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Multi-objective cuckoo search algorithm for optimized pathways for 75 % renewable electricity mix by 2050 in Algeria

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ABSTRACT

The transition to an energy system with a focus on electricity sector is becoming more and more crucial to increase the life expectancy of fossil fuels, but also to meet the current commitments regarding greenhouse gas emissions. This paper presents the most credible options to increase the share of renewable energy resource in the Algerian electricity power system by 2050. Screening curve method is used to assess the levelized cost of electricity (LCOE) of different technologies for electricity generation and EnergyPlan tool is used to estimate total annual cost, annual investment cost, renewable energy resource share and CO_2 emissions during the time horizon. The efficiency and the simplicity of multi-objective cuckoo search algorithm make it a powerful approach for solving energy strategy multi-optimization problem. Considering LCOE economic order and the availability of renewable energy resource, the energy transition strategy is established by minimizing the total annual cost and maximizing renewable energy share in 2035, 2040, 2045, and 2050 using multi-objective cuckoo search algorithm. The results revealed that achieving 75% is technically feasible but will require significant investment.

1. Introduction

Algeria is divided into two main distinct climatic zones with different potential of renewable energy resources (RES), particularly in wind and solar (W&S) resources [1]. Early in 2000, Algeria started to deploy W&S energy, however at a very modest scale and mainly for research and development purposes. In 2019, the total installed photovoltaic (PV) capacity reached 344.1 MW; while the wind power capacity was 10.2 MW [2].

However much of the potential has yet to be exploited. In the future, according to Algeria's national renewable energy plan [3], the share of solar energy in the electricity mix will be much more important.

Potentially, fossil fuels, mainly natural gas, and RESs might contribute in a substantial way to the future Algerian electricity power system (AEPS). However, adopting the most cost-effective resource implies the optimization of different technologies, installed capacity while taking into consideration their environmental benefits. More precisely, considering the low capacity factors (CF) of W&S technologies, high investments are needed to cope with the electrical load demand (ELD) growth.

Long-term power generation expansion planning requires finding the feasible mix and optimizing the installed capacity based on several technology options [4,5], enabling secure operation of an electrical system, in particular the need for regulation and matching supply and demand. If Screening Curve Method (SCM) is a powerful approach for comparing production costs of different generation technologies [6], the study must be supported by determining the level of integration of renewable, without altering electricity supply-demand balance. For each generation technology, the SCM considers operating capacity, fixed and variable costs of operation and maintenance, investment cost, and useful life of the power plant. From the SCM, the Levelized Cost of Electricity (LCOE) allows the comparison of different technologies (e.g., wind, solar PV, CSP, natural gas, nuclear, etc.) of unequal life spans, project size, different costs, and capacities.

However, the SCM is not an adequate substitute for detailed production cost or expansion planning analysis. For instance, the SCM neglects plant start-up costs, forced outages, and system reliability like transmission and ancillary services [7–11].

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Nomenclature

AEPS	Algerian Electricity Power System
AIC	Annual Investment Cost
APC	Annual Production Cost
AR4	Fourth Assessment Report
Bio	Biomass
CF	Capacity Factors
CPG	Conventional Power Generations
CSA	Cuckoo Search Algorithm
CSP	Concentrated Solar Power
EGC	Energy Generation Cost
ELD	Electrical Load Demand
FC	Fuel cost
Geo	Geothermal
I	Investment cost
i	annual interest rate
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
k	Number of technology
LCOE	Levelized Cost Of Electricity
LDC	Load Demand Curve
MOCSA	Multi-Objective Cuckoo Search Algorithm
MOEA	Multi-Objective Evolutionary Algorithm
MOP	Multi-Objective Optimization Problem
NGCC	Natural Gas Combined Cycle
NGT	Natural Gas Turbine
NPP	Nuclear Power Plant
Nucl	Nuclear
O&M	Operation and Maintenance
PEP	Power Electricity Production
r_i^T	Annual capital recovery factor
RCP	Representative Concentration Pathways
REPS	Renewable Energy Power Share
RES	Renewable Energy Resources
RET	Renewable Energy Technologies
SCM	Screening Curve Method
T	Plant expectancy life
TAC	Total Annual Cost
TERI	Innovative Solutions for Sustainable Development
VC	Variable cost
W&S	Wind and Solar

To remedy the SCMs deficiencies, the open source EnergyPlan [12] tool, for long-term energy planning, is able to simulate operation of a smart energy system on an hourly basis for a whole year. The EnergyPLAN integrates different energy end uses and sectors (heating, cooling, transport, and electricity), including electrical vehicle and storage. The EnergyPlan allows introducing technology efficiency, specific CO_2 emissions, and fuel costs. The environmental impacts in terms of CO_2 emissions as well as the share of RESs in primary energy supply and electricity production are given in its output file. However, it does not consider grid topology and consequently, optimal location of generation units is not addressed.

1.1. Literature review

Make the right choice of energy system models and tools are crucial for policy analysis and decision making of energy transition. Fattahi et al. [13] presented the major challenges of modelling low-carbon energy system. Chang et al. [14] reviewed the current trends in energy system modelling. Application aspects of different modelling tools, perceived policy-relevance, user accessibility, and model linkages are presented. Applications, scenario analyses and performance indicators, implemented on EnergyPLAN are reviewed in Ref. [15].

Several energy transition studies based on EnergyPLAN tool have been developed recently. Aiming to decarbonise future expansion capacity of the Italian energy system, Prina et al. [16] coupled EnergyPLAN with hill climbing algorithm and introduced the marginal abatement cost-curve as a new approach. In Ref. [17], the future Lebanon's electricity generation mix is studied. The best combinations of different RES are carried out on Excel solver optimization calculator tool, which allows modelling least-cost electricity generation portfolio, total investment, and carbon emissions.

Further studies motivated the energy transition investments with 100% RES can be found in the literature. Bamisile et al. [18] proposed a novel approach for sustainable and economic energy planning to ensure 100% electrification of Nigeria by 2030. Different scenarios of electricity generation mix (natural gas, wind onshore, wind offshore, photovoltaic, concentrated solar power, and hydropower) are built on EnergyPLAN. A projection to a 100% renewable energy system for the city of Cuenca, Ecuador by the horizon 2050, presented by Icaza et al. [19]. Authors of Ref. [20] coupled EnergyPLAN with GWO algorithm to trace an optimized scenario considering 100% renewable energy with high share of hydropower and the case of Portugal is studied to perform the proposed approach. A feasibility study to reach 100% renewable electricity production by 2040 in Swedish presented in Ref. [21]. In Ref. [22], a demonstrative study carried out on EnergyPLAN to design smart energy cities of Aalborg municipalities within the perspective of achieving 100% RES is presented. The authors identify the best solutions for implementing a suitable transition by 2050 at the national and international levels, while local action is suggested. Child et al. [23] used LUT Energy System Transition Model to study the feasibility transition towards a 100% renewable energy system for Europe by 2050. By developing large-scale hydropower and wind farms, such transition can be completed. In Ref. [24], energy cost, demand, and energy mix are introduced to optimize future 100% renewable energy system in Portugal. Bogdanov et al. [25] presented a suitable energy transition by coupling different energy sectors such as, power, heat, transport and desalination. Eventual issues and challenges results from the transition towards 100% renewable generation in Canary Islands are presented in Ref. [26].

