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Impact of integration of renewable energies and energy efficiency on the reliability of the national electricity grid

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ABSTRACT

This article consists of studying the reliability of the Moroccan electricity grid as well as verifying the plan of production for 2030. To propose an adequate production plan for 2050, a production plan where renewable energies take a large place in the production park. Our objective is the planning and optimization of the Moroccan energy system with a strong integration of renewable energy sources or even 100% integration by guaranteeing the reliability of the electrical system. In this study, we evaluated the reliability of the Moroccan electricity grid in the presence of renewable electricity production based on the energy plan simulator supplemented by Monte Carlo simulations based on probabilistic approaches. The first part of this work consists of projecting demand for 2030-2050 and studying the impact of energy efficiency on forecasts. In the second part, we integrated the existing means of production and the projected demand on energy plan. In the third part we studied the reliability of the Moroccan electricity grid in the presence of the production of wind, solar photovoltaic (PV) and concentrated solar (CSP) electricity according to different stages of study (from 2017 to 2050).

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NOMENCLATURES

LOLP	:	Loss of load probability
LOLE	:	Loss of load expectation
EFOR	:	Effective forced-outage rate
PV	:	Photovoltaic power plant
CSP	:	Concentrated solar power plant
PS	:	Pumped storage
RE	:	Renewable energy
MW	:	Megawatt
TWh	:	Tera watt hour

1. INTRODUCTION

Sustainable development has been a main objective of Moroccan politics since 2009. Renewable energies and energy efficiency are increasingly present in the political discussion in Morocco. In a context of rising oil prices, with a considerable impact on the trade balance, they represent the most interesting alternative for reducing the country's economic vulnerability in the energy sector. They constitute immense wealth, almost untapped until present, for the country. Indeed, energy is a crucial issue in achieving economic and social development at national, regional and local levels. From this perspective, the new national energy strategy, adopted since March 2009 [1], considers the achievement of its major objectives, security of energy supply at the best cost, availability of energy and its accessibility to all, as an imperative to promote balanced, harmonious and equitable development. Especially since the unprecedented growth that Morocco will experience in the coming decades, through the modernization of its agriculture, the revitalization of its industrial fabric, the reinforcement and extension of its infrastructure, the construction of new cities, will cause the growth of energy needs with the tripling of the demand for primary energy and the quadrupling of that of electricity by 2030 compared to their 2008 levels [2]. This development, which will be deployed on the entire national territory, requires more than ever to provide the necessary energy on a regionalized basis. Hence, we must diversify the sources and origins of imported energy, develop national energy potential, particularly renewable energy, multiply the infrastructure for receiving and transporting energy products, and strengthen the means of storage and distribution. Production units based on renewable energy, except hydroelectric power stations, were, at the beginning of their development, mostly small. These units were therefore first connected to the distribution grid, hence the term decentralized production, which qualifies any source of energy connected directly to the distribution network [2] or after the meter on the consumer side often used to designate them. As technologies develop, renewable energy generating units become larger and therefore are connected to higher voltage levels (transmission grid). This arrival of production at all levels is both a new and important challenge for network managers. The latter operate a system that has been designed for unidirectional power flows from production plants to consumers, passing first through the transmission network and then through the distribution network. In addition to flowing in one direction, electricity comes from conventional power stations whose production is controlled. The arrival of renewable energies, in particular on the distribution networks, changes the situation (variable production, possible inversion of power flow in the lines) and can generate a certain number of problems and constraints whose effects must be limited [3].

The problem is reflected in the first instance by the constraints of planning the expansion of production and interconnections under uncertainty (technical feasibility of the various technologies at lower cost). On the other hand, by studying the reliability of the electrical system, the risk of the capacity of the means of production not supplying the energy requested at the various points of consumption according to acceptable criteria, these constraints have led to the definition of rules or technical conditions for connecting the production of renewable energy to the grid [4]. It is therefore necessary to carry out studies of the impact of renewable energies on the networks to analyze these constraints, anticipate the problems linked to the future development of these energies and seek appropriate solutions. These studies are based in particular on the modeling of electricity production units from renewable sources. The first studies of wind or photovoltaic insertion in electrical systems were carried out using deterministic methods [5] mainly due to the lack of appropriate probabilistic modeling and the initially relatively small importance of these production units in the production fleet. These deterministic analyses are based on the examination of a limited number of situations considered a priori as problematic (“the worst cases”) for which the behavior of the electrical system is checked. We make the implicit assumption that the other situations that may occur are less constraining.

The probabilistic approach is another way of approaching the problem [6]. In principle, it amounts to considering all possible cases with their probability of occurrence to estimate the risk of not respecting a system constraint. The consequences of noncompliance with the constraint will of course have to be weighed against their “seriousness” or severity for the system. The network manager must first establish a risk policy. The probabilistic approach should thus make it possible to “scan” all the possible configurations (or cases), taking into account the hazards linked to renewable production, the availability of conventional units and lines, on demand, and therefore to more finely identify the risks incurred with the level of severity and the probability of occurrence of constraining situations. The objective is then to seek new solutions that are technically and economically viable while guaranteeing the safety of people and property [7]. Indeed, in addition to probabilistic modeling of the electrical system, the use of this type of approach requires the development of a new methodology for integration studies and the use of appropriate tools. On the other hand, the implementation of the new solutions to which they could lead will probably have to be based on advanced means of management and control of farms and networks and could require an evolution of the regulatory and contractual framework [8].

