYS), which is used for integrated evaluation and energy planning [15]. OSeMOSYS seeks to accomplish this by considering various technological, economic, and environmental factors, all while striving to achieve the lowest possible total discounted cost [16]. This model's designers constructed it to divide its functionality into several "blocks." These features are connected to the following aspects: prices, capacity adequacy, energy balance, emissions, and provisions for renewable energies [17]. What distinguishes one block from another are the equations, the formulae and the restrictions, the intermediate variables, and the parameters introduced by the analyst. [15, 16, 18].

Initially, the code for OSeMOSYS was developed in GNU MathProg. More recently, it has been rewritten in the GAMS (General algebraic modeling system) and Python programming languages [19]. Within the context of the conference publication [1], we carried out the simulation utilizing the GAMS implementation of the model. However, in this version, with the additional information we were able to obtain throughout our research project, we could carry out the simulation using the Python version that was running under pyomo.

### 2.2 Basic Code Adjustments

Our modeling of the Moroccan power system aims to determine the most efficient way to meet the country's predicted long-term electricity demand, while also considering Morocco's energy strategy targets in terms of the amount of renewable capacity that may be built. In the original version of OSeMOSYS, constraints relating to the availability of resources, the characteristics of renewable technologies, and the development of demand were already incorporated. Although, the requirements of EnR integration into the power system are stated in terms of yearly renewable energy production considerations.

The modeler may introduce the integrative constraint for RES in the energy system by using Equation 1. The different terms of the equation are detailed in Table 1. "r" and "y" represent the data sets for the region and the modeling year, respectively. This equation is encoded using the Pyomo coding scheme, as in box 01. Nevertheless, applying this equation to the specific situation of Morocco's energy strategy is not an ideal solution.

$$\forall_{r,y} \quad REmPT_{r,y} \times RETPA_{r,y} \leq TREPA_{r,y} \tag{1}$$

$$\forall_{r,y} \quad REmCT_{r,y} \times TPCA_{r,y} \leq TRECA_{r,y} \tag{2}$$

Therefore, to accurately represent the constraints imposed by the renewable installed capacity, we had to convert the previous mathematical "equation (1)" into the new "equation (2)". The different terms of the "equation (2)" are detailed in Table 2. Additionally, constraints were introduced to the original code, as demonstrated in "box 02". The technique of obtaining the TotalRECapacityAnnual variable is determined by "equation (3)", "t" symbolizes technologies' power plants. The different terms of "equation 3" are detailed in Table 3. The second term in "equation (2)" is the variable TotalPowerCapacityAnnual derived from the TotalCapacityAnnual variable and the PowerTagTechnology parameter as shown in "equation (4)". The additional parameter PowerTagTechnology was included to allow the model to distinguish between electricity-generating technologies and other technologies defined in the model. The different terms of the "equation (4)" are detailed in Table 4. The REMinCapacityTarget(r, y) parameter is the third component of the "equation (2)". It was created in order to set a minimum target for renewable capacity.

$$\forall_{r,t,y} \quad \sum_t TCA_{r,t,y} \times REtgT_{r,t,y} = TRECA_{r,y} \tag{3}$$

$$\forall_{r,t,y} \quad \sum_t TCA_{r,t,y} \times PtgT_{r,t,y} = TPCAnnual_{r,y} \tag{4}$$

Table 1: Summary of datasets used

| Abbreviation | OSeMOSYS designation | Description |
|---|---|---|
| **REmPT** | REMinProductionTarget | The minimum renewable production target desired by the analyst (parameter) |
| RETPA | RETotalProductionOfTargetFuelAnnual | The Annual Production of the fuels marked as renewable in the model (variable) |
| TREPA | TotalREProductionAnnual | The annual production of all technologies marked as renewable in the model |
| **REmCT** | REMinCapacityTarget | The minimum renewable capacity target desired by the analyst (parameter) |
| TPCA | TotalPowerCapacityAnnual | Annual capacities of technologies that convert primary energy into power (new variable) |
| TRECA | TotalRECapacityAnnual | A new variable introduced to the system to identifie the total annual renewable capacity |
| **REtgT** | RETagTechnology | A binary parameter indicating renewable technologies, with a value of 1 indicating renewable technologies and 0 otherwise (parameter) |
| TCA | TotalCapacityAnnual | The existing total capacity of technology "t" for year "y" (variable). |
| **PtgT** | PowerTagTechnology | A binary parameter indicating power technologies, with a value of 1 indicating electricity-generating technologies and 0 otherwise (parameter) |

# 3 Data Collection and Analysis Approach

## 3.1 *Base year data*

The year 2010 will serve as the foundation for building our analysis, as was said earlier. As a result, when the model was created, the current properties of the power system were used as starting parameters for the optimization process. Consequently, the treatment got off to the most effective beginning point imaginable. As a result, our model considers the electricity generation industry in Morocco at the end of 2009 [20]. There is information supplied on the capacity that was built before the year 2010. (Figure 1).

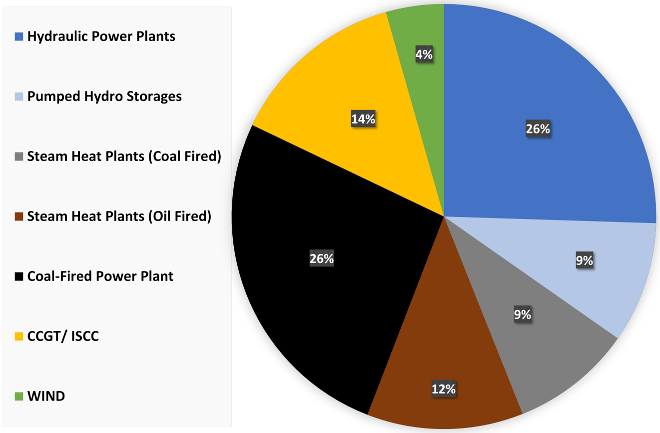

Figure 1: Installed capacity at the end of 2009 in Morocco [20]

It is important to note that the electricity system in Morocco does not cover the entire kingdom territory. This is mainly some generation capacity installed on the demand side in remote areas, such as the kingdom's south. These regions are supplied with power by gas turbines and diesel generators connected to a local grid. In our research, we did not take into consideration these capacities. Instead, we have considered the fact that the electricity fleet must connect to the national grid to meet the demand associated with this region.

## 3.2 *Reference Energy System*

When modeling energy systems, it is common practice to employ a representation in the form of a network for all the practical tasks required to provide end-users with a variety of energy sources. The term "Reference Energy System" (RES) refers to this particular representation [21]. In the context of our study, the selected RES is shown in Figure 2. The block denotes the various technologies in the RES, while the lines stand in for the various energy carriers. Technologies can refer to all kinds of processes performed on certain energy carriers, such as extraction, refinement, conversion, transportation, distribution, and usage of that energy carrier.

In the case of Morocco, where energy is primarily obtained through imports, we have not considered the relatively insignificant sector of primary energy extraction. On the other hand, the refinery has not been considered because its activity level dropped significantly after 2010 and stopped in 2015. As we had stated previously, when it came to converting primary energy into electricity, we depended on the technologies already in place at the beginning of 2010. These include coal-fired power plants, natural gas-fired power plants, oil-fired power plants, grid-connected diesel generators, wind farms, hydroelectric power plants, and a pumped storage power station. We have included in this mixture two technologies that are candidates for the development of renewable capacity. These technologies are photovoltaic and solar concentration.

The capacity of these power stations has been aggregated in a modeled setting. In other words, we do not simulate each power plant isolated. Instead, a block of power plants that convert one type of primary energy into power will be depicted together. Decision-makers can then pick the size of the new capacity required after obtaining the total ideal capacity required. In the case of transmission and distribution networks, precisely the same method was taken. These grids were modeled as a single technology that transforms the electricity from these plants into transmission electricity for the transmission grid, and then another technology that transforms this electricity into electricity for end users for the distribution grid. The transmission grid and the distribution grid were both modeled as separate technologies. On the demand side, each type of electricity consumption was combined into a single estimate for the national electricity demand.

## 3.3 *Inputs and assumptions*

OSeMOSYS's simulation of the Moroccan power system relied on several assumptions to generate accurate results.

### 3.3.1 *Temporal precision*

In the conference paper [1], we decided to sequence the modeling horizon over five years. In this extended essay paper, however, we have chosen annual modeling. In addition, to simulate the seasonal and daily variation of electricity demand and the intermittent nature of renewable energy sources, we divided each year of the model into a total of six-time steps. There are two periods each day: day and night. There are also three seasons: winter, intermediate, and summer. This gives us a total of six periods: WD and WN for the daytime and the night of a day during the winter; ID and IN for the daytime and the night of a day during the intermediate season; and SD and SN for the daytime and the night of a day during the summer.

### 3.3.2 *Electricity Demand*

According to the data provided by ONEE in its numerous activity reports [22], the yearly increase rate of energy consumption was around 6% from 2010 to 2016. This growth rate was observed throughout the entire period. Thereafter, this rate continued to fall until it reached 5% in 2018. Furthermore, the Moroccan Ministry of Energy analyzed energy demand until 2050 [23], which established three different demand evolution scenarios for the time spanning from 2020 to 2050. A trend macroeconomic scenario, in which the Moroccan economy maintains the same trend (3.5%) recorded from 2009 to 2018; a high macroeconomic scenario, in which a gradual economic recovery is expected to reach 5% in 2050; and a pessimistic macroeconomic scenario, in which the downward trend recorded from 2009 to 2018 is expected to continue to 2% in 2050. ONEE statistics have been used as the basis for our examination of demand from 2010 through 2018. On the other hand, for 2019-2050, we have decided to go with the findings of the trend scenario developed through the research carried out by the Ministry of Energy (Figure 3).