By solving multi-objective optimization problem (MOP), it is possible to find the optimal energy mix with 100% share of RESs. Coupling EnergyPLAN to Multi-Objective Evolutionary Algorithm (MOEA) has been widely used in the literature. Refs. [27,28] used MOEA for long-term energy planning considering different trade-off scenarios and then elaborating a method to identify the best energy transition. In Ref. [29], a comprehensive optimal hourly-resolution approach to facilitate the transition from fossil to renewable energy of the Indian electricity system in 2030 is analyzed. The scenarios proposed by IRENA and TERI are analyzed using EnergyPLAN along with multi-objective evolutionary algorithm. Sadiqa et al. [30] applied MOEA to Pakistan's energy system. The MOEA and the EnergyPLAN are applied to the Italian energy system in Ref. [31]. Their approach includes cost decrease of technologies year by year and decommissioning of old plants. Prina et al. [32] coupled the EPLANopt and EnergyPlan tools to analyse energy system efficiency in buildings. Ref. [33] proposed a techno-economic feasibility study for Jordan aimed at 100% renewable energy system scenario considering the mix of natural gas, nuclear, oil shale, and renewable energy technologies (RET). Bin Lu et al. [34] investigated the Australia's electricity demand growth at affordable prices by considering 90% and 100% share of renewable electricity. Pefenninger et al. [35] compared different scenarios that consist of costs, emissions, and energy security of renewable, fossil fuels, and nuclear with and without carbon capture and storage technologies. They concluded that for more than 80% renewable generation share under technically feasible scenario, large-scale storage or more share of domestic dispatchable renewable energy must be developed.

Giving the huge RES potential in North Africa, several studies are conducted for suitable energy systems. Zhao et al. [36] developed an optimal planning model for minimizing construction costs and power curtailment rate. The LCOE is used as an index for assessing economic feasibility. Different combinations of RES (wind, PV, and CSP) for Morocco, Egypt, and Tunisia energy systems are evaluated and transnational interconnection modes are introduced to realize mutual benefits of RES. Bouabid et al. [37] investigated a transition pathway to achieve 52% of installed capacity of renewable energy in Morocco by 2030. The authors show that important share of wind energy is suitable a solution to achieve this objective. Long-term optimization approach of the Tunisian power system is presented in Ref. [38]. Ref [39] presented a comprehensive assessment of potential and developing various RES, including solar energy, wind (onshore & offshore), biomass, wave and geothermal energy, in Libya.

Since the first edition of renewable energy development program in 2011, few papers addressed energy transition in Algeria [40–44]. Messaoudi et al. [45] proposed a geographical information systems based on multi-criteria decision to evaluate the suitability of sites for hydrogen production from solar energy. Bouraiou et al. [46] reviewed the studies carried out on potential and utilization of renewable energy in Algeria. Bouchouicha et al. [47] developed a new predictive model to estimate the global solar irradiations in the South of Algeria. Their model is based on measured ground data of air temperature and sunshine hours, as well as the day/month data. The standard K-fold cross-validation method is [2]used to verify their proposed model. In Ref. [48], a methodology for managing the potential of renewable and non-renewable energy in Algeria is presented.

1.2. Purpose and structure of the paper

However, to date there is no study quantify integration of RES share in the future AEPS. In this context, both economic and environment aspects, for reliable AEPS at different time horizons need to be studied.

Moreover, all of the previous studies on energy transition cited in section literature review are based on the extrapolation of only one year of renewable energy power output data for all the time horizons. Moreover, none of them considered the impact of climate change i.e. greenhouse gas emissions. In addition, RES potential maps for future energy system planning have not been considered in these studies, although they significantly influence the energy efficiency and renewable energy integration. Hence, according to the Atlas and development program of renewable energies [1], more sites to estimate the future RES power outputs should be added. This approach can notably improve the renewable mix capacity and foster renewable energy integration in AEPS.

The aim of this paper is to develop a long-term vision, till 2050, of Algeria's electricity mix, and to explore strategic pathways for energy transition, not only serves as the overarching framework for policy making, but also guides the development of future action for advancing the transition process towards low carbon electricity generation. More thoroughly, the present study assesses the long-term planning (2025–2050) of AEPS. To have a more holistic view, a straightforward economic analysis of the annual production cost, using SCM is carried out. Economic and environment analysis of future generation electricity expansion plans, including the possible role of nuclear power are presented. Then, preliminary examination of total annual cost (TAC), annual investment cost (AIC), RES share, and environment benefit of the RES of the horizons 2025 and 2030 according to the Algeria's energy development plan [3] are presented. By using Multi-Objective Cuckoo Search Algorithm (MOCSA), an optimized new energy expansion is carried out over a long-term planning horizon, from 2035 to 2050. In addition; a first systemic study on the LCOE of renewable energy technology in Algeria is presented in this paper.

The TAC depends on the overnight cost, fixed and variable costs, operation and maintenance (O&M) costs, fuel cost, and operating time duration of each generation technology. Therefore, MOCSA is used to find the best mix of power plants taking into account the optimization of investments costs. This is achieved by minimizing the TAC and maximizing the renewable energy power share (REPS).

The paper is organized as follows: Section 2 presents the wind and solar potential in Algeria. Section 3 analyses the Algerian power systems and renewable energy deployment. Section 4 describes the mathematical formulation of the optimal planning of the integrated energy supply system. Section 5 is about the simulation results of the case studies. Concluding remarks are presenting in Section 6.

2. Wind and solar energy potential in Algeria

Wind and solar energy are one of the most promising energy alternatives [40–49]. Large-scale integration of W&S energy into existing energy system is expected to significantly increase the importance of meteorological and weather data, due to their strong impact on the planning of energy system with RES integration.

Knowledge of W&S energy potential for a region is essential before installing and sizing any renewable power technology (RPT). Type and size of RPT depend strongly on the availability of network connection points, population density, topography, land and water availability, and protected areas [50–59].

In this context, and in order to stimulate further investment of specific technologies, this section provides maps for W&S energy. The Algeria's maps illustrated in Fig. 1 and Fig. 2 show the available global horizontal irradiation (GHI) and the distribution of the mean wind speed at 80 m a.g.l, respectively [1,4].

As shown in Fig. 1, solar energy has a great potential in Algeria. In less sunny locations, approximately 5.75 kWh/m^2/day can be generated. The southernmost region of the East is the sunniest region, with large areas of GHI values above 7 kWh/m^2 per day.

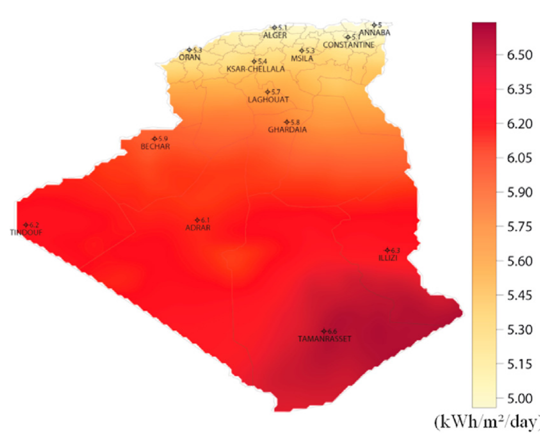

Fig. 1. Algeria's global horizontal irradiation map [1].