The development of conventional means of production, of a large number of small production units of the wind, solar, hydraulic, or even thermal type in the form of cogeneration, is reflected in the distribution networks by a two-way circulation of the energy produced. In addition to this phenomenon, in particular, for wind and photovoltaic production, energy will only be available intermittently; this last aspect impacts the entire electrical system. The two-way circulation of energy and the intermittency of the production of new units require an adaptation of the management of electrical systems to maintain their level of security. Due to the intermittent nature of the energy source and the resulting fluctuations in the power produced by a renewable energy-generating unit, connecting it to any electrical system has a significant impact, which depends on the technology used and on the type of network. In general, it can be said that the higher the penetration rate, is the greater the impact of the integration of renewable energies into the networks. A distinction can be made between local impacts which concern all types of networks and global impacts, which concern transport networks in particular [9]. Local impacts are impacts that occur in the (electrical) vicinity of the unit's connection point and that can be attributed directly to the unit. Local impacts are generally independent of the overall penetration rate of renewable energy production units in the system. They concern two main aspects: the capacity of the network and the quality of the voltage. Apart from the local impacts that have effects approximately the connection point, renewable energy production units can have more global impacts on a regional scale, especially if they are connected to the transmission network [10].

Reliability is linked to a fundamental aspect of the operation of electrical systems: adequacy, which is the system's ability to satisfy overall demand at any time, taking into account operating constraints and unavailability (accidental or scheduled) [11]. Production units and network structures. Suitability is associated with the static conditions of the system. Adequacy studies are carried out as part of the planning of the electrical system [12]. The probabilistic approach of the Monte-Carlo type is the most considered to evaluate the reliability of the electrical networks since it lends itself to computer tools, this method will be projected for the first time on the Moroccan grid [13]. The most widely used reliability indices are probabilistic criteria of production-consumption adequacy (without taking the network into account). There are three main types of reliability indices [14]:
- Force outage rate (FOR): The calculation of the FOR index initially applies to a simple two-state model (available/unavailable) which is only valid for evaluating the reliability of one or more devices over a very long period of use
- Loss of load probability (LOLP): this is the oldest and most basic of the criteria. It defines the probability of not satisfying the demand over a given period [15]
- Loss of load expectation (LOLE): it is defined as the mathematical expectation of the number of hours (resp. days) of the year during which the peak hourly demand (resp. daily) is not satisfactory due to the production capacity [16]

This article aims to the evaluation of the probabilistic application methods to study the impact of renewable energies on electrical systems compared to deterministic methods. This contribution will be assessed in particular for long-term impact studies (planning type). The achievement of this main objective was divided into four stages. Namely, 2017-2018, 2020, 2025, 2030. The steps that we followed chronologically in our overall study are described in Figure 1.

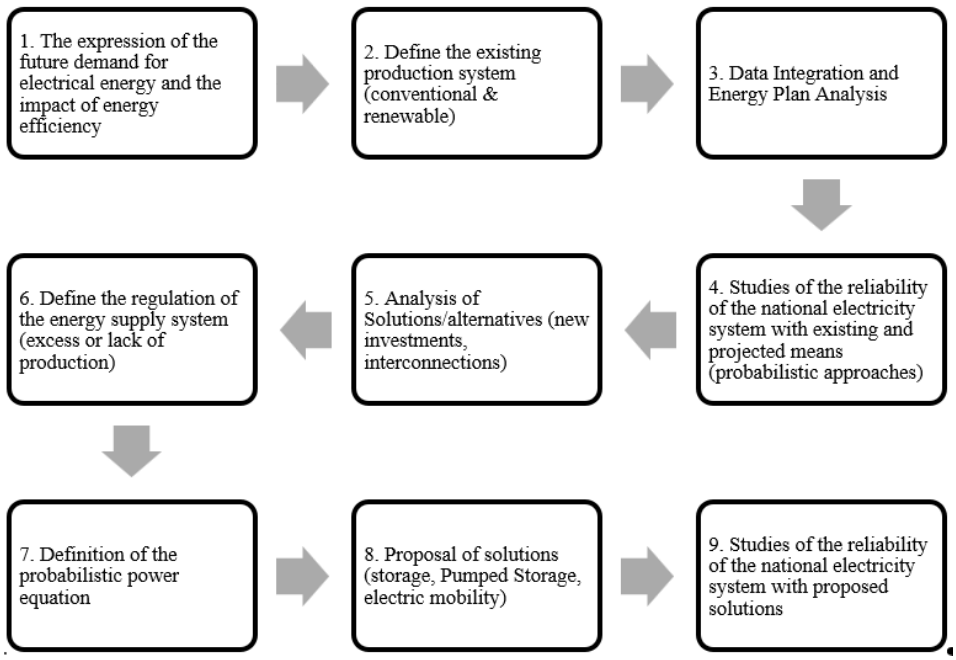

Figure 1. The study methodology

However, we will limit ourselves in this article to the study of the reliability of the 2017 stages until 2030 and the other results will be the subject of our future articles. Four operations are followed in order to achieve this study, which are respectively:
- Forecast of electrical energy demand in the medium and long term
- Measurement of the impact of energy efficiency on demand forecasting
- Integration and analysis of data on energy plan
- Probabilistic modeling of the electrical system: This involves characterizing the variation of several system parameters by random variables, and developing methods for calculating the probability distributions of these random variables.

2. DEVELOPMENT OF PRODCUTION PLAN AND RELIABILITY STUDIES OF THE DIFFERENT STAGES BY 2050

2.1. Study of stage 2017-2018

This study will use three steps to evaluate the ratability of power grid and examination the plan production of the proposed stage. Namely, the demand forecasting, the production plan, and the reliability of the network. These steps will be discussed in detail for the first stage compared with the other stages.