### 3.3.3 *Costs*

Any such study relies highly on the investment prices selected for the technologies being considered, in addition to the costs of fuel, operation and maintenance (O&M), and non-operational expenditures. The investment costs and fixed operation and maintenance (O&M) expenses were expressed in USD per kW of installed capacity. with variable O&M costs stated in US dollars per gigajoule and fuel costs expressed in US dollars per unit. These costs were gathered from various sources [24–30], and we have displayed them in Figures 4,5, and 6, respectively.

### 3.3.4 *Common data and hypothesis*

Several other statistics and assumptions are shared in all scenarios. These figures were obtained from a variety of sources [24, 31–33]. Table 2 summarizes the various values estimated during the modeling period.

The capacity factor is the most crucial criterion to consider in this category. It represents the available capacity for each period, usually given as a proportion of the total installed capacity. This value remains constant throughout the year for conventional technologies, making it possible to consider unplanned disruptions. On the other hand, the value of renewable energy sources fluctuates depending on the period in question. Thus, the intermittent nature of these technologies is also represented here. Figure 7 provides a visual representation of the various capacity factors of renewable energy that were taken into account in our research.

The second parameter is the Availability Factor. It represents the most extended period that a particular technology can function throughout an entire year, represented as a percentage of the year ranging from 0 to 1. It enables breaks to be scheduled in advance. The third one is the operational Life Cycle, which is the usable life of a technology measured in years. The other metrics include each technology's efficiency and CO2 emission rate.

To establish certain constraints, we had to make some additional assumptions. Among these assumptions is the discount rate, set at 5%, based on the average rate applied to loans by Moroccan banks [34]. Furthermore, the reserve margin was set at 20% of the installed capacity, and no emission limits were imposed.

### 3.3.5 *Assumptions and Scenario characteristics*

Under the Moroccan energy plan approved in 2009, three scenarios have been selected for implementation. The main difference between these scenarios is the share of renewable energy in the installed electricity capacity. The first scenario is a Business As Usual (BAU) scenario that does not impose a lower limit on the share of renewables. This scenario reflects a trend in the electricity mix. At the same time, the optimization model is proposed to incorporate renewable energies. The second scenario is the one that matches the target of the Moroccan energy policy, which is to reach a rate of 42% of installed renewable power in 2020 and 52% in 2030. The third scenario is the scenario that estimates the feasibility of increasing the rate of integration of renewable energy in the electricity mix. For this purpose, the Moroccan energy strategy's objective has been revised to 60% of installed renewable power in 2030 and 80% in 2050.

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# 4 Results and Discussion

To fully comprehend the results of the Moroccan energy policy, the findings are contrasted with the real situation that occurred on the reality in Morocco from 2010 to 2018. Recommendations will be based on the research done for the years 2019–2050.

## *4.1 Power Generation Capacity*

If we look at the three scenarios together, we see that, in the first scenario, the proportion of renewable energy sources is relatively low (Figures 8;9;10). Indeed, renewable energy is scarce from 2010 to 2035; This results from the very high cost of these technologies at the onset of the modeling period and the unavailability of a minimum renewable capacity target. In this scenario, solar energy has not been chosen to be included, but the incorporation of wind energy into the mix will begin in earnest in the year 2035. This can be explained by the fact that technology relating to wind energy has become more economically mature than those relating to solar energy.

On the other hand, one can make the observation that the total capacity required to fulfill the demand in the third scenario is more significant than that required in the first two scenarios. The high integration rate of RE, which reached 60% in 2030 and 80% in 2050, is the reason for this gap in capacity. In addition, it appears that the retirement of coal-fired power plants is happening faster as a result of investments in RE. In fact, coal-fired generation capacities are still present until 2040 in the first scenario; however, in the second and third scenarios, these capacities are almost nonexistent beyond 2030. Regarding the utilization of natural gas, we can observe that this production method is present in each scenario. Furthermore, the supremacy of this conventional technology over its alternatives can be attributed to the reliability of the technology and the low cost of the commodity, in this case, natural gas, compared to the cost of fuel oil.

Table 2: Data and hypothesis common to all scenarios [24, 31–33]

| | | Technology | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Units | Coal_PP | Oil_PP | GAS_PP | WIND | PV | CSP | HYD | PHS |
| Avarage capacity factor | % | 85 | 90 | 87 | 35 | 27 | 70 | 51 | 100 |
| Availability factor | % | 84 | 89 | 91 | 100 | 100 | 100 | 95 | 100 |
| Life cycle | Years | 40 | 25 | 30 | 25 | 25 | 25 | 80 | 50 |
| Efficiency | % | 39 | 35 | 54 | 100 | 100 | 100 | 32 | 100 |
| CO2 emissions | ton/PJ | 0.0905 | 0.0589 | 0.0503 | 0 | 0 | 0 | 0 | 0 |

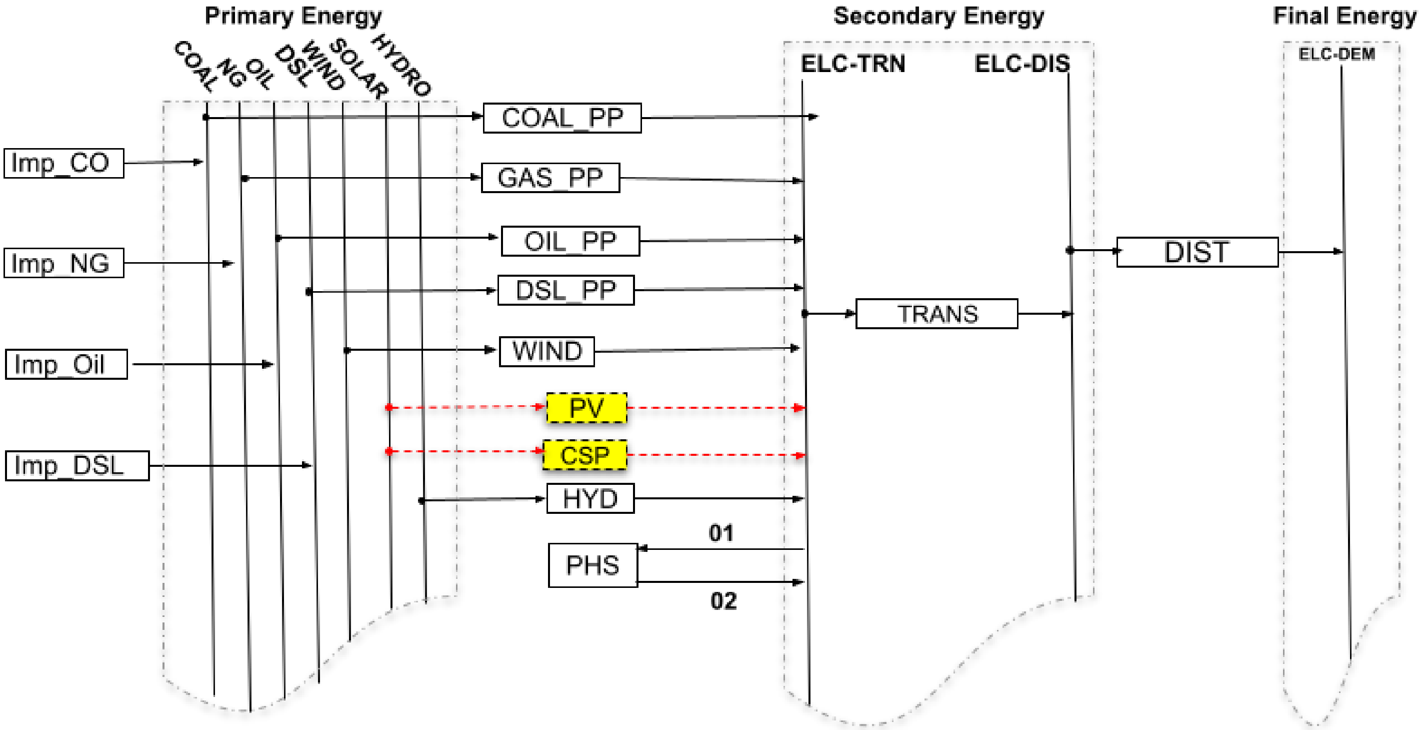

Figure 2: Electricity supply model of Morocco's reference energy system in OSeMOSYS/ source : illustration, made by the authors