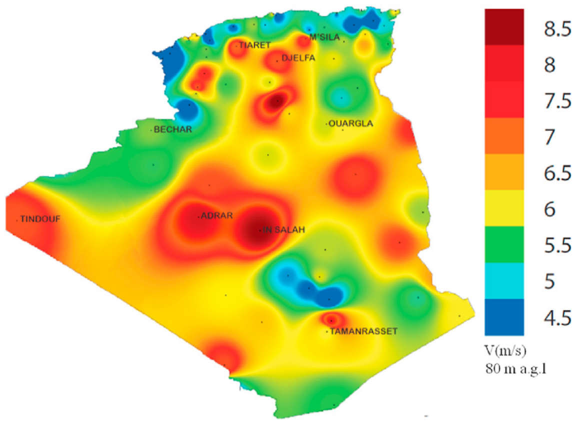

Fig. 2. Distribution of the mean wind speed at 80 m a.g.l [1].

Regions in the South of Algeria also endow significant wind energy potential. Based on the distribution of the mean wind speed map illustrated in Fig. 2, the regional potential is mapped. There are few regions in the north suitable for wind development with average wind speed of 4.5 m/s. The greatest wind potential in Algeria is located in the southwest, where the average wind speed is above 8.5 m/s.

3. Algerian power system and renewable energy deployment

The current AEPS is based on large conventional fossil fuel power plants. Currently, most installed capacity comes from 97.7% of fossil power plants. The total installed capacity reached 20.96 GW in 2018 of which 20.48 GW from conventional power plants mainly natural gas and 0.35 GW from renewable energy, mainly PV [59].

Fig. 3 illustrates the hourly ELD for specific days from 2000 to 2020. As illustrated, the peak demand moved from 7 p.m. to 2 p.m. during the summer season. Due to the nationwide heat wave, a peak of 15.6 GW was recorded on August 7, 2019, at 2 p.m., an increase of nearly 12.6% compared to the same period of the previous year. The improvement in the service quality and the strong growth of household's electricity consumption, especially for air-conditioning, explain recorded this peak in summer between 12 and 3 p.m. This is an opportunity for a large deployment of solar energy.

Fig. 4 shows that low ELD in 2019 was between 10 p.m. and 07am. During these hours, solar energy is not available unless CSP with storage is deployed on a large scale. The hours of high ELD are between 1 p.m. and 2:30 p.m., which coincides with the best time for solar resources availability. In 2020, the maximal ELD recorded

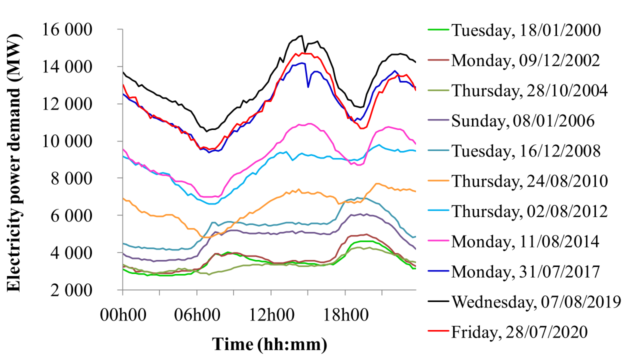

Fig. 3. The 2000–2020 daily load demand profile.

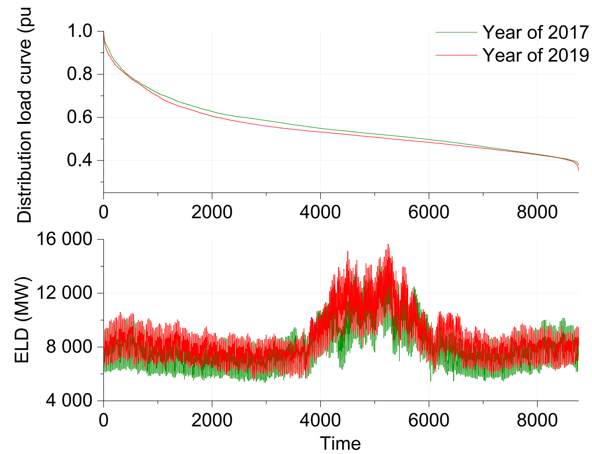

Fig. 4. Algeria's ELD in 2017 and 2019.

on July 28 and reached 14.714 GW, a decrease of 6% compared to that of 2019, due to the exceptional situation linked to the impact of the Covid-19 pandemic.

Indeed, during the low ELD, the equipment and installations are more subject to technical failures. With large-scale RES, particularly solar PV, the hours of occurrence of the maximum and the minimum ELD are very important for planning and operating a power system [49,60,61].

To cope with the growing demand and to preserve fossil fuels, the Ministry of Energy and Mines has set ambitious goals for renewable electricity. It is planned to deploy 22 GW from RES by 2030.i.e.nearly 27% share of the total electricity generation and 37% of the installed capacity [62,63].

With awareness of climate change issues and the growing demand, it is necessary to develop an energy transition model aimed at the optimization of renewable energy sources (RES). According to the Algeria's renewable energy plan published in 2015 [62], renewable energy will have a major contribution in achieving low carbon electricity system. In addition, based on Intended Nationally Determined Contribution (INDC) [64], Algeria will reduce its greenhouse gases emissions by 7%–22%, by 2030, compared to a business as usual scenario, conditional on external support in terms of finance, technology development and transfer, and capacity building. The 7% GHG reduction will be achieved with national means [65–68].

3.1. Methodology

In order to develop a feasible strategy of 75% of renewable electricity share by 2050, the fossil fuels power plants and the renewable energy technology parameters data are presented. The RES data are obtained from METEONORM tool, and power outputs of each technology were estimated based on mathematical models using System Advisor Model (SAM) tool [69].

The capacity factor of W&S energy strongly depends on short term weather variations (minutes, hours, days, and seasons), and even long-period (over years and decades) climate variations [2,41]. Therefore, the W&S data under different future scenarios (2025, 2030, 2040, and 2050) are estimated considering global climate models. The most integrated global climate models presented in the IPCC's Fifth Assessment Report are the Representative Concentration Pathways (RCPs) [70,71]. RCP assesses four scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) of climate predictions and projections pathway extending up to the horizon of 2100. The RCP models principally include time series of emissions and concentrations of the greenhouse gases. RCP2.6 consider lowest temperature projections and low emissions reduction. Mid- and high-rates of climate change are adopted in the RCP4.5 and RCP6.0 scenarios respectively. Risks on climate change can be significantly reduced under the RCP8.5 scenario that considers a highest temperature projections and high emissions reduction. Under the RCP2.6 scenario, the radiative forcing peaks at approximately 3 W/m^2 before 2100, while for RCP4.5 and RCP6.0, it stabilised at 4.5 W/m^2 and 6.0 W/m^2 after 2100 and reaches 8.5 W/m^2 by 2100 for RCP8.5 [70,71].

Following the evolution of Algerian's population growth and economic parameters, the RCP2.6 scenario is adopted for the horizon 2030. The RCP4.5 is set for the horizon 2040–2050.

The accuracy of EnergyPLAN tool in designing energy transition pathway is verified considering the current Algeria's renewable energy plan development [3] and to estimate REPS; CO_2 emission, and TACs for 2025 and 2030.

In order to address the daily and monthly fluctuations and manage suitably the reserve margin, a gradual increase rate in the REPS until a 75% limit by 2050 is adopted. The scenario considering 40% of renewable electricity share for the horizons 2035, 2040, and 2045 are presented and discussed.

3.1.1. Electricity load demand (ELD) assessment

ELD is a key determinant in designing the electricity strategy. Expected electricity imports and/or exports, future investments for power generation and the power system infrastructure are conceptualized from the ELD's assessment.

The ELD level all year round is evaluated from the annual load demand curve, which shows all individual load hours in a subsequent order. Fig. 4 shows the hourly Algeria's ELD of the years 2017 and 2019 as well as their distribution. This data is essential to analyse the relation between generating capacity and ELD.