2.1.1. Demand forecastsing

The first step consists of forecasting the demand at each study stage of the four stages, using the results of the first part, the studied stages are 2017, 2020, 2025, 2030, 2035, 2040, 2045, 2050. As we discussed before, only the first four stages are considered in this study. An average progression of 23% from one stage to another was observed in Figure 2 which represents the forecast demand for 2050. The first scenario studied is that of the low trend in energy efficiency in demand forecasting with the aim of sizing our electrical system and planning a more reliable production plant after studying the existing plant and ensuring reliability and stability of the national electricity grid, scenario number 1 represents the pessimistic scenario while that of energy efficiency represents the optimistic scenario. The demand integrated into the energy plan system is 37.79 TWh spread over 8760 h of the year according to the load distribution of 2017. The nonsatisfaction of the demand for electrical energy will result in an increase in the import of electricity via the two interconnections Morocco-Spain and Morocc-Algeria according to their maximum capacities i.e. the nominal capacity of the EHV/HV lines providing this interconnection [17].

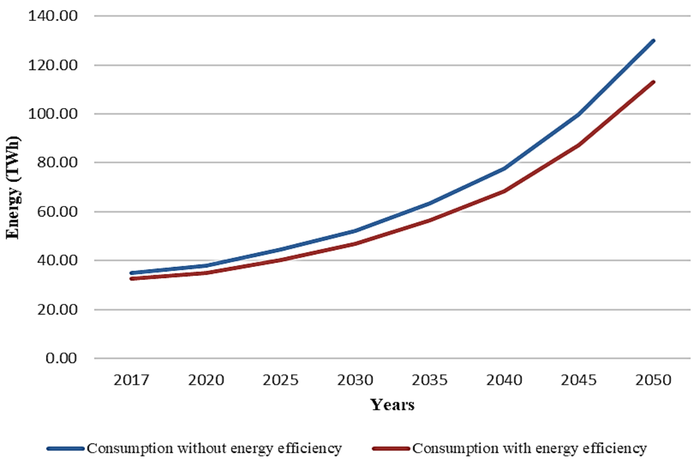

Figure 2. Demand forecast for 2050

In Figure 3, the study reflected a huge lack in demand over the twelve months of the year, which is not filled by the means of production specific to the Moroccan network operator. Thus, the use of the Morocco-Spain interconnection becomes a necessity. In Figure 4, the study reflected a huge lack in demand over the twelve months of the year, which is not filled by the means of production specific to the Moroccan network operator. Thus, the use of the Morocco-Spain interconnection becomes a necessity. Furthermore, the maximum value of energy is reached in August since the peak was recorded in this month (4646 MW). It is clear that at this stage Morocco imports more than it exports. In 2017, electricity exports to Spain amounted to 10.180 GWh against 5.745 GWh imported.

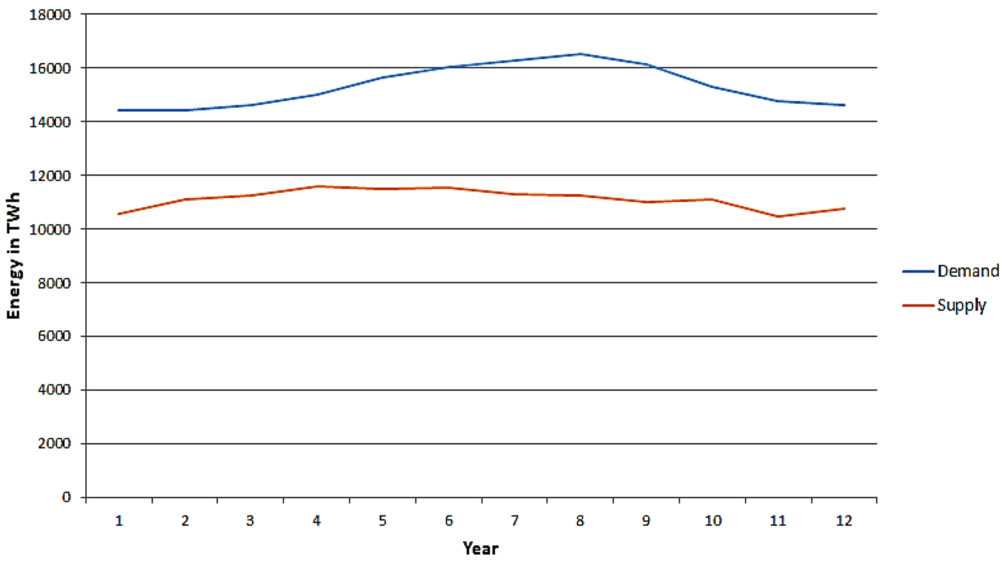

Figure 3. Demand and supply of 8760 hours

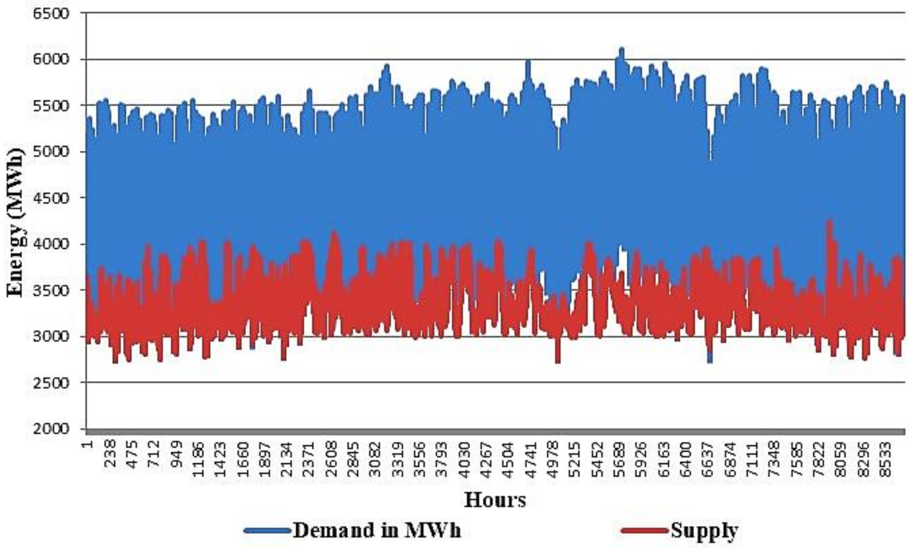

Figure 4. Demand and production of stage 2017 (in MWh)