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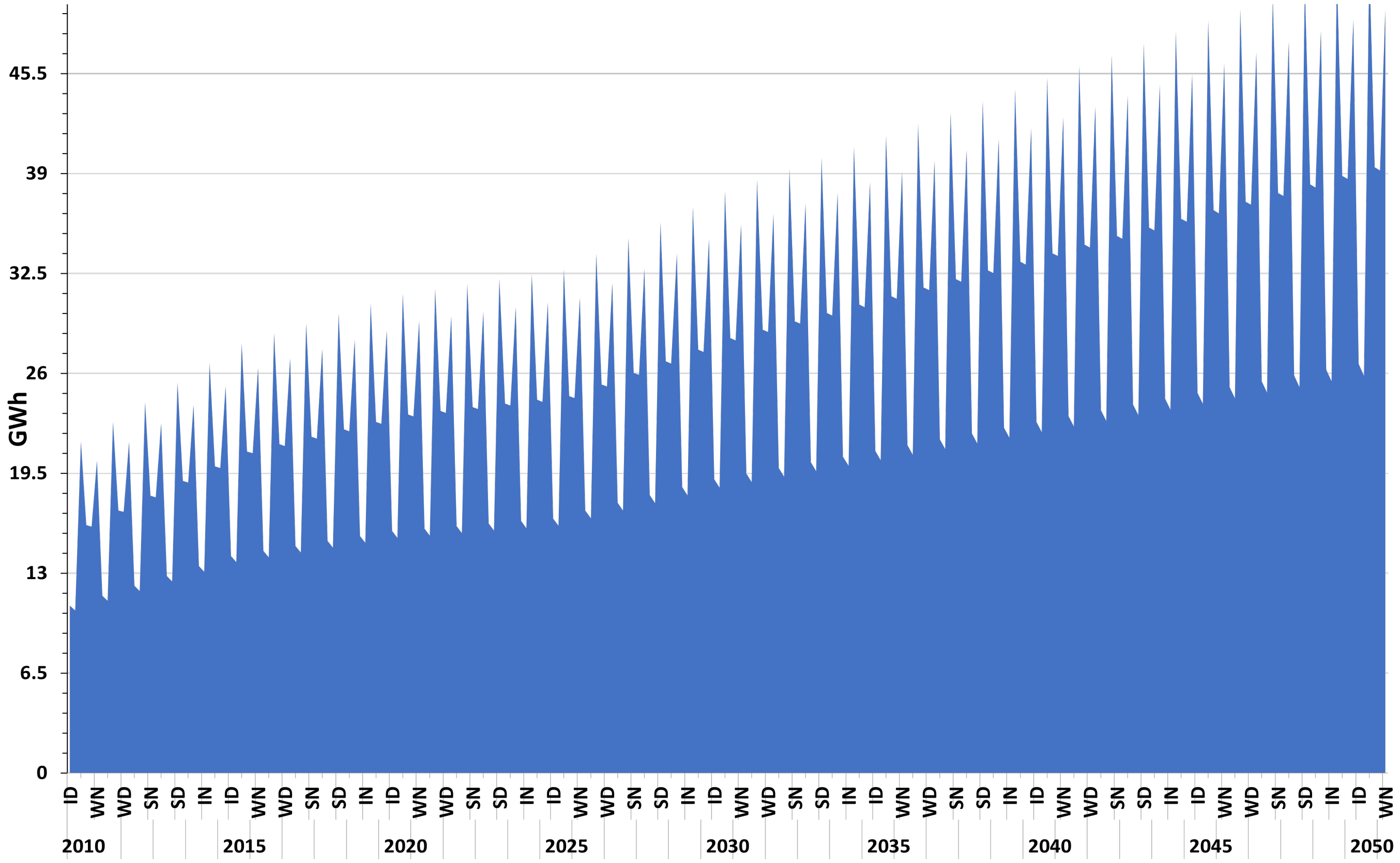