It can already be seen from Fig. 4 that the hours on the left side are those supplied at low production cost from base load plants such as NGCC, which are characterised, by high capacity factors and cost-effectiveness in this situation. The hours on the right side (Fig. 4) are the ones supplied with high production cost by peak load power plants such as NGT, which are efficient options when their use is limited to meeting the peak demand.

As the Fig. 4 shows, through increasing ELD, the base load plants capacity must be reduced while the peak load plant capacity is increased. The problem is to evaluate the decreasing and increasing capacity by the calculation of secondary and tertiary reserve.

Renewable energy share in a power system depends strongly on the level of ELD, in other words the studied scenario. Therefore, according to economic evolution and population growth of Algeria, and considering that the energy efficiency is under study and will take long time to affect ELD, the present study assumed the strong scenario of ELD for 2025 and 2030, while the medium scenario of ELD evolution is adopted for the horizon 2035 to 2050. Using the ELD data recorded from 1990 to 2019, the electricity consumption was extrapolated until the year 2050 by fitting a linear curve on the existing data considering medium electricity consumption growth assumption. Considering historic ELD rate since 2015, a 9.6% increase is considered for the period of 2020–2025. From 2026 to 2040, the evolution rate of 3% is set, and 2% is considered from 2041 to 2050.

By introducing in EnegyPLAN the load demand curve of the year 2019 and the predicted energy consumption, the ELD is given in the output of the EnegyPLAN. Table 1 gives the expected electricity generation and ELD adopted in our study. Final electricity generation is expected to increase by nearly 43% between 2025 and 2050.

3.1.2. Power generation assumptions

The energy model encompasses eight types of power generation technologies: NGT, NCCG, Nuclear (Nucl), biomass (Bio), onshore wind, CSP, geothermal (Geo), and PV. These technologies represent the most credible mix for a low carbon electricity system in Algeria.

After analysing different economic parameters of each technology considered in different countries similar to Algeria's economic and potential situation, we have adopted for our study the parameters of all potential technologies given in Table 2 [27,72–75].

CO_2 emission factors for different fuels used in EnergyPLAN tool are taken from the Refs. [76–78] and given in Table3.

The situation of development of renewable energies in Algeria shows a big delay in implementing renewable energy program and this situation considerably obstructs the long term vision of achieving 75% of renewable share by 2050. Therefore, renewable integration targets are assumed to grow progressively from 15% by 2025, 30% by 2030, 40% by 2035, and 40–50% by 2050. Accordingly, the planning reserve margin increases gradually to ensure the system reliability. Table 4 gives the renewable energy, cogeneration and nuclear growth scenario.

3.2. Screening curve method

SCM as a simple representation combines generation costs and load demand curve (LDC). The SCM approximates the best technology mix that corresponds to the intersection points of the LDC and the cost curves. The intersection points determine the most cost-effective operating regimes and capacities for each technology [4,5,79].

A cost curve depicts for each candidate unit the Annual Production Cost (APC), defined by the following equation [80]:

$$\mathrm{APC}\ (\mathrm{US\$}/kW-year) = \mathrm{r_i^T} \times \mathrm{I} + \frac{(\mathrm{i} \times \mathrm{FIC})}{100} + 12 \times \left(\mathrm{O\&}M_{\mathrm{fixed}}\right) + 8.76 \times \left[(\mathrm{FC})_{\mathrm{CF}} + (\mathrm{O\&}M_{\mathrm{variable}})\right] \times \frac{\mathrm{f}}{100} \tag{1}$$

$$\mathrm{r_i^T} = \frac{\mathrm{i} \times (1+\mathrm{i})^{\mathrm{T}}}{(1+\mathrm{i}) - 1} \tag{2}$$

where:

I is the investment cost.
FC is the fuel cost.
O&M is the operation and maintenance cost.
T is plant expectancy life
i is annual interest rate.
CF is the average annual capacity factor of the plant (%)
$\mathrm{r_i^T}$ is the annual capital recovery factor.

As a simplified decision model, the LCOE is often used to directly perform different power generating technologies roles. LCOE combines the FC and variable cost (VC) into a single value [79].

$$LCOE = \frac{sum\ of\ costs\ over\ lifetime}{sum\ of\ energy\ generated\ over\ lifetime} \tag{3}$$

$$LCOE = \frac{\sum (I + O\&M + VC)\frac{1}{(1+i)^T}}{\sum E \times \frac{1}{(1+i)^T}} \tag{4}$$

E is the amount of energy generated, expressed in MWh.

3.3. Energy transition optimization using EnergyPlan-MOCSA

Since cuckoo search algorithm (CSA) was introduced [81], it has

Table 1
Algeria's electricity generation and ELD.

	Year					
	2025	2030	2035	2040	2045	2050
Total electricity generation (TWh)	123	165	154	179	197	217
ELD (GW)	25.548	34.272	31.987	37.18	40.919	45.073

Table 2
Economic parameters of the eight technology options [27,72–75].

Horizon 2025									
Parameter	Unity	Technology							
		GT100	GT200	NGCC	GEO	BIO	CSP	WP	PV
Rated power	MW	100	200	400	20	15	50	50	20
Lifetime	Years	25	25	25	25	25	25	25	25
Investment cost	US$ kW	916	916	1214	3611	3968	5390	1982	1349
Combustible price	US$/Gcal	3408	3408	3408	0.00	907	0	0	0
Fixed O&M costs	US$/kW-year	17.0	11.6	10.5	71.6	105.3	66.0	45.0	17
Variables O&M costs	US$/MWh	5.0	3.5	3.0	0.95	8.8	5.7	2.5	0
CF	%	25	60	85.0	80	56	50.0	20.0	27
Horizon 2030–2040									
Parameter	Unity	**Technology**							
		GT100	GT200	NGCC	GEO	BIO	CSP	WP	PV
Rated power	MW	100	200	400	20	15	50	50	20
Lifetime	Years	25	30	30	25	25	35	25	30
Investment cost	US$/kW	814	621	957	3611	3779	4681	1844	832
Combustible price	US$/Gcal	3408	3408	3408	0	907	0	0	0
Fixed O&M costs	US$/kW-year	17.5	16.4	11.6	71.6	105.3	51.0	39	25.5
Variables O&M costs	US$/MWh	4.2	3.7	2.8	0.95	8.8	0	2.3	0
CF	%	30	60	83.2	80	56	52.0	22.8	27
Horizon 2045–2050									
Parameter	Unity	**Technology**							
		Nucl	GT200	NGCC	GEO	BIO	CSP	WP	PV
Rated power	MW	1500	200	400	20	15	50	50	20
Lifetime	Years	40	35	30	25	25	35	25	30
Investment cost	US$/kW	5471	800	1214	3611	3779	3537	1800	683
Combustible price	US$/Gcal	251	3408	3408	0	907	0	0	0
Fixed O&M costs	US$/kW-year	101.0	11.6	10.5	71.6	105.3	51.0	33	8
Variables O&M costs	US$/MWh	2.0	3.5	2.8	0.95	8.8	0	2.1	0
CF	%	92	60	80.0	80	56	52.0	27.0	27

Table 3
CO_2 emission factors.

Fuel	Natural Gas	Biomass
Emission factor (kg/GJ)	56.7	32.5

Table 4
Deployment of renewable energy, cogeneration and nuclear scenarios.