The 10.180 GWh corresponds to the consumption of a village. With the completion of the renewable energy strategy, which aims to vary the energy mix, exports will be increased. Electricity imports from Algeria reached 302.311 GWh against 153.201 GWh exported. Between Morocco and Algeria, the exchange "takes place on a zero balance sheet". It allows the assistance of the two networks by pooling the spinning reserve between the two countries. Morocco is connected to Spain via an interconnection with a total exchange capacity of 1,400 MW via two submarine cables. The first was commissioned in 1997. The second was in 2006 [18]. The Moroccan energy company operates on the Spanish spot market, where it has the status of Spanish market agent. A status that allows it to sell and buy electricity on this market according to its availability and cost. Morocco is also interconnected with Algeria by two 225 kV power lines. With a capacity of 200 MW each, they were commissioned in 1988 and 2006 respectively. A third 400 kV was installed in 2009. This brings the exchange capacity between the two countries to 1200 MW.

In the case of the Moroccan-Algerian interconnection, it is rather an exchange that falls within a framework of mutual aid between ONEE and Sonelgaz, intended to ensure the security of supply and the stability of the networks [19]. Electricity imports and exports follow the lowest cost principle. The supply is made from the Spanish market when the production cost is more attractive than in Morocco. It exports when it has a surplus that cannot be consumed by local demand, which we will notice in the coming stages.

2.1.2. Production plan

In this case, two means of production exist. The conventional plants constitute a share of 68% of the national installed capacity in this stage. Table 1 gives an overview of conventional power plants used in this stage (2017-2018), from the commissioning of the first thermal power plant in 1985 until today. The fourth column of Table 1 represents unplanned unavailability rate, which is indicated by the parameter T. The last column of the same table gives the unavailability rate of each power station, which will be used later in the calculation of the LOLP reliability index. This unavailability rate Fossil fuels are an important part of the mixed energy in Morocco and many other economies. They are particularly important in the production of electricity, and more than 60% of electricity is produced from fuels mainly coal and natural gas. Globally, the increase in total energy production is projected to increasingly rely on fossil fuels, at least until 2050, particularly in a number of key geo-economics areas.

Furthermore, the means of renewable production is gradually integrated according to the date of commissioning of the power plants. Namely, the wind plant, the photovoltaic plant (PV), and the concentrated solar power plant (CSP), and pumped storage (PS), which is translated by gradual penetration rates to measure the impact of a high penetration rate on the reliability of the national grid [17]. Table 2 gives an overview of the different renewable power plants used in our stage, which currently exist on the Moroccan grid. We observe that the wind power plant represents 928MW, the CSP presents 180MW of energy, 1299MW for the hydraulic power with almost a total of 29 plants, while the pumped storage presents 464MW.

Table 1. Conventional power plants

Plants	Commissioning year	Power (MW)	Unplanned unavailability rate (%)	d = 1-T
PC 1	2017	16	0.04	0.96
PC 2	2017	72	0.04	0.96
PC 3	1992	99	0.06	0.94
PC 4	2007	99	0.06	0.94
PC 5	2009	119	0.05	0.95
PC 6	1994	198	0.06	0.94
PC 7	1985	300	0.07	0.93
PC 8	2010	300	0.04	0.96
PC 9	2012	315	0.04	0.96
PC 10	2017	350	0.04	0.96
PC 11	2005	384	0.04	0.96
PC 12	2010	470	0.04	0.96
PC 13	1998	680	0.06	0.94
PC 14	2013	700	0.06	0.94
PC 15	1998	700	0.06	0.94
PC 16	2017	1386	0.04	0.96
Power in MW		6188		

Table 2. Renewable power plants

Source	Destination	Power (MW)
	Plant number 1	50
North Wind	Plant number 2	200
	Plant number 3	50
	Plant number 4	32
Total of North Wind		332
South Wind	Plant number 5	200
	Plant number 6	300
Total of south Wind		500
Central Wind	Plant number 7	60
	Plant number 8	36
Total of Central Wind		96
Total of Wind Power plants		928
CSP of South	P CSP1	160
CSP of East	P CSP2	20
CSP Power		180
Hydraulic power	A total of 29 plants	1299.5
Total Hydraulic Power		1299.5
Pumped Storage	PS1	464
Total Pumped Storage		464
Total Renewable Energies		2871.5

In this study, hydropower plants constitute a 45% share of renewable means of production, the reason for which they are considered as conventional means of production, while pumped storage is considered an emergency resource and not a stable means of production [20]. This production plan showed a lack of production subsequently the non-satisfaction of national demand, the thing that will be translated by the investment in renewable energies and energy efficiency. We note that the photovoltaic plant for the stage 2017-2018 is not included because it was not yet used.

2.1.3. The reliability of the network and probabilistic calculations

As discussed previously, the study of the reliability of electrical networks using the Monte-Carlo method essentially consists of simulating the probabilistic behavior of an electrical network in a loop by integrating changes in state or parameters dictated by a defined probability [21]. In our case, the Monte-Carlo simulation requires the calculation of all reliability indices such as EFOR, LOLP and LOLE; the calculation of these indices differs from one technology to another, in the case of renewable energies, the calculation of EFOR is different from conventional technology given the intermittency of renewable energy (RE) [22]. The proposed method considered in this work will allow us to calculate more precisely the reliability of the Moroccan electricity system where wind power plants provide high power levels. The technique used is a simple extension to existing and well-known methods that are applied to conventional power plants. The technique used designed to retain the hourly variability of wind energy production, while maintaining an assessment of the probability that actual wind energy production will be above or below the expected level. This technique is an extension of the existing convolution procedure, which applied to conventional generators. However, a key element of these new methods is to evaluate an effective force outage rate (FOR) for the wind farm that changes over time, since several analytically calculated reliability indices are derived from the processing of one or more FOR [23] indices that evaluate the probability that a piece of equipment is unavailable. To better explain the calculation of the FOR index in both cases, conventional power plants and wind power plants as an example, we will proceed to the treatment of the two examples [24].