Figure 3: Electricity demand 2010-2050 in GWh

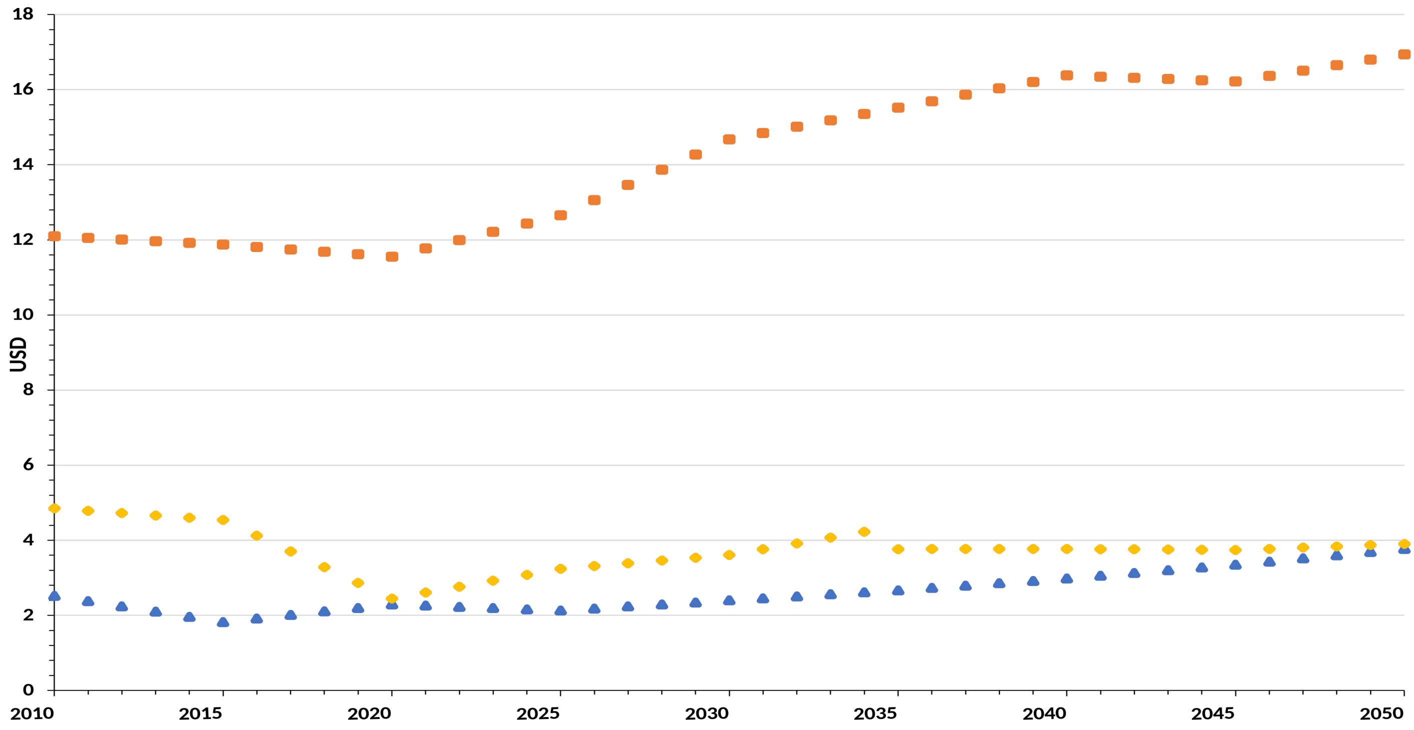

Figure 4: Energy Prices by Source, 2010-2050

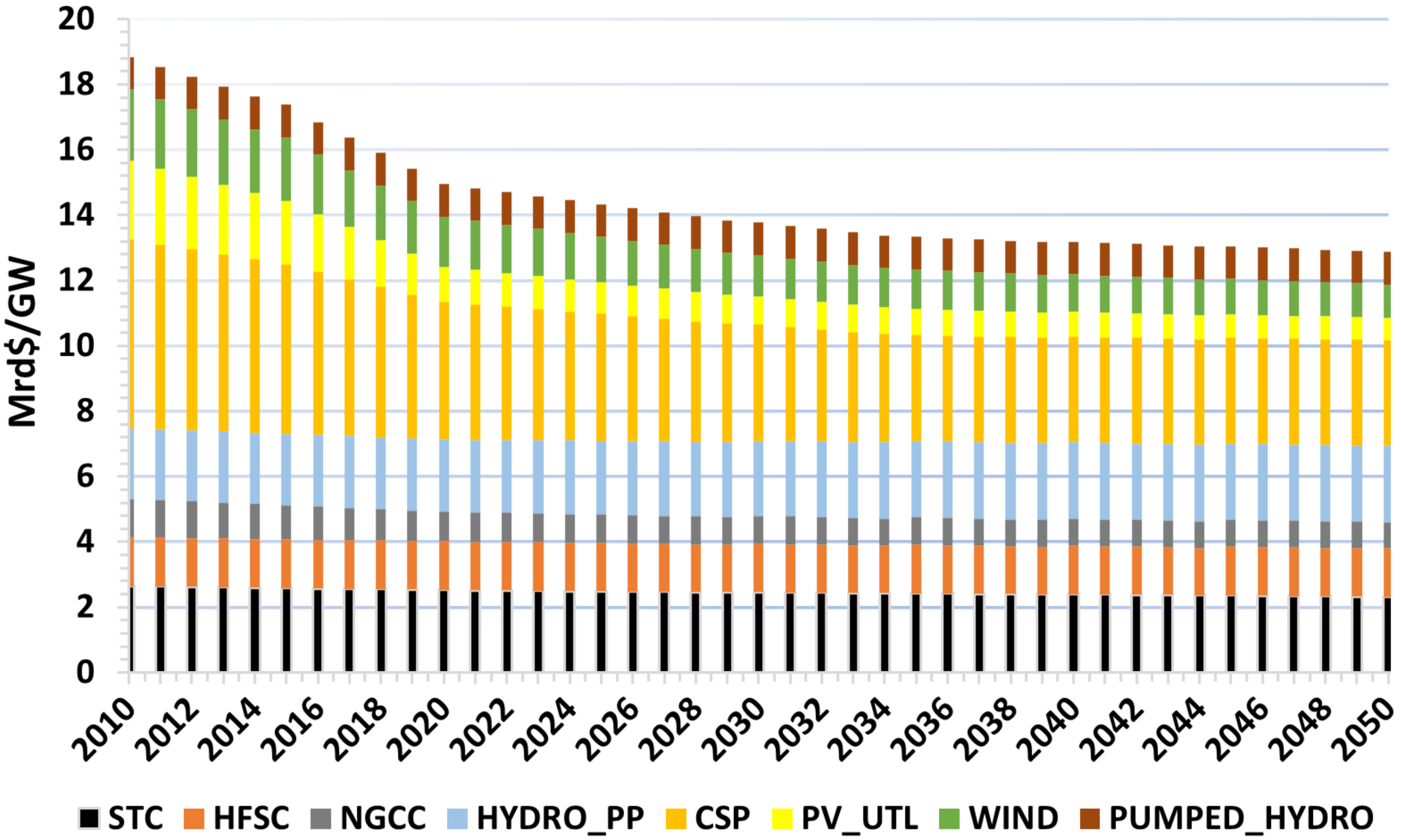

Figure 5: Capital cost for power plants 2010-2050

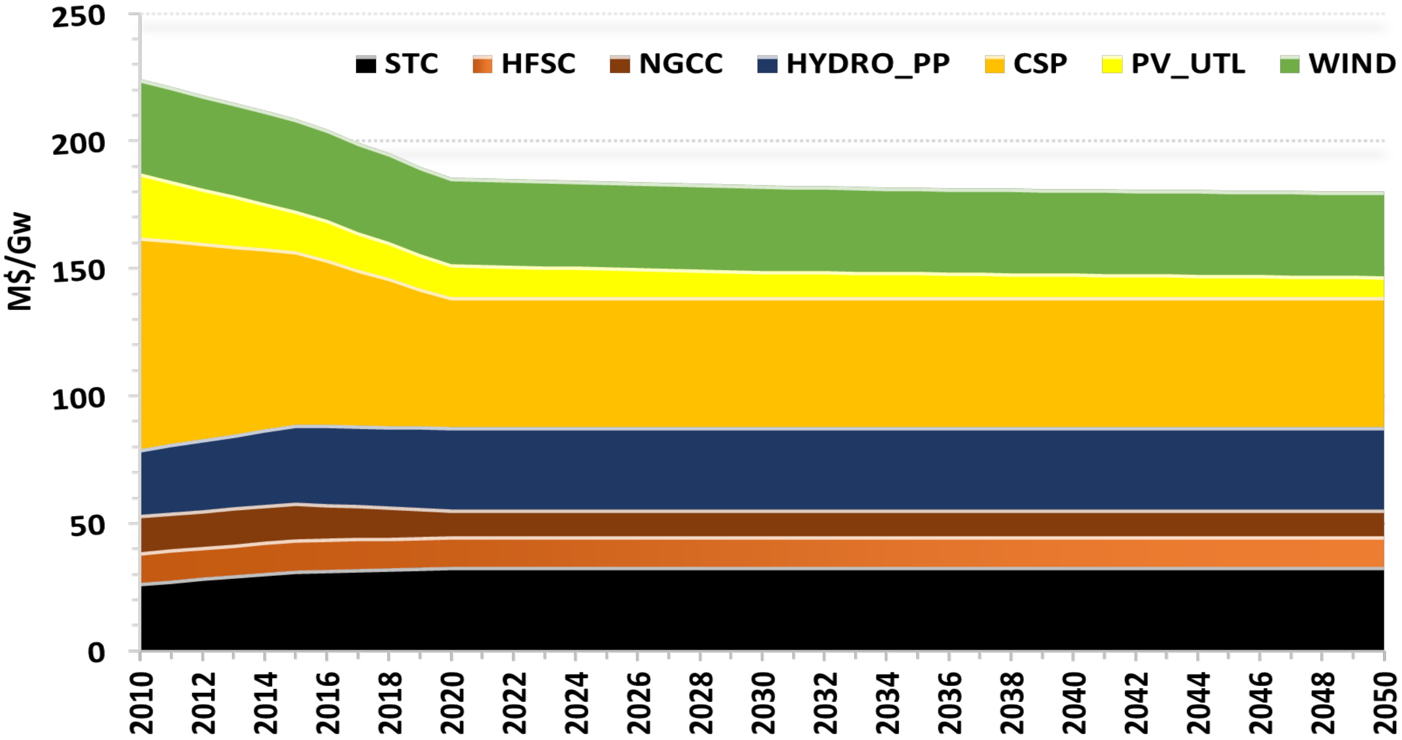

Figure 6: Fixed O&M costs for power plants,2010-2050

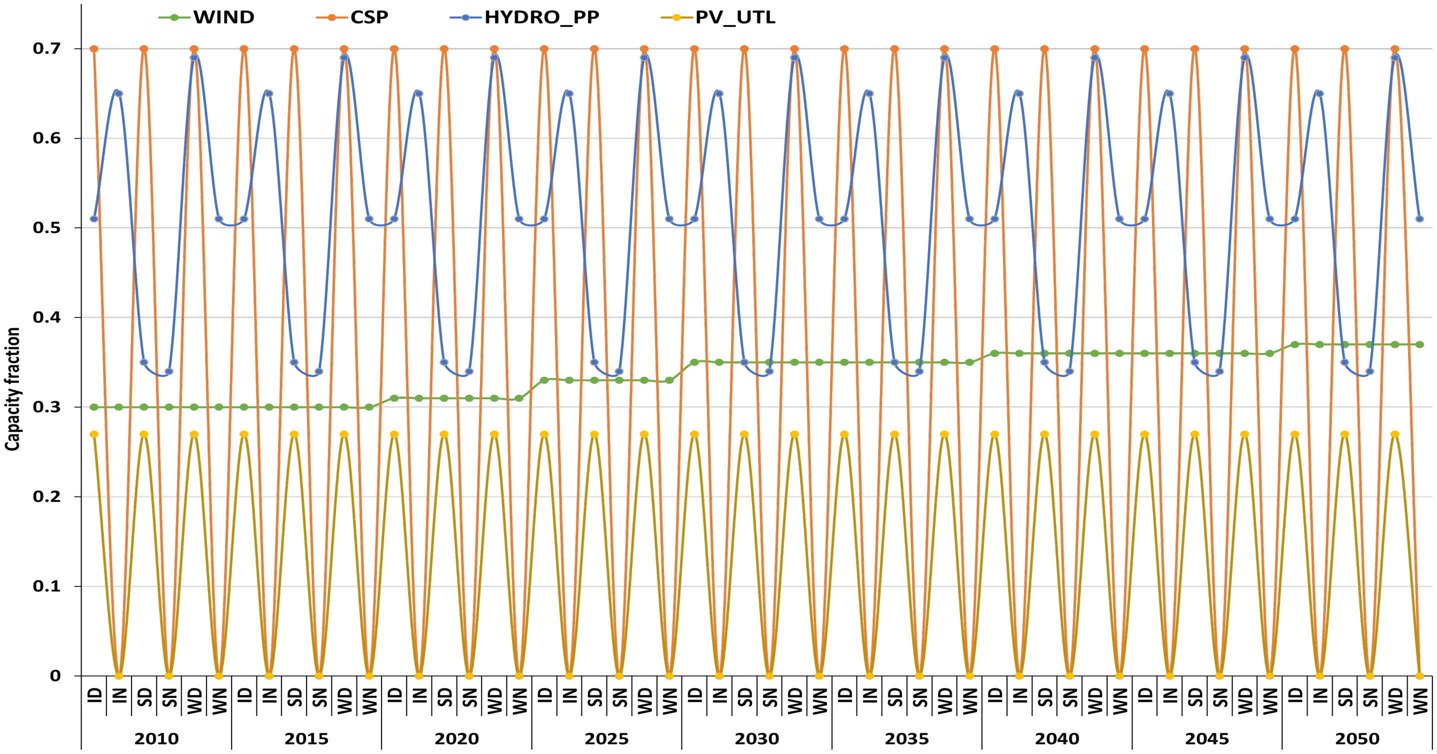

Figure 7: Capacity Factor Renewable Energy

Furthermore, we note that only two of the three possible renewable technologies were chosen, Wind energy and solar photovoltaic energy. However, none of the possible results involve using concentrated solar electricity. A finding that sheds light on Morocco's decisions in 2010 regarding the technologies it plans to deploy.

Figure 4 demonstrates that the majority of the electricity mix in the BAU scenario is composed of conventional technologies. Renewable energy sources account for just 6% of the total capacity in the year 2030, and this percentage will not reach 42% until the year 2050. In 2035, pumped storage technology will account for 48% percent of total installed capacity, making it one of the technologies with the most significant proportion of installed capacity. This focus on PHS can be explained by the fact that the capacity and availability factors were estimated at 100%. In addition, the model did not stipulate an upper capacity limit for the system. In light of these assumptions, one can question the veracity of the results. These assumptions, however, may be appropriate even in the lack of reliable facts on the issue. For starters, pumped storage power stations can run as long as the upstream reservoir is adequately replenished. This can be achieved by either flowing water from a river or pumping water from the downstream tank. Then, for the availability factor and unexpected shutdowns and maintenance, two pumping units and two turbine units are sufficient to ensure the station's operation. Furthermore, regarding available capacity, Morocco has a relatively vast coastline that may be utilized as marine PHS, considerably improving Morocco's potential in this technology.

In contrast to scenario 01, solar PV is the first renewable technology to be integrated into the electricity mix in the 2e scenario (Figure 9), with wind beginning to gain a significant role from 2035 to 2050. We also find that the share of gas power plants is directly proportional to the integration rate of renewable energy sources. Indeed, in 2050, the share of NG-PP approaches 50% in scenario 02, whereas it does not exceed 40% in scenario 01. This result demonstrates the significance of this technology in the context of the vast development of renewable energies.

This observation is corroborated in scenario 03 (Figure 10), when the rates of renewable energy integration rise substantially. This is owing to the model's need to meet significant minimum capacity demand. This is also something we observe at this time. The built wind capacity had expanded dramatically at the start of the modeling period, in contrast to what we stated in Scenario 2. It should be highlighted that, based on current price trends, solar PV will be pretty competitive for average renewable energy integration between 2020 and 2040. However, technology to offer backup is required. Wind power, however, is critical for rapid integration with a high percentage of renewable energy. Indeed, with rates reaching 60% from the start of the projected period, significant investments in natural gas power plants have been made, highlighting the critical potential of this technology to offer the necessary reserve to deal with renewable energy's intermittent nature. Once the integration rate reaches 80%, establishing PHS facilities becomes imperative. This is what we notice in the year 2050.