Technology	Year								
	2025	2030	2035	2040	2045	2050			
	Installed capacity (MW) [65]		REPS target (%)						
CSP	1530	2000	40	40	40	50	60	70	75
Onshore WP	430	5010							
PV	1300	13575							
Cogeneration	150	400							
Geothermal	15	15							
Biomass	360	1000							
Nuclear	–	–	–	–	–	3 × 1500 MW			
Total	3785	22000	To be achieved by MOSCA						

A simplified approach to rapid economic analysis of the competitiveness of different technologies is examined based on the SCM. This approach separates the costs associated with a technology into "fixed" and "variable" costs and then calculate for each technology the total LCOE defined as US $/kW-year and US $/MWh.

attracted a great deal of attention in science and engineering applications. The first CSA proposed for solving single objective optimization problems was extended later to solve MOPs [82]. The efficiency to guarantee convergence to the global optimal solution and to explore large search areas makes MOCSA a powerful approach for solving energy strategy MOP. Rules and more details of CSA and MOCSA can be found in [61,81–83].

In order to optimize energy transition strategy of Algeria's electricity system, the multi-objective function is solved considering two different objective functions. The first one represents the total annual cost (TACs) given by Eq. (5) and the second one is the power electricity production (PEP) share from RES given by Eq. (6).

$$TACs = \sum\left(\sum_{i=1}^{k}(\text{Variable cost}_i + \text{Fixed operation cost}_i + \text{Annual investment cost}_i)\right) \tag{5}$$

$$PEP = \frac{RES\ electricity\ production}{Electricity\ demand} \tag{6}$$

where k is the number of technology.

The multi-objective function is defined by Eq. (7).

$$\text{multi objective function} = \min\begin{bmatrix} TACs \\ |\mathrm{RES}_{\mathrm{target}} - PEP| \end{bmatrix} \tag{7}$$

where $\mathrm{RES}_{\mathrm{target}}$ is PEP that must be achieved.

Subjected to:

$$P_{PV}^{min} \le P_{PV} \le P_{PV}^{max} \tag{8}$$

$$P_{WP}^{min} \le P_{WP} \le P_{PW}^{max} \tag{9}$$

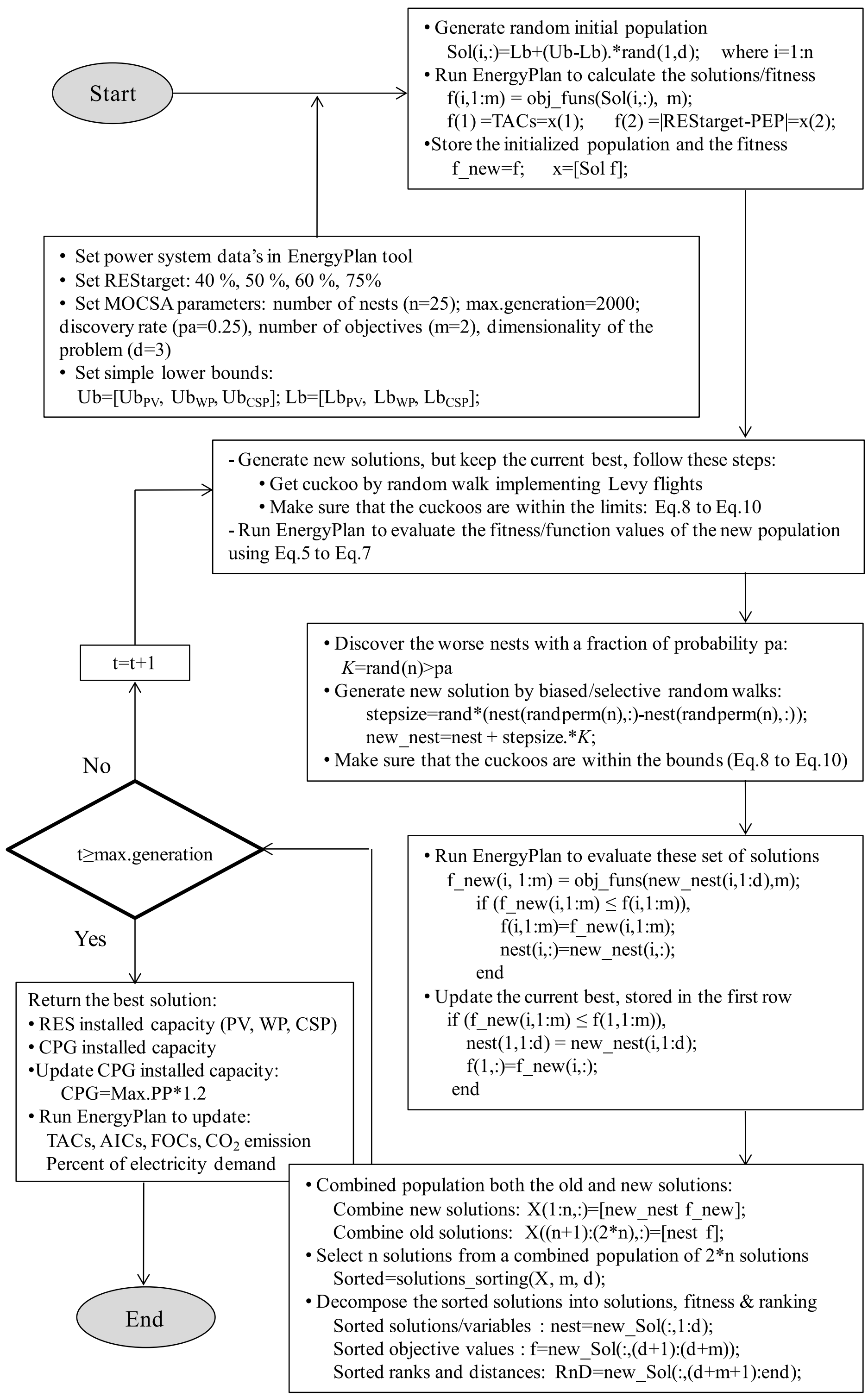

Fig. 5. Flow chart for Energy transition using EnergyPlan-MOCSA.

$$P_{CSP}^{min} \le P_{CSP} \le P_{CSP}^{max} \quad (10)$$

Detailed flowchart of the proposed approaches for solving energy transition problem by coupling EnergyPlan to MOCSA is presented in Fig. 5. The flowchart includes the rules and equations with its implementation in Matlab software.

4. Results and discussions

4.1. Analysis of the energy generation cost

In order to support both ELD growth and increasing integration of RES during the planned timeframe, we first analyse the Energy Generation Cost (EGC) obtained from the SCM. Fig. 6 to Fig. 8 illustrate the EGC estimated at different capacity factors (CFs) for the years 2025, 2030, and 2050.

Fig. 6 shows that for a CF of 10%, there is a sharp difference between the generation cost of wind power and PV technologies. However, with a CF of 25%, there is still a gap between the two technologies although less important with 108 US$/MWh for wind and 65 US$/MWh for PV. At a CF of 30%, the generation cost of CSP reaches 223 US$/MWh. Furthermore, for a CF of 40%, CSP technology has the highest generation cost. CSP power plant is only competitive with biomass power plant at a CF of 45%.