The means of renewable production is evaluated according to penetration rate, which is based on the date of commissioning of the power plants to measure the impact of a high penetration rate on the reliability of the national grid. Thus, the contribution of renewable energy in the production plan of this stage (2017-2018) is given by four penetration rates, which will be are evaluated in the next sections. These rates are 0%, 4.25%, 11%, and 13%, respectively.

a) Penetration of 0% of renewable energies

The objective is to inject renewable energy gradually into the network and simulate the impact of the penetration rate on the reliability of the network. We recall the conventional means of production at this stage, as mentioned above, production is at 6188 MW, which represents 100% of the conventional production. The presentation of production and demand is plotted in the Figure 5, without the integration of renewable energies (0%). The problem of dissatisfaction of the demand for electrical energy arises, and that resolved by the import and lack of production as explained above and as shown in Figure 6. Based on Monte-Carlo simulations, the probabilistic calculation gives us a probability that varies between 3.84E-08 and 0.823.

b) Penetration of 4.25% of renewable energies

We proceed to the study of this section according to different time intervals where the wind production differs (max, average, min), the demand for electrical energy is 37.79 TWh and an exchange of 850 MW (import/export), remainder of the means of production, which are as follows:

The thermal means, a technical maximum of 2585 MW and a technical minimum of 1644 MW.

- 1299.5 MW of Hydraulic
- 464 MW of Pumping
- 332 MW of North Wind
- 500 MW of Wind South
- 60 MW of Wind Center
- 160 MW of CSP 1 [25]
- 20 MW of CSP 2

In this tranche, we consider that the commissioning of the Wind Nord 332MW (for RE).

- The choice of a time slot where the wind production is maximum to calculate the EFOR in (1). The maximum capacity of the wind turbines injected into this section is 332MW and which concerns the wind turbines of the North according to the plan presented previously, for 84 hours of the interval time [2626h; 2709h] of the year the production varies from 85% to 100%. Wind generation in this case represents 6% to 10% of national demand.

$$EFOR = 1 - \left(\frac{26835}{84 \times 332}\right) = 0.0377 \tag{1}$$

- The choice of a time slot or wind production is minimal to calculate the EFOR. The maximum capacity of the wind turbines injected into this section is 332MW, which concerns the wind turbines of the North according to the plan presented previously, for 84 hours of the interval time [2509 h; 2592 h] of the year the production varies from 0% to 4%. Wind generation in this case represents 0% to 5% of national demand.

$$EFOR = 1 - \left(\frac{6599}{84 \times 332}\right) = 0.7633 \quad (2)$$

– The choice of a time slot where wind generation is average, during 84 hours of the time interval [276 hours; 359 hours] of the year, production varies from 1% to 6% as shown in (3).

$$EFOR = 1 - \left(\frac{9615}{84 \times 332}\right) = 0.6552 \quad (3)$$

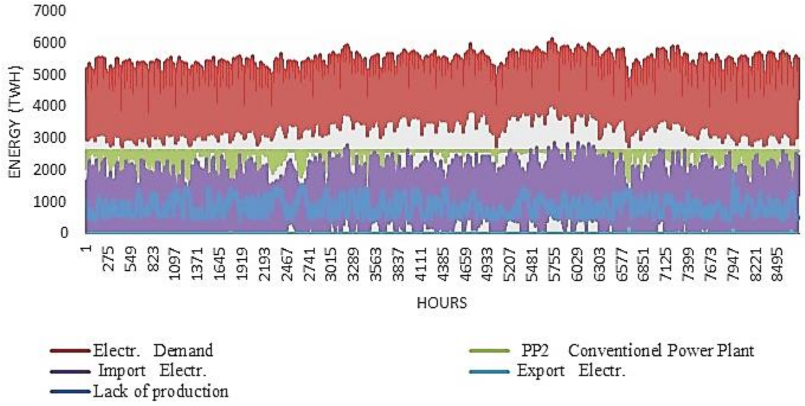

Figure 5. Demand and supply of 2017

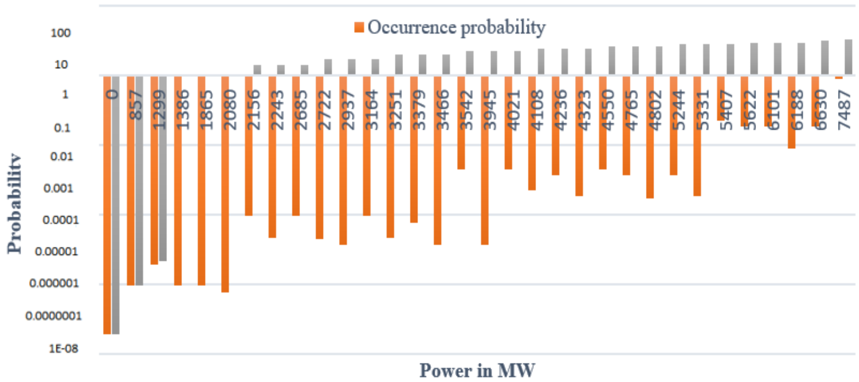

Figure 6. Occurrence and cumulative probability

c) Penetration of 11% of renewable energies

By keeping the same parameters of energy demand as well as the maximum capacity of the exchange between our neighbors with a penetration rate of 11%, in this case it is necessary to provide all the means of wind production including 332 MW of North Wind, 500 MW Wind South, and 96 MW Wind Center.