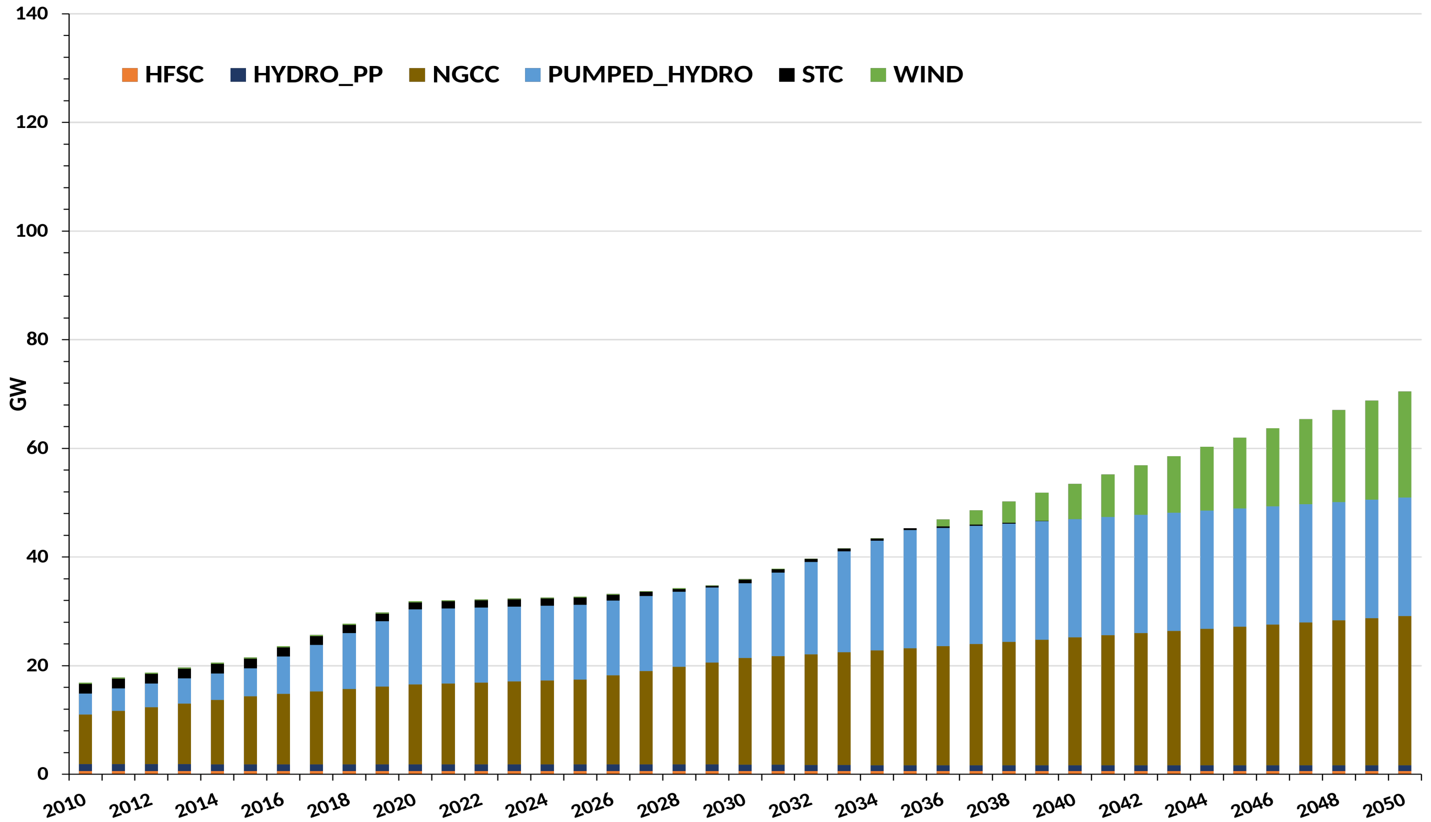

Figure 8: Total Annual Capacity (Scenario 1)

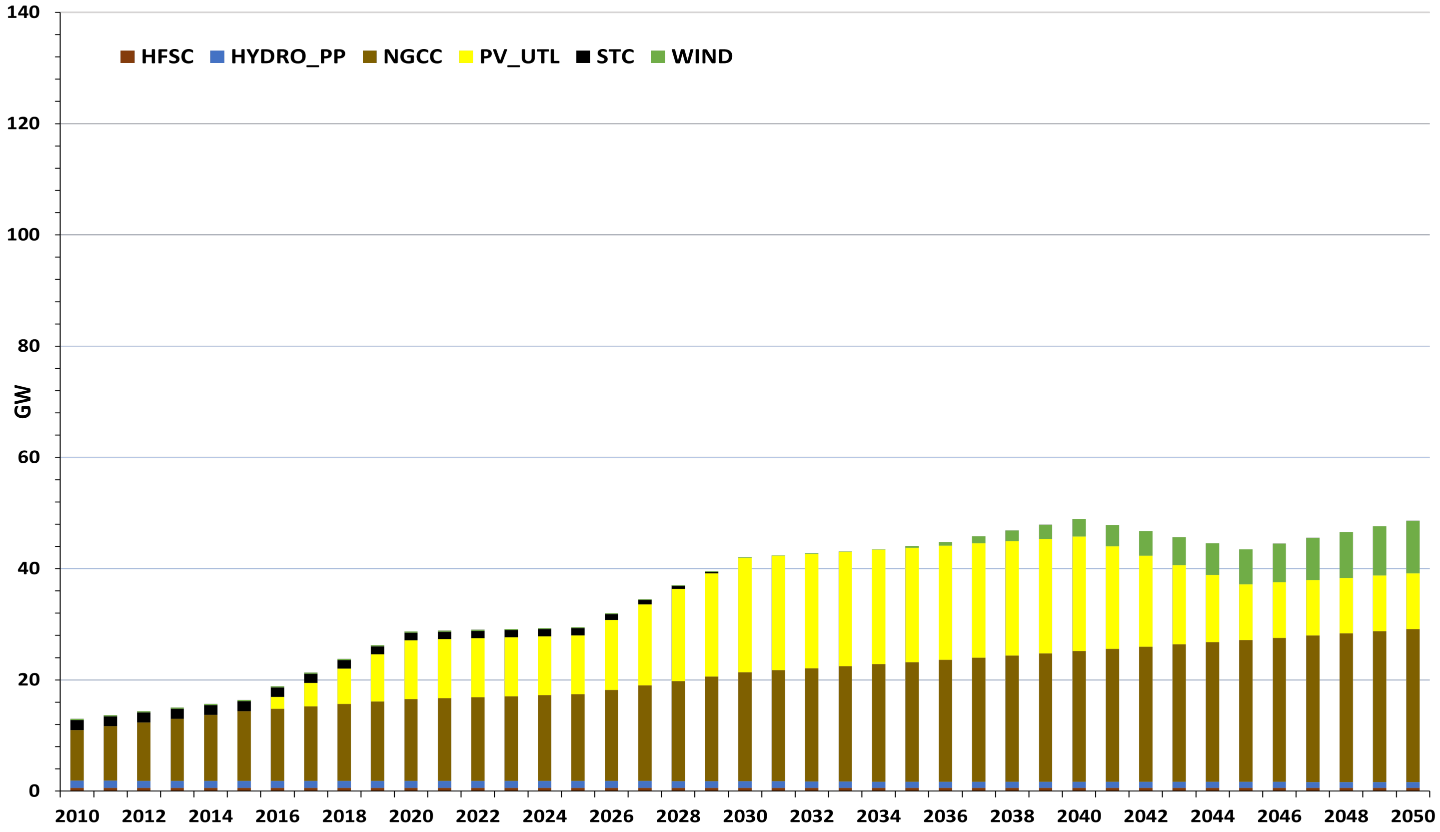

Figure 9: Total Annual Capacity (Scenario 2)

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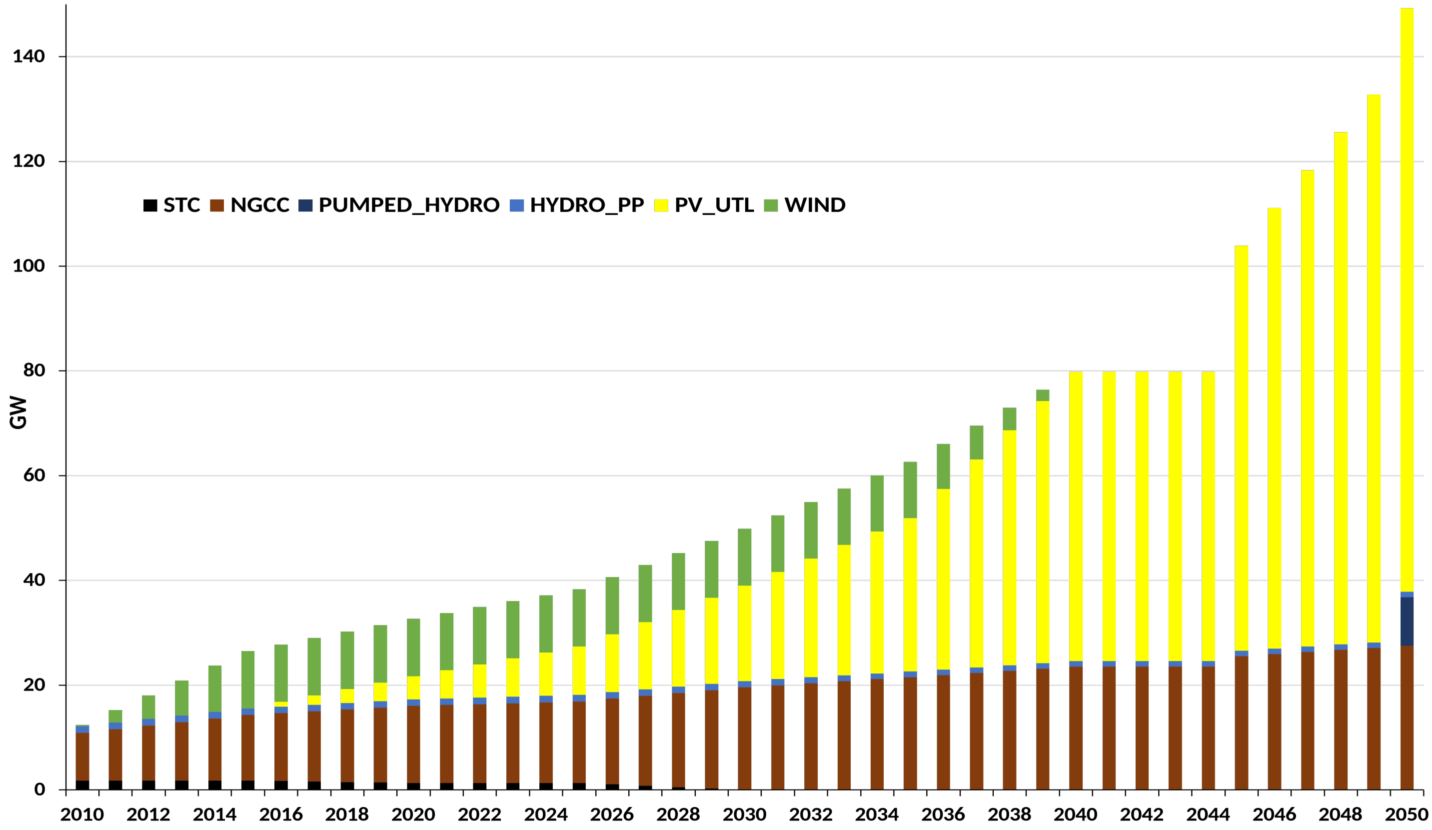