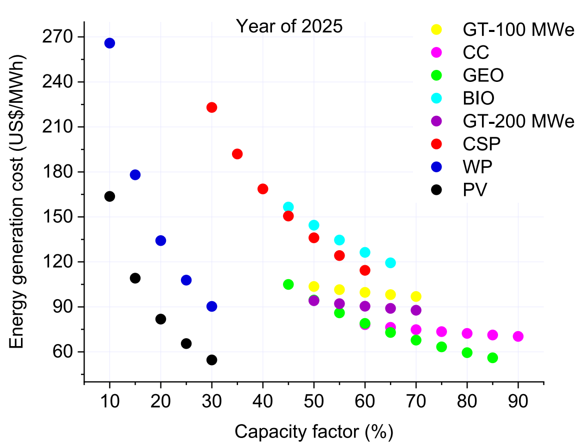

Fig. 6. EGC for different technologies using the 2025 SCM.

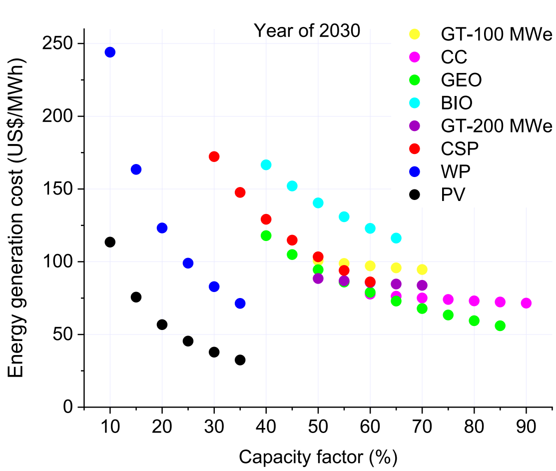

Fig. 7. EGC for different technologies, using the 2030 SCM.

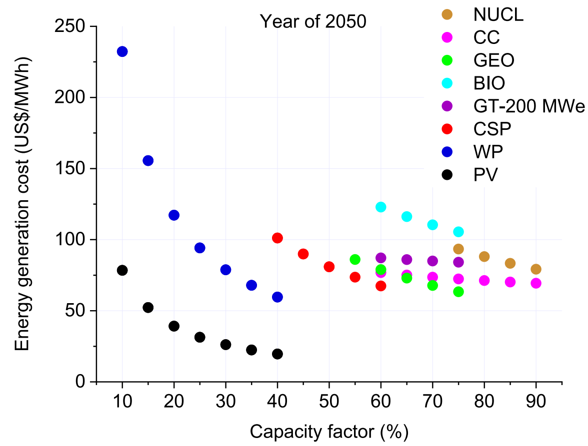

Fig. 8. EGC for different technologies, using the 2050SCM.

Below a 65% CF, the generation cost of CSP and biomass technologies are higher than of the CPGs as well as the geothermal technology. This explains why currently, Algeria has not planned the deployment of large CSP and biomass for the horizon 2025 (see the Table 3). For geothermal technology, despite its low generation, the development plant for the horizon 2025is limited to 15 MW installed capacity due to the lack of potential resource suitable for electricity generation and expertise in this technology.

A comparison between conventional power plants (CC, GT-100 MW, and 200 MW) and renewable shows that PV power plant is cost effective even with capacity factors below 20%.

As far as 2030 is concerned (Fig. 7), PV technology is the most cost-effective option for capacity factors above 20%. Even for a 15% capacity factor, PV remains the best energy option with a generation cost of 76 US$/MWh against all other main fossil and renewable options such as CSP and wind energy.

Compared to 2025, the CSP generation cost shows a significant decrease and is close to that of the geothermal technology for a 45% capacity factor.

The generation cost at the 2050 horizon is illustrated in Fig. 8.

As expected, meeting the highest ELD of 45.073 GW requires high expansion in the base load generating capacity. Fig. 8 shows that generation costs of the biomass, geothermal, NGT and NGCC technologies remain at a level close to that of estimated in 2030, while the generation cost of CSP, solar PV and wind power slightly decreases.

Solar PV remains the most effective option in 2050 for all capacity factors. For capacity factors above 30% wind energy is a cheapest option compared with conventional technologies and CSP. It is therefore expected that by 2050 solar PV and to a lesser extent wind energy will be predominant in Algeria's electricity mix.

In 2050, we have assumed the deployment of 1500 MW nuclear power plant (NUCL) as a component of the electricity mix. However, cost generation of nuclear power plants is higher than natural gas power plants such as NGCC. For instance for an 85% capacity factor, the generation costs of NUCL and NGCC are respectively 83 US$/MWh and 70 US$/MWh.

The results of the LCOE for all the technology options are presented in Fig. 9 and Fig. 10. The results are based on the assumptions on capacity factors (Table 2) and the timeframe (2025–2050). For all the time horizons i.e. 2025, 2030, and 2050, the lowest LCOE is obtained from the PV with under 60 US$/MWh in 2025. As a comparison, the LCOE's wind power is 140 US$/MWh in 2025 decreasing to 87 US$/MWh in 2050. Compared with CSP, wind option is attractive only in 2025. However, PV and wind energy

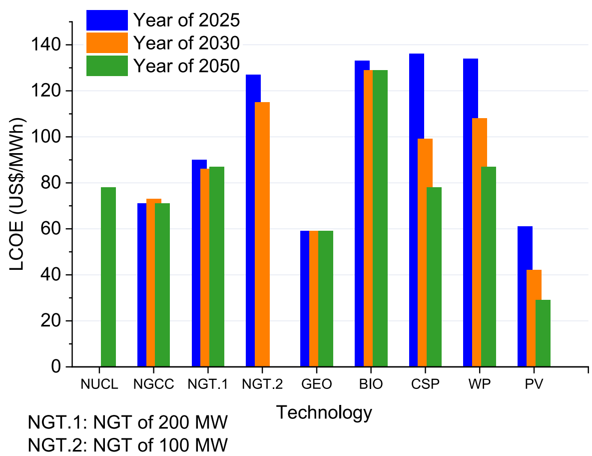

Fig. 9. LCOE comparison between different power plants as US$/MWh.

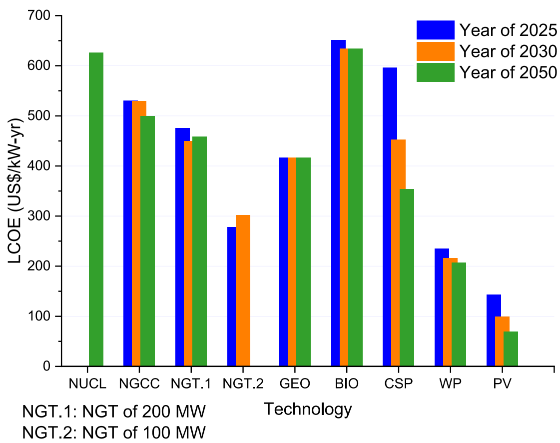

Fig. 10. LCOE comparison between different power plants as US$/MW-year.

Table 5
Economic order expressed as US$/MWh and US$/kW-year.

Technology	Economic order given in US$/MWh			Economic order given in US$/kW-year		
	2025	2030	2050	2025	2030	2050
NUCL			4			7
NGCC	3	3	3	7	6	6
NGT200 MW	4	4	5	5	5	5
NGT100 MW	5	7	6	3	3	
GEO	1	2	2	4	4	4
BIO	6	8	7	8	7	8
CSP	8	5	4	6	5	3
WP	7	6	5	2	2	2
PV	2	1	1	1	1	1

must not be considered as competing options but rather complementary options as very often their availability does not occur at the same time.

With regard to conventional power plants, the NGCC technology is the most cost effective option for all the time horizons. NGCC is cheaper than nuclear power and even cheaper than CSP for all the time horizons, while the LCOE of geothermal technology remains constant and relatively low.