– The choice of a time slot where the wind generation is maximum to calculate the EFOR, which is 886 MW a rate of 95% that translates into a satisfaction of 15% of the national demand. The maximum capacity of the wind turbines injected into this section is 928 MW, which concerns the wind turbines of the North, South and Center, during 84 hours of the time interval [2626h; 2709h] of the year the production varies from 85% to 100%. Wind generation in this case represents 6% to 10% of national demand as shown in (4).

$$EFOR = 1 - \left(\frac{72101}{84 \times 332}\right) = 0.031 \quad (4)$$

In this case, wind generation represents 17% to 28% of national demand.

– The choice of a time slot where wind generation is at a minimum to calculate EFOR [0%, 12%] of national demand, production varies from 3% to 38% during the time slot [2509 h; 2558 h] as shown in (5).

$$EFOR = 1 - \left(\frac{5714}{50 \times 886}\right) = 0.87 \quad (5)$$

– The choice of a time slot where the wind generation is average to calculate EFOR, the production varies from 12% to 73% during the time slot [276 h; 359 h] in (6).

$$EFOR = 1 - \left(\frac{25836}{84 \times 886}\right) = 0.6528 \quad (6)$$

d) Penetration of 13% of renewable energies

In this case the commissioning of the 180 MW CSP plants in addition to the 928 MW Wind, the other conventional plants remain the same.

– The choice of a time slot where the wind generation is maximum to calculate the EFOR given by Equation (7) which is 886 MW a rate of 95%, the maximum capacity of the wind turbines injected into this section is 928 MW and the maximum capacity of the CSP is 180 MW. Demand satisfaction in this case is 18%, renewable production represents 15% to 29% of national electricity demand. During 84h of the time interval [2626 h; 2709 h] of the year, the production varies from 71% to 99%.

$$EFOR = 1 - \left(\frac{76870}{84 \times 1066}\right) = 0.1415 \quad (7)$$

– The choice of a time slot where the production in RE is at least [2519 h; 2552 h] (34 hours), the production varies from [0% to 23%] and a contribution of 0% to 5% in the satisfaction of the national demand in (8).

$$EFOR = 1 - \left(\frac{4002}{34 \times 1066}\right) = 0.89 \quad (8)$$

– The choice of a time slot where the production in RE is on average [276 h;359 h] for 84 h the production is between [11%; 56%] in (9).

$$EFOR = 1 - \left(\frac{28185}{34 \times 1066}\right) = 0.685 \quad (9)$$

In general, the average of EFOR is given by (10).

$$EFOR = 1 - \left(\frac{\text{total production}}{8760 \times \text{installed power}}\right) = 0.62 \quad (10)$$

Summary of the 2017 Stage results is shown in Figure 7 and Table 3 in which the average of the LOLP decreases as the penetration rate increase (from 0.0046 to 0.0011).

Table 3. Summary of the 2017 stage

Reliability index	Without ER (0%)	Penetration rate of 4.25%	Penetration rate of 11%	Penetration rate of 13%
LOLP (avg)	0.0046	0.0019	0.001122	0.0011
LOLP (%)	0.460%	0.190%	0.112%	0.110%
LOLE (h)	40.296	16.644	9.829	9.636

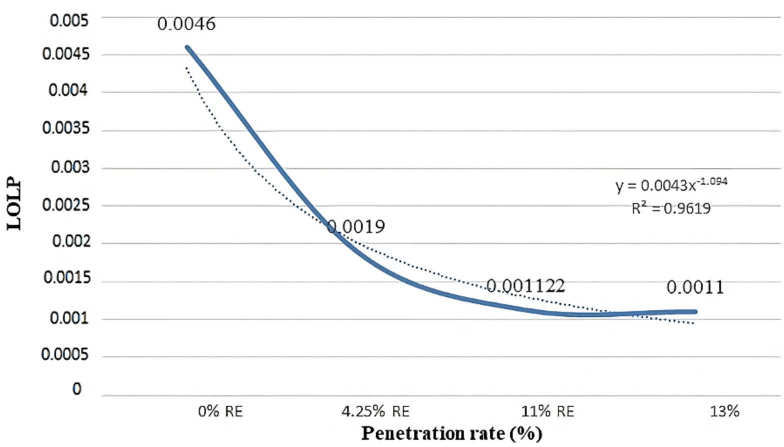

Figure 7. Evolution of the LOLP depending on RE penetration in 2017

2.2. Study of stage 2020

In the same way, we will proceed to the study of the 2020 stage according to the four tranches. A load demand of 41.72 TWh and a simulated peak power of 6747 MW, the maximum power exchanged via the interconnections is 850 MW. The production fleet at this stage is made up of:

– Thermal Pmax = 3874.2 MW; Pmin = 2372.8 MW
– 464 MW of Pumping
– 1299.5 MW of Hydraulic
– 652 MW of Wind North
– 300 MW of Wind East
– 1100 MW of Wind South
– 296 MW of Wind Center
– 160 MW of CSP 1
– 20 MW of CSP 2

According to the four tranches studied, we tried to increase the penetration rate of renewable energies in the energy mix to examine the impact on the reliability indicator. In Table 4 we have tried to calculate the EFOR index which is calculated as follows: EFOR= 1- FOR = 1- (the total production in a time interval/ (the number of hours in the interval × installed power)). We have chosen different time intervals where the production of renewables differs from one interval to another from the smallest production to the largest in order to examine the variation of the EFOR index. This operation is repeated at each increase in renewable energies in the network. We observe that it differs from one interval to another from 0.07 to 0.9.