Figure 10: Total Annual Capacity (Scenario 3)

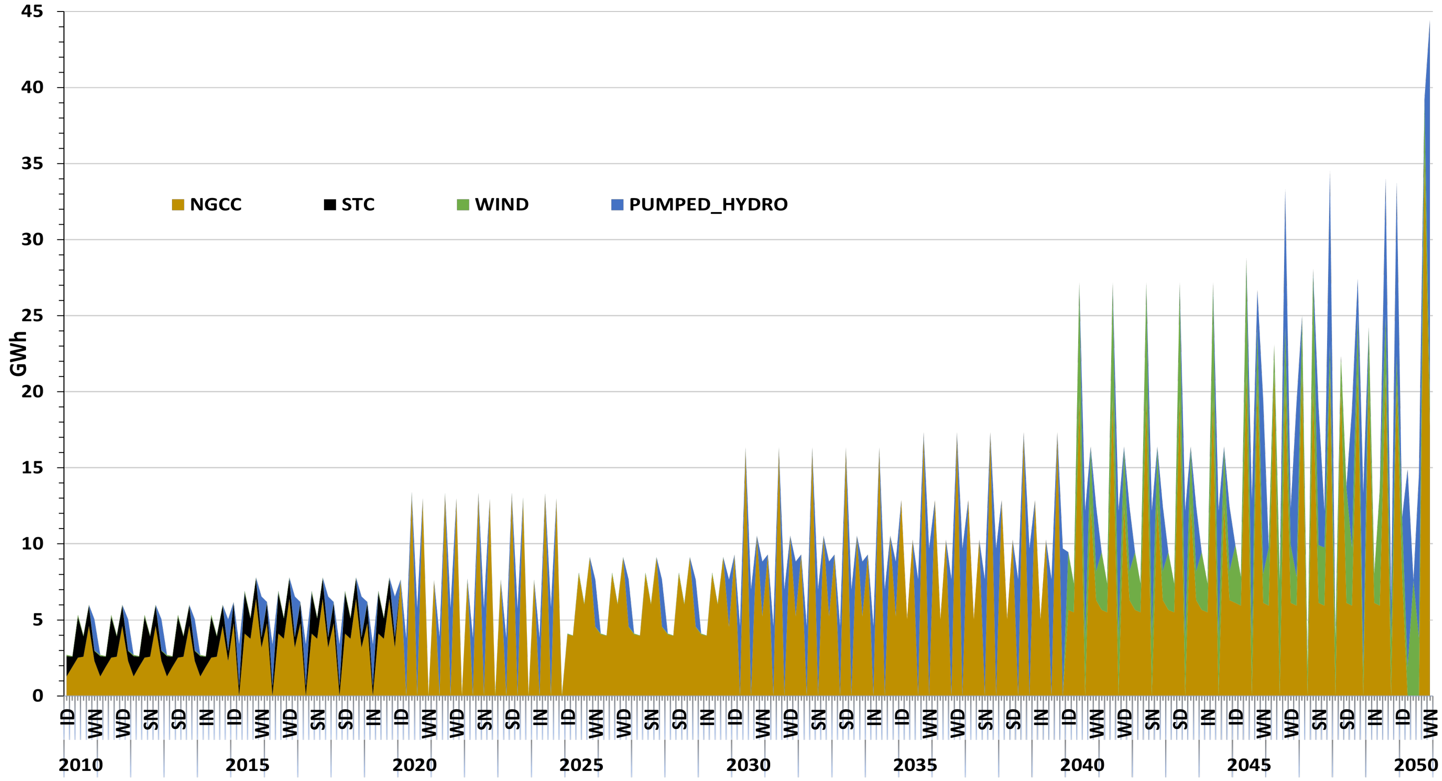

Figure 11: Technology Production by Time Slice (Scenario 1)

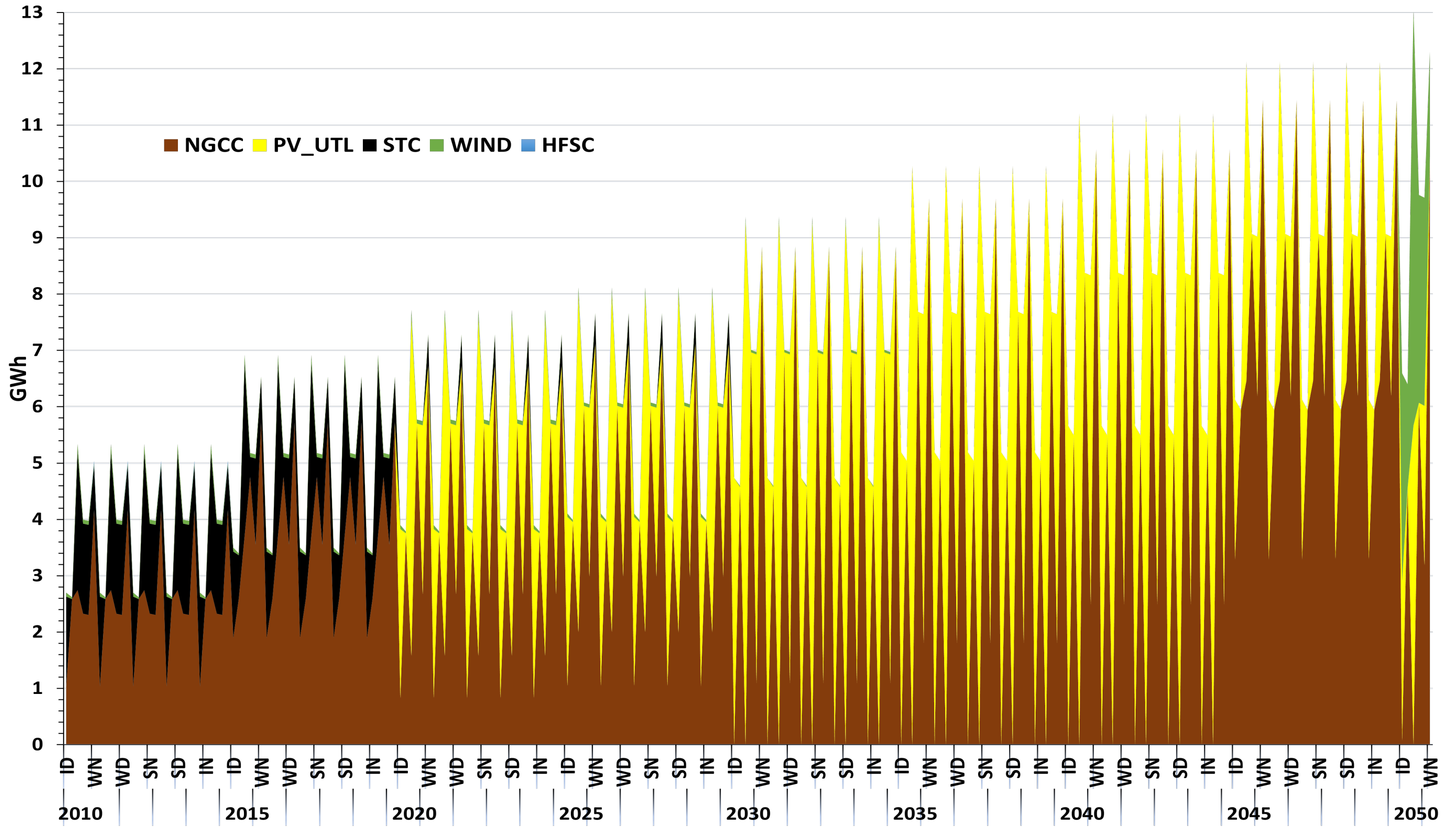

Figure 12: Technology Production by Time Slice (Scenario 2)