When we consider a US$/kW-year analysis, the general trend is confirmed with however some minor differences. PV technology is the cheapest option, for the whole 2025–2050 period, compared with all other technologies, renewable, fossil, and nuclear. In 2050, the LCOE of CSP and nuclear technologies are relatively close. However, NGCC remains more cost-effective than nuclear.

Based on the results derived from Figs. 9 and 10, the economic order of all technologies is presented (Table 5) to support the decision making process for low carbon energy transition in Algeria.

Results presented in Table 5 of the economic order expressed in US $/MWh, show that from 2030, the cost of production of PV is the cheapest technology followed by geothermal energy. CSP and wind technologies are ranked last in 2025, but in 2050, take the 5th place with nuclear technology. Among fossil fuel technologies, the cost of production of NGCC is the cheapest and is the third best technology when considering renewable and non-renewable options.

Geothermal is well ranked in terms of generation cost per MWh. Nevertheless, the large deployment of this technology will be constrained by its limited potential in Algeria.

When the results are expressed in US$/kW-year, PV and wind energies are the best options from 2030 onwards. CSP is the third best option only in 2050. Nuclear and conventional power plants are among the least preferred options.

4.2. Energy transition pathways

Based on LCOE economic order and availability RES in Algeria, this section presents the energy transition strategy to achieve 75% REPS by 2050. In addition to LCOE, in the optimization process, the power limits (P_{min} and P_{max}) of each technology are important parameters to optimize the energy transition.

Based on LCOE, PV technology is the best option and large deployment of PV must be considered. From 2030 onwards CSP becomes the second best option and its deployment on large should be considered.

One purpose of analyzing the Algeria's development plan was to verify the accuracy of EnergyPLAN model in designing Algeria's energy transition. In Table 6, the first phase of the energy transition for 2025 and 2030 horizons are presented. In addition, this table synthesises the energy transition based on the optimization of the electricity mix to reach 75% of renewable energy production share (REPS) by 2050.

The installed capacity for each technology is presented in Table 7.

As mentioned, the key assumption is derived from the 2015 Algeria's renewable energy program, which is aimed at achieving 27% renewable energy share of the total electricity generation and 37% in terms of the total installed capacity by 2030. By using EnergyPlan tool, hourly analysis of the horizon of 2030 shows similar level of renewable energy share. It confirmed that installing 22 GW of renewable will contribute to cover 26.8% of the total energy generation in 2030.

By 2025, 14.4 TWh will be generated from RES equivalent to 11.7% of the total electricity mix. In 2030, this proportion will reach 36.1%, equivalent to 59.5 TWh. To meet ELD in 2030, the installed capacity of conventional power plant should be extended to 29.4 GW, an increase of 17% compared with 2025.

The optimal energy mix presented in Table 7, shows that meeting 40% of the demand from RES in 2035 needs adding more renewable electricity capacity. The additional installed capacity

Table 6
Energy transition pathway results.

Year	ELD	Percent of electricity demand	REPS	Energy from RES	TAC	AICs	FOCs*	CO_2 emission	CO_2 emission/ELD
	TWh/y	%	%	TWh	M$	M$	M$	Mton	Mton/TWh
2025	123	6.9	11.7	14.4	3699	1581	1271	48.43	0.39
2030	165	26.8	36.1	59.5	4960	2195	2083	39.01	0.24
2035	154	26.4	40.0	61.6	4496	1969	1804	41.31	0.27
2040	179	26.2	40.0	71.5	5172	2246	2084	48.11	0.27
2045	197	26.0	40.0	78.7	5440	2632	1883	52.91	0.27
2050	217	38.7	50.0	108.4	7159	3900	2562	39.82	0.18
2050	217	48.6	60.0	130.1	10223	5909	3756	31.9	0.15
2050	217	60.2	70.0	151.8	16333	9777	6143	23.68	0.11
2050	217	66.4	75.0	162.6	22105	13427	8333	19.72	0.09

*FOCs is fixed operating costs.

Table 7
Installed capacity of renewable energy technology (RET) and conventional power plants.

Installed capacity (MW)	Reference scenario		Optimized scenario						
	2025	2030	2035	2040	2045	2050			
						50% of RES	60% of RES	70% of RES	75% of RES
WP	430	5010	5040	5250	5510	9990	26000	61300	94000
PV	1300	13575	14320	17800	19210	42200	43000	78000	118000
CSP	1530	2000	2100	2140	2920	5600	15500	20000	24000
Geo	5	15	100	150	150	200	200	300	300
Waste power	360	1000	1000	1000	1000	1000	1000	1000	1000
Cogeneration	150	400	400	400	400	500	500	600	600
Total installed RET	3775	22000	22960	26740	29190	59490	86200	161200	237900
Conventional power plant	24400	29400	28290	32920	36390	39950	39100	37420	37450
Total	28175	51400	28290	59660	65580	99440	125300	198620	276760

should reach 960 MW of which 30 MW of wind, 745 MW PV, 100 MW of CSP, and 85 MW geothermal power plants.

The principal aspect of the second phase of the energy transition is moving gradually from conventional power plants to more renewable energy technology. This transition requires more investment costs. Under 50% of REPS, the installed capacity of renewable energies and the conventional power plants reaches 59.49 GW and 39.95 GW by 2050 respectively, that needs 3,9 M$ as AICs. An extra AIC of 13,4 M$ is required to satisfy 75% of REPS.

In the 50% renewable energy share scenario, the total electricity capacity mix will reach 99.44 GW by 2050 split between 59.49 GW of renewable, and 39.95 GW of conventional power plants. Over 108 TWh will be generated from renewable energy sources.

The CO_2 emissions fall from 52.91 Mton in 2045 to only around 39.82 Mton in 2050 and just 19.7 Mton under the 75% REPS scenario. CO_2 emissions per TWh will also experience a significant decrease from 0.39 Mton/TWh in 2025 to 0.18 Mton/TWh in 2050 for the 50% REPS scenario and just 0.09 Mton/TWh if 75% REPS scenario is adopted.

In order to accommodate 50% of REPS, the total annual costs (TAC) will rise from 4496 M$ in 2030 to 7159 M$, while the 75% renewable scenario will require 22,105 M$ of TAC.

Fig. 11 gives the minimum and maximum power productions of RES and CPG. The maximum power produced by RES in 2025 may reach 3.64 GW, which represents 96% of the total installed capacity of RES, while in 2030; a maximum of 21.32 GW may be produced. Under the scenario of 50% of RES, a maximum of 45.07 GW may be produced by RESs and 39.94 GW by the CPGs.

Fig. 12 illustrates the annual energy produced by each technology, left in TWh/yr and right in %. They show that from 60% RES share, the total energy produced from PV plants decreases significantly, while the energy produced from the CSP plants increases considerably.

If 75% of RES share is adopted, large amount of energy of 82.4 TWh/yr will be produced from CSP plants, which represents

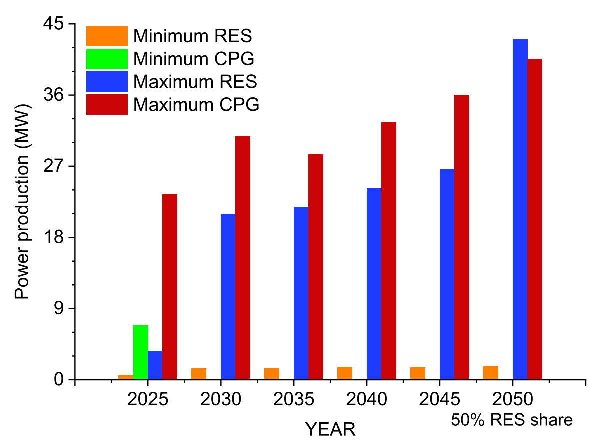

Fig. 11. Minimum and maximum RES and CPG productions.

38% of the total annual energy produced in 2050. As can be seen, despite we develop more wind power and PV generations, their share in 2050 remains below 25%. An important reduction in annual energy production of the CPG can be achieved only if 75% of renewable energy share is adopted. However, despite we develop an additional CPG during the horizon 2025 to 2050, under the scenario of 50% of RES, the annual energy production of the CPG remains at the same level of 104 TWh/yr, this due that to growth of the demand for electricity in 2050.

Fig. 13 illustrates the maximum power production of each technology. We note that these maximum powers are not recorded at the same hour and day.

The yearly power system balance (ELD, CPG and total RES productions) of the years 2025, 2030, 2040, and 2050 are illustrated in Fig. 14. For the horizon 2050, the scenario of 50% of RES is

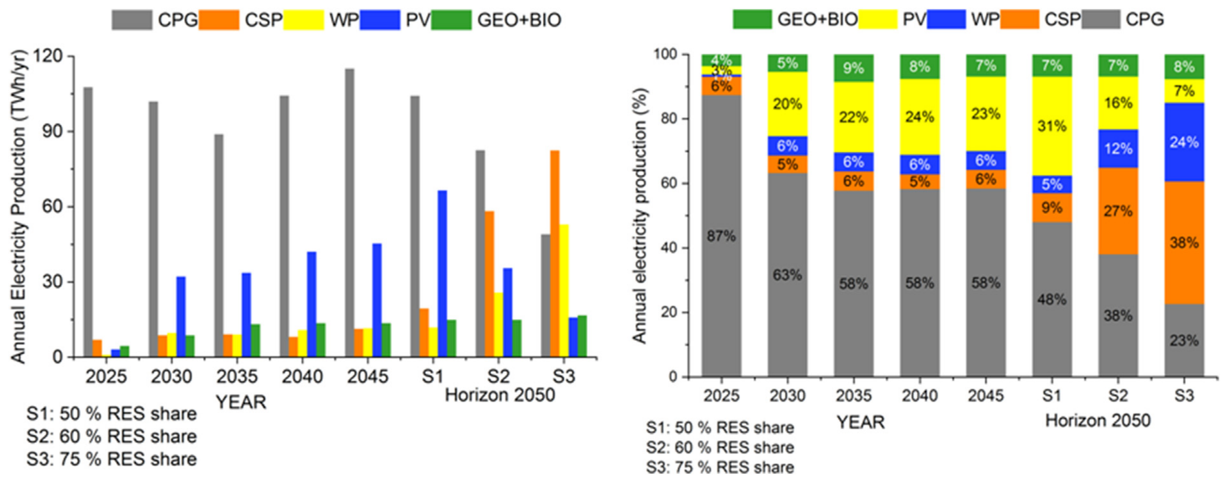

Fig. 12. Annual electricity production, left in TWh/yr and right in %.

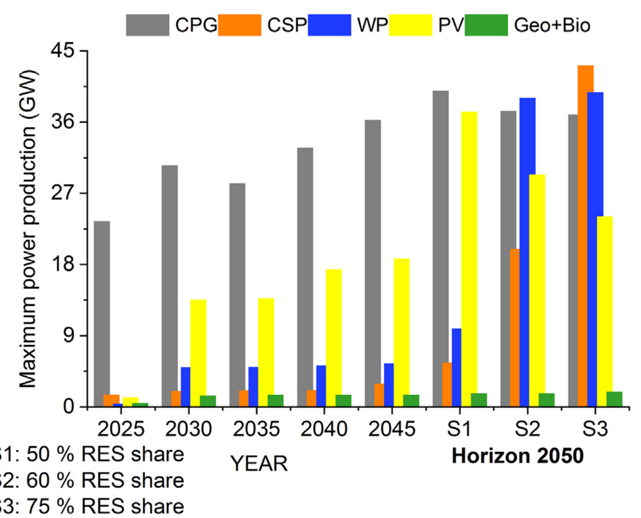

Fig. 13. Maximum power production.

represented. A representation of three successive days from 23rd to 26th March is illustrated in these figures too. As can be seen, with increase the RES capacity, the CPGs may be stopped in several times to balance the demand and the supply where RESs can fulfil the ELD during the day from 11 a.m. to 16 p.m., when the solar resources are available.

4.3. Impact of NPPs on installed capacity of RETs

Deployment of nuclear energy takes a long time from the policy decision to completion. We have therefore considered the introduction of nuclear energy only by 2050. This section assesses the impact of installing 4.5 GW (3 × 1500 MW) of nuclear power plant (NPP) capacity instead of conventional power generations (CPG) by 2050.

Table 8 presents the investment required to install 4.5 GW of NPP.

As the capacity factor of the NPPs, 92% in our case, is higher than that of CPGs, installing 4.5 GW of NPP requires reducing of 4.37 GW of CPGs. Furthermore, the deployment of nuclear plants will lead to a decrease of REPS from 50% to 44.4% and from 75% to 64.4% by 2050. It is therefore necessary to install more RET to achieve the initial goal of 50%, 60% or 75% REPS scenarios, this will also require more investment.

It must be pointed out that replacing 4.37 GW of CPGs by 4.5 GW of NPPs increases the TAC as well as the AIC. In the 50% REPS scenario, the TAC increases from 7159 M$ to 8013 M$ and the AICs from 3,9 M$ to be 4411 M$.

As nuclear is CO_2 emissions free, its deployment will limit the emissions to 31.04 Mton under the 50% REPS scenario. However, there are other environmental risks such as the disposal of nuclear waste and the safety and security of the nuclear power plants.

Fig. 15 presents the results of installed capacity of renewable and conventional power plants further to the deployment of nuclear power plants. The deployment of 4.5 GW of nuclear by 2050 will imply increasing renewable capacity. An impressive result is observed under 60% of REPS, where the installed capacity of PV and wind plants increases significantly to reach 58 GW by 2050.

Fig. 16 gives the TAC and AICs for 50% and 60% REPS scenarios. This figure shows that more investment is required for developing of NPPs and achieving 60% of REPS. Under this scenario, the TAC of 18 M$ and AIC of 10,8 M$ are required.

From the results analysis, we suggest that it would be economically beneficial to develop the nuclear plants under 60% of RES share.

Fig. 17 and Fig. 18 show the monthly electricity productions of CPG and NPPs to meet the ELD considering 50% and 60% of RES share respectively.

It is important to note that if the scenarios of 50% of REPS and supplying 4.1 GW from NPPs are adopted; meeting high demand of 33 GW in July requires reducing CPG production to 11 GW (green line in the Fig. 17). Furthermore, meeting low demand of 20.968 GW during April requires reducing more CPG production to 4.6 GW.

4.4. Discussion

In practice an increase from 40% to 75% renewable energy through short period (for example, five years), requires decommissioning a large number of conventional power plants including power plants with still life expectancy. Such a sharp transition will be very for the electricity system stability and security. Therefore, the presented results are limited to a future capacity of energy production mix by 2050 and not address these technical issues.

Despite we install more RES between the period of 2030–2035, the TAC, AICs and FOCs in 2035 is well minimised, for the reason that the total installed capacity of conventional power generations