Table 4. Calculation of EFOR

Reliability index	Penetration rate of 8%	Penetration rate of 21.46%	Penetration rate of 28.75%	Penetration rate of 30.96%
A_{pmax}	0.07	0.072	0.22	0.172
B_{pmin}	0.907	0.907	0.922	0.904
C_{pavg}	0.57	0.573	0.65	0.66

By calculating the average over the whole year 2020 gives us (11):

$$EFOR = 1 - \left(\frac{7488678}{8760 \times 2528}\right) = 0.66 \quad (11)$$

summary of the 2020 Stage in shown in Figure 8 and Table 5 in which the average of the LOLP decreases as the penetration rate increase (from 0.0155 to 0.0039).

Table 5. Summary of the 2020 stage

Reliability index	Penetration rate of 8%	Penetration rate of 21.46%	Penetration rate of 28.75%	Penetration rate of 30.96%
LOLP (avg)	0.0155	0.0052	0.0035	0.0039
LOLP (%)	155%	53%	35%	39%
LOLE (h)	136.07	46.13	30.72	33.99

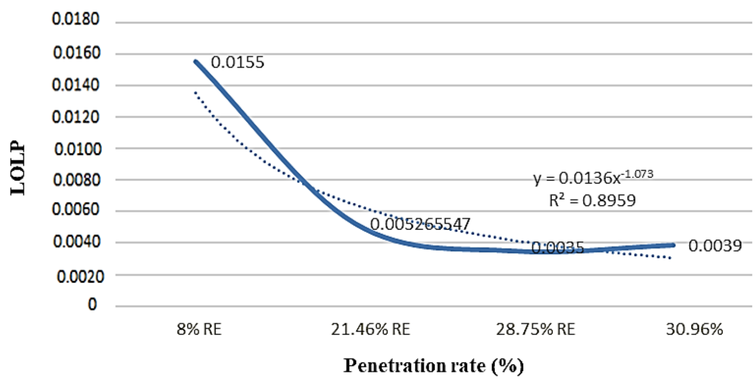

Figure 8. Evolution of the LOLP depending on RE penetration in 2020

2.3. Study of stage 2025

In the same way, we will proceed to the study of the 2025 stage according to the seven sections this time. A load call of 48.98TWh and a peak power simulated at 7921 MW, the maximum power exchanged via the interconnections by 2025 in which the interconnection exists now represent 1900 MW and in the future the addition of 1700MW in the total we have 3600MW (Table 6).

The production fleet at this stage is made up of:

- Thermal Pmax = 5374 MW; Pmin = 3216 MW
- 1114 MW of Pumping
- 1724.5 MW of Hydraulic
- 747 MW of Wind North
- 300 MW of Wind East
- 1520 MW of Wind South
- 586 MW of Wind Center
- 510 MW of CSP 1;2&3
- 340 MW of CSP East
- 2293 MW of PV South
- 1046 MW of PV East

Table 6. Future interconnections

Interconnection programmed	Country concerned	Power	Line
Existing	Morocco-Spain	1400 MW	Two-line 400 kV
	Morocco-Algeria	200 MW	Two-line 225 kV
	Morocco-Algeria	300 MW	Two-line 400 kV
Future	Morocco-Spain	700 MW	line 400 kV
	Morocco-Portugal	1000 MW	Line 400 kV
	Morocco-Portugal	-	Line 225 kV

According to the seven tranches studied, we tried to increase the penetration rate of renewable energies in the energy mix to examine the impact on the reliability indicator. In Table 7 we have tried to calculate the EFOR index we repeat the operation like in the Table 4 in this stage we have chosen different time intervals where the production of renewables differs from one interval to another from the smallest production to the largest in order to examine the variation of the EFOR index. This operation was repeated at each increase in renewable energies in the network. We observe that it differs from one interval to another from 0.07 to 0.9 is shown in Table 7.

Table 7. Calculation of EFOR

Reliability index	Penetration rate of 5%	Penetration rate of 15.34%	Penetration rate of 21.33%	Penetration rate of 24.78%	Penetration rate of 35.07%	Penetration rate of 37.37%	Penetration rate of 44.44%
A_{pmax}	0.078	0.078	0.243	0.2	0.29	0.31	0.34
B_{pmin}	0.9	0.907	0.923	0.91	0.84	0.83	0.807
C_{pavg}	0.576	0.576	0.66	0.67	0.69	0.69	0.695

Calculating the average over the whole year 2025 lead us to (12).

$$EFOR = 1 - \left(\frac{16272132}{8760 \times 6570}\right) = 0.7172 \quad (12)$$

Summary of the 2025 Stage results is shown in Figure 9 and Table 8 in which the average of the LOLP decreases as the penetration rate increase (from 0.0078 to 0.0010).

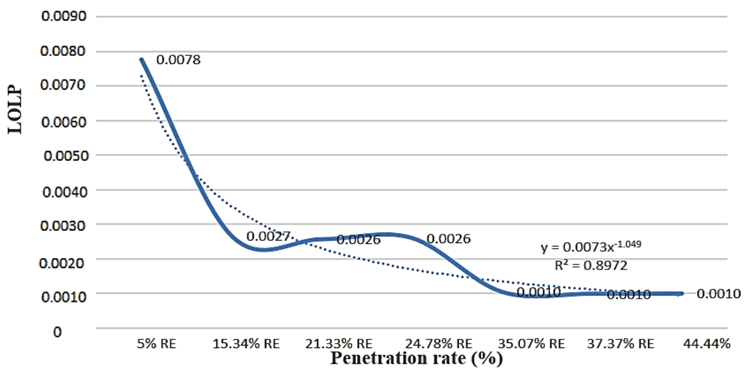

Figure 9. Evolution of the LOLP depending on RE penetration in 2025

Table 8. Summary of the 2025 stage

Reliability index	Penetration rate of 5%	Penetration rate of 15.34%	Penetration rate of 21.33%	Penetration rate of 24.78%	Penetration rate of 35.07%	Penetration rate of 37.37%	Penetration rate of 44.44%
LOLP (avg)	0.0078	0.0027	0.0026	0.0026	0.0010	0.0010	0.0010
LOLE (h)	68.02	23.34	22.49	22.83	9.17	8.68	8.73