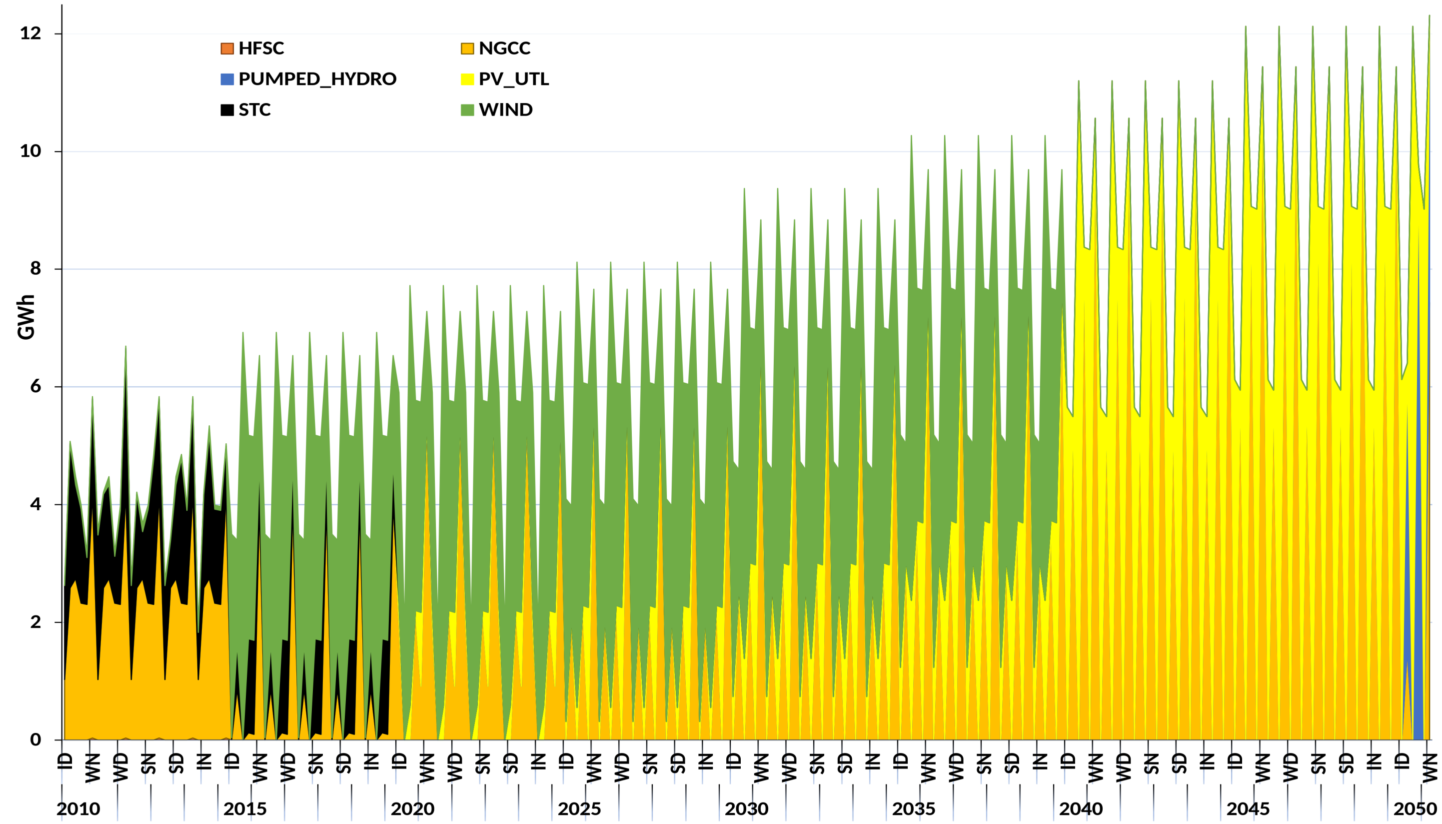

Figure 13: Technology Production by Time Slice (Scenario 3)

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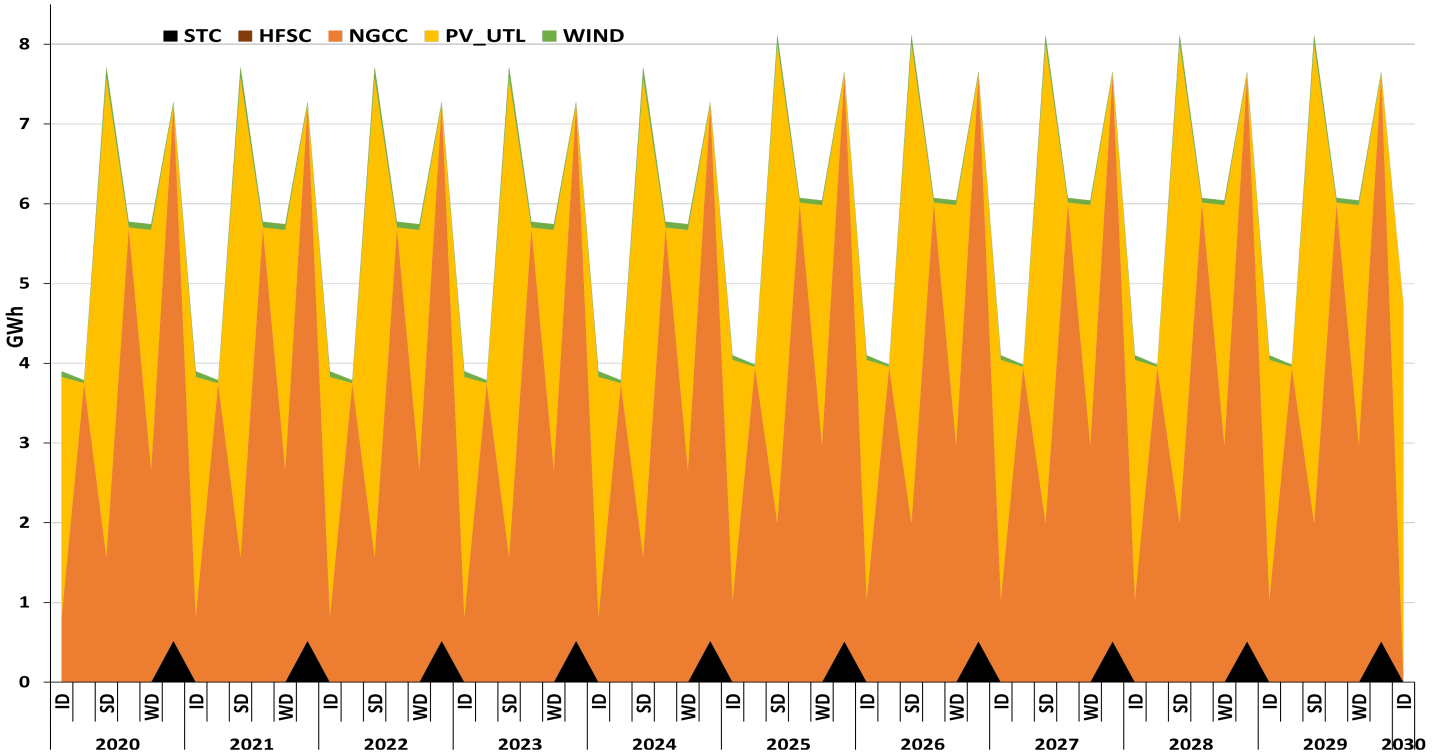

Figure 14: Technology Production by Time Slice 2020-2030 (Scenario 02)

## 4.2 *Electricity Production Aspects*

Figures 11, 12, and 13 shows how energy output is allocated in three scenarios; We can instantly see that scenario 1 produces substantially more energy than the other two situations. Indeed, scenario 01's total output is 17% higher than scenario 02's and 22% higher than scenario 03's. Although all three scenarios have the same overall demand that must be satisfied, Scenario 01's high use of PHS causes additional demand to be met through the pumping required to fill the quantity tanks. When we look at the breakdown of power generated to fulfill demand between 2010 and 2015, coal and gas come out on top. Second, in Scenarios 02 and 03, conventional generation facilities are predominantly centered on natural gas-fired plants. The second point to note is the variation in generation by time slice in the 02 and 03 scenarios. Because renewable energy sources are intermittent, this was to be expected.

We already mentioned in Scenario 01 that natural gas and coal will be the dominant energy generation sources, as seen in Figure 5. Indeed, the competitiveness of renewable energy in electricity production remains questionable because no minimum production constraint or installed capacity limit is imposed. Wind energy, on the other hand, will become more competitive by 2040 and will naturally be included in the optimal electricity mix. This is attributed to lower wind energy costs and higher generating capacity.

On the modeled days, photovoltaic (PV) generation is the primary contributor to satisfying power demand first thing in the morning in the second scenario. Gas-fired power plants increase output to meet the increased demand for electricity in the evening. Between 2010 and 2020, there will be virtually no visible difference in power generation between conventional and renewable energy sources. However, between 2020 and 2030, the difference between the two will expand slightly. The fundamental cause of this increase is the amplitude of photovoltaic generation, which decreases dramatically when the sun sets. Figure 14, which focuses solely on this period, clearly illustrates this argument. Wind farms will be used to compensate for the decreasing amount of solar power available in the evenings beginning in 2040. As a result, it is less likely that gas-fired power plants will be used to the same extent until the end of the period predicted.

When compared to the conclusion of the period evaluated in Scenario 2, the amount of power generated by NG-PP plants falls at a much steeper and faster pace in Scenario 3. Furthermore, as illustrated in Figure 7, which depicts the distribution of electricity generation by time slice for Scenario 03, the utilization of NG-PP is primarily related to peak load. The latter is mainly used during peak demand or at night to compensate for the fact that renewable energy sources often do not produce at night.

## 4.3 *Carbon emissions*

Figure 15 exemplifies this notion. The simulation findings reveal that the initial scenario causes the most severe pollution. Compared to the first scenario, CO2 emissions reported for scenarios 2 and 3 were reduced by 25% and 72%, respectively. It is possible to avoid between 62 and 135 Ktones of CO2 emissions. The operation of thermal power plants is a significant source of carbon dioxide emissions. Given that the 1st scenario is dominated by power plants of this sort and that pulverized coal is a significant component of the production mix, it is not unexpected that these emissions are at their highest level. Consider the objectives that the Moroccan government has set for itself. We can see that Scenarios 2nd and 3rd will considerably contribute to the desired carbon intensity reduction. It would also be interesting to see how the model reacts when environmental limitations are introduced to the basic scenario.

### *4.4 Total Costs*

As shown in Figure 15, the BAU scenario will result in the lowest total expenditure. In this scenario, the cost of fossil fuels represents more than 80% of the total expenditure, taking into account the absence of any intervention on the installed capacity. The total discounted costs of scenario 3 are 2% higher than the total discounted costs of scenario 1. The total discounted cost of Scenario 2 is only 0.5% higher than the total cost of Scenario 1.

The lower fuel prices almost fully compensate for the investments in the second scenario. This also results in a positive energy independence benefit, at a cost almost comparable to that of Scenario 1. However, this result would not have been achieved without the lower fossil fuel prices. In the third scenario, the discounted costs are the highest of the other scenarios. This is because the model has been forced to make large investments in renewable technologies, the relatively high costs.

Scenarios 02 and 03 are distinguished by considerable growth in the use of renewable energy sources. This results in less dependence on fossil fuels and greater self-sufficiency in imports. On the other hand, scenario 01 is characterized by an increased sensitivity to fluctuations in fossil fuel prices, which have been unstable in recent years and which may create a precarious situation in the long term. Therefore, Morocco relies on policymakers to consider that, even if the scenarios with efficient RE integration are slightly more expensive than those without renewable limits, they will reduce the country's dependence on fossil fuels.

Currently, more studies are being conducted to determine the best integration rates for each renewable energy option. This includes photovoltaics and wind power and selecting the best combination of reserve systems. The aim is to manage the effects of these renewables' intermittent nature while maintaining the national grid's stability [35].

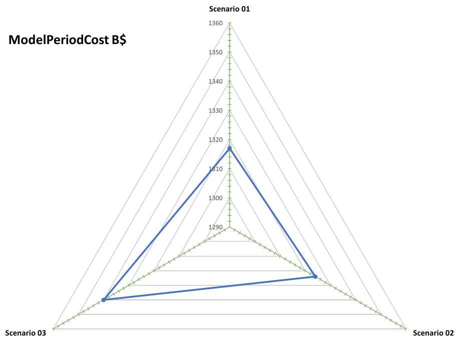

Figure 15: Total discounted cost of the scenarios

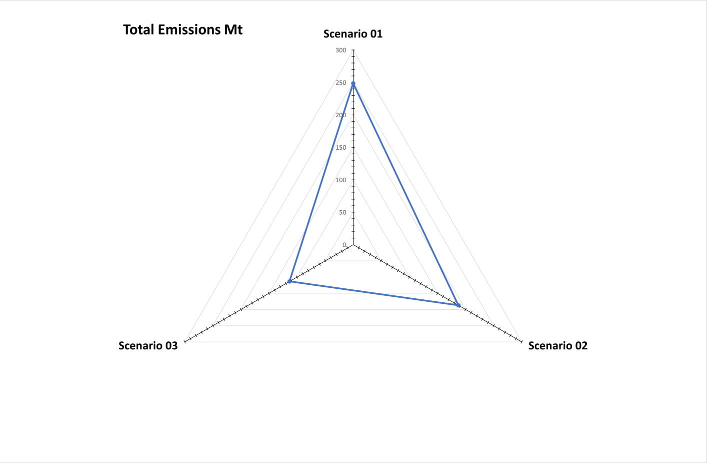

Figure 16: CO2 Emissions by scenario

In view of the results of this study, the following question arises: why has Morocco not created more natural gas power plants and made do with the two power plants of Ain Bnimathar and Tahaddart, which have played an important role in meeting demand and ensuring the stability of the network?

The answer to this question is based on two axes. The first is the absence of this resource on the national territory, while coal has long been extracted from the mines of Jerrada, in the east of the kingdom [36]. The second is the low level of gas infrastructure. Indeed, in our analysis, the infrastructure necessary for the use of natural gas for electricity generation has not been considered, notably in terms of storage capacity and delivery network from the port. This is justified by the fact that the gas-fired power plants in operation so far have benefited from the proximity of the GME (Gazoduc Maghreb Europe) and from the fee in kind paid by Algeria for allowing the use of Moroccan territory for the transport of its natural gas to Europe. All these parameters, as well as others such as the required electrical storage capacity and the optimal storage technology, as well as electricity exchanges with Europe, power to X, and demand management, will be the subject of future analysis.

## 5 Conclusion

According to the results of this study, the different technological options for electricity generation chosen at the beginning of Morocco's energy transition are not always ideal. Indeed, the decision to develop CSP as the leading renewable source and coal as a backup load source appear controversial. This result leads us to question the primary basis for this choice. This result leads us to question the primary basis for this choice. Actually, at the time, cost reductions of solar PV, derived from its three-decade learning curves, were already far more promising than the modest cost reductions of solar thermal power. These results are from several feedback reports from the Kramer Junction solar thermal power plants in the United States [37].

In addition, while CSP offers enormous storage capacity at acceptable costs, its large-scale growth is limited by the demand for land, making it a centralised power generation technology that requires the creation of a large grid to transmit the output [38].

Furthermore, while coal-fired power plants are an attractive technology for meeting demand and maintaining grid stability, they cannot be used as a back-up technology with a large share of renewables in the electricity mix [39]. This will limit the use of renewable capacity because coal is not very flexible. The third scenario also showed that RE has the potential to become the main source of energy in the Moroccan electricity system. However, for this to happen, they will need to be integrated with flexible generation systems such as gas-fired power plants and energy transfer stations [40, 41].

Besides, as the third scenario shows, increases in renewable energy capacity targets have not always been reflected in total costs. In fact, the total costs remained relatively similar to those in the second scenario. Our results are consistent with the findings of experts in the field. For example, [42] estimated that if Morocco had made the necessary efforts to accelerate the development of power transfer stations, notably the Abdelmoumen project, which was to be commissioned in 2008, it would not have needed as much storage as the CSP plants offer. Moreover, PHS could have been used to compensate for the intermittency of wind power, which is not possible with CSP storage. On the other hand, [42] states that if Morocco had advanced the wind projects, it could have had about 3,000 GWh/year of wind energy, acquired at a price (0.03 USD/kWh). This amount corresponds to the 1050 GWh/year of solar thermodynamic energy currently purchased (at about 0.14 USD/kWh on average).

**Further Research** Other concerns regarding the energy sector in Morocco will be studied in the near future as part of our ongoing research. A new configuration of the model will be carried out to achieve this objective. This will involve taking into account new parameters, such as the possibility of exporting electricity and the impact that this option will have on the Kingdom's trade balance. In addition, other new parameters will be analyzed, such as the exchange of electricity with neighboring countries. In addition, we will study the storage capacities needed to support the development of renewable energy sources, among others.

Various improvements will also be made to the OSeMOSYS model to analyse concepts such as the stochastic aspect of raw material costs, the fluctuations of RE, as well as the impact of the energy strategy on other sectors such as air quality and environmental preservation, water resource management, or industry and its competitiveness in the context of new carbon taxes introduced and planned by the European market.

**Conflict of Interest** The authors declare no conflict of interest.

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# Appendix

```
# Parameters
model.RETagTechnology = Param(model.REGION, model.TECHNOLOGY, model.YEAR, default=0)
model.RETagFuel = Param(model.REGION, model.FUEL, model.YEAR, default=0)
model.REMinProductionTarget = Param(model.REGION, model.YEAR, default=0)
#   Model Variables
model.TotalREProductionAnnual = Var(model.REGION, model.YEAR, initialize=0.0)
model.RETotalProductionOfTargetFuelAnnual = Var(model.REGION, model.YEAR,initialize=0.0)

def FuelProductionByTechnologyAnnual_rule(model, r, t, f, y):
  return (
    sum(
      model.ProductionByTechnology[r, l, t, f, y]
      for l in model.TIMESLICE
    )
    == model.ProductionByTechnologyAnnual[r, t, f, y]
  )

model.FuelProductionByTechnologyAnnual = Constraint(
  model.REGION, model.TECHNOLOGY, model.FUEL, model.YEAR, rule=FuelProductionByTechnologyAnnual_rule
)

def TechIncluded_rule(model, r, y):
  return (
    sum(
      model.ProductionByTechnologyAnnual[r, t, f, y]
      * model.RETagTechnology[r, t, y]
      for t in model.TECHNOLOGY
      for f in model.FUEL
    )
    == model.TotalREProductionAnnual[r, y]
  )


model.TechIncluded = Constraint(
  model.REGION, model.YEAR, rule=TechIncluded_rule
)


def FuelIncluded_rule(model, r, y):
  return (
    sum(
      model.RateOfProduction[r, l, f, y]
      * model.RETagFuel[r, f, y]
      * model.YearSplit[l, y]
      for f in model.FUEL
      for l in model.TIMESLICE
    )
    == model.RETotalProductionOfTargetFuelAnnual[r, y]
  )


model.FuelIncluded = Constraint(
  model.REGION, model.YEAR, rule=FuelIncluded_rule
)


def EnergyConstraint_rule(model, r, y):
  return (
    model.REMinProductionTarget[r, y]
    * model.RETotalProductionOfTargetFuelAnnual[r, y]
    <= model.TotalREProductionAnnual[r, y]
  )


model.EnergyConstraint = Constraint(
  model.REGION, model.YEAR, rule=EnergyConstraint_rule
)
```

Listing 1: Original Renewable energy constraint coding on Pyomo

```
# Parameters
model.PowerTagTechnology = Param(model.REGION, model.TECHNOLOGY, model.YEAR, default=0)
model.REMinCapacityTarget = Param(model.REGION, model.YEAR, default=0)

#   Model Variables
model.TotalRECapacityAnnual = Var(model.REGION, model.YEAR, initialize=0.0)

##################  RE Capacity Target equations  ###########
def PWTechIncluded_rule(model, r, y):
  return(
    sum (
        model.TotalCapacityAnnual[r, t, y]
        * model.PowerTagTechnology[r, t, y]
        for t in model.TECHNOLOGY
       )
      == model.TotalPowerCapacityAnnual[r,  y]
    )
model.PWTechIncluded = Constraint(
  model.REGION, model.YEAR, rule=PWTechIncluded_rule
)

def RETechIncluded_rule(model, r, y):
    return (
      sum(
        model.TotalCapacityAnnual[r, t, y]
        *model.RETagTechnology[r, t, y]
        for t in model.TECHNOLOGY
        )
      == model.TotalRECapacityAnnual[r, y]
    )
model.RETechIncluded = Constraint(
  model.REGION, model.YEAR, rule=RETechIncluded_rule
)

def RECapacityConstraint_rule(model, r, y):
  return (
    model.REMinCapacityTarget[r, y]*
        model.TotalPowerCapacityAnnual[r, y]
    <= model.TotalRECapacityAnnual[r, y]
  )
model.RECapacityConstraint = Constraint(
  model.REGION, model.YEAR, rule=RECapacityConstraint_rule
)
```

Listing 2: New Renewable energy constraint coding on Pyomo