2.4. Study of stage 2030

In the same way we will proceed to the study of the 2030 stage according to the seven sections this time. A load call of 58.69 TWh and a peak power simulated at 9492 MW, the maximum power exchanged via the interconnections by 2030 is 3600 MW. The production fleet at this stage is made up of Thermal Pmax = 8221 MW, Pmin = 5003 MW. Furthermore, 1614 MW of Pumping, 1724.5 MW of Hydraulic, 747 MW of Wind North, 300 MW of Wind East, 2220 MW of Wind South, 786 MW of Wind Center, 510 MW of CSP 1;2&3, 340 MW of CSP East, 2293 MW of South PV, and 1046 MW of PV East. According to the seven tranches studied, in Figure 9, we tried to increase the penetration rate of renewable energies in the energy mix to examine the impact on the reliability indicator. In addition, we have tried to calculate the EFOR index we repeat the operation like in the previous stage, this operation was repeated at each increase in renewable energies in the network as shown in Table 9. We observe that it differs from one interval to another. It moves from 0.07 to 0.9 like the previous results. Calculating the average over the whole year 2030 given by (13).

$$EFOR = 1 - \left(\frac{20586570}{8760 \times 8242}\right) = 0.7148671 \tag{13}$$

A summary of the 2030 stage is presented in Figure 10 in which the average of the LOLP decreases as the penetration rate increase (from 0.0019 to 0.0002).

Like the previous stage, the Table 10 represents the result calculation of reliability indexes LOLP and LOLE. We observe that there is a degradation of the reliability of our system since the LOLP index decreases from one rate to another (by increasing the penetration rate of renewables in the network). According to the results obtained in each stage (2017-2030), we notice that the reliability of the electrical system has a descending trend by increasing the rate of penetration of renewable energies in the energy system. These results in a threat to the stability of the system and the non-satisfaction of the request at some point. Therefore, we deduce that the reliability of the system follows a power law, which is given by (14),

$$y = a\,x^{-b} \tag{14}$$

with $0.0025 < a < 0.01$ and $1.04 < b < 1.2$. As electrical energy is not easily storable and to meet national demand, it is necessary to invest in storage means to ensure the security of electrical energy supply and to strengthen interconnections with neighboring countries to ensure the N-1 relief to any major incident in the transport network.

Table 9. Calculation of EFOR

Reliability index	Penetration rate of 4%	Penetration rate of 14.96%	Penetration rate of 20.44%	Penetration rate of 23.01%	Penetration rate of 34.58%	Penetration rate of 36.29%	Penetration rate of 41.57%
A_{pmax}	0.0781	0.07814	0.236	0.184448	0.3199	0.3319801	0.3374291
B_{pmin}	0.7768	0.907	0.92302	0.9178	0.85192	0.8456769	0.811266
C_{pavg}	0.7552	0.755	0.802235	0.6726	0.703674	0.7025127	0.6949328

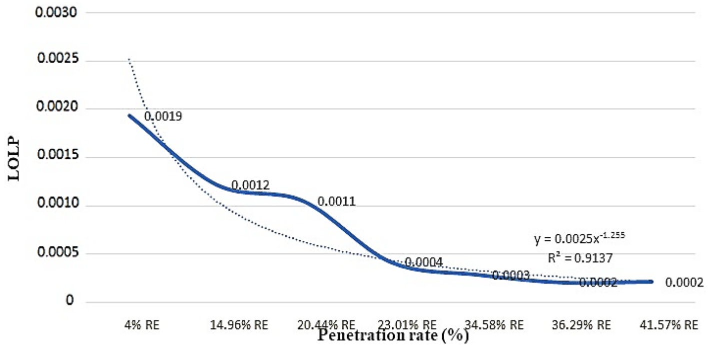

Figure 10. Evolution of the LOLP depending on RE penetration in 2030

Table 10. Summary of the 2030 stage

Reliability index	Penetration rate of 4%	Penetration rate of 14.96%	Penetration rate of 20.44%	Penetration rate of 23.01%	Penetration rate of 34.58%	Penetration rate of 36.29%	Penetration rate of 41.57%
LOLP (avg)	0.0019	0.0012	0.0011	0.0004	0.0003	0.0002	0.0002
LOLE (h)	16.92	10.69	9.20	3.71	2.56	1.85	1.93

3. CONCLUSION

This article describes a probabilistic methodology for impact studies of the integration of renewable energy production units in electrical systems and evaluates its contribution compared to the traditional deterministic methodology. According to the results of reliability studies of the Moroccan grid by gradually injecting renewable energy into the energy mix, reliability deteriorates by reaching a maximum rate of almost 45% in terms of energy and not installed power (will be translated by a higher rate in terms of installed power). On the other hand, these results are examined in relation to the existing and future storage means, which will be programmed by 2030.

Moving towards a predominantly renewable electricity mix is technically feasible in Morocco. However, many levers will have to be activated to ensure the country's security of supply. The integration of a very high proportion of renewable energies in the Moroccan electricity system is possible while ensuring security of supply. Yet, several conditions must be strictly observed and be cumulative: increasing flexibility, resizing reserves (means of storage), adapting the transmission network and maintaining stability (frequency). Technical solutions should be available by 2030 and 2050. They must nevertheless prove themselves on a large scale through demonstrations.

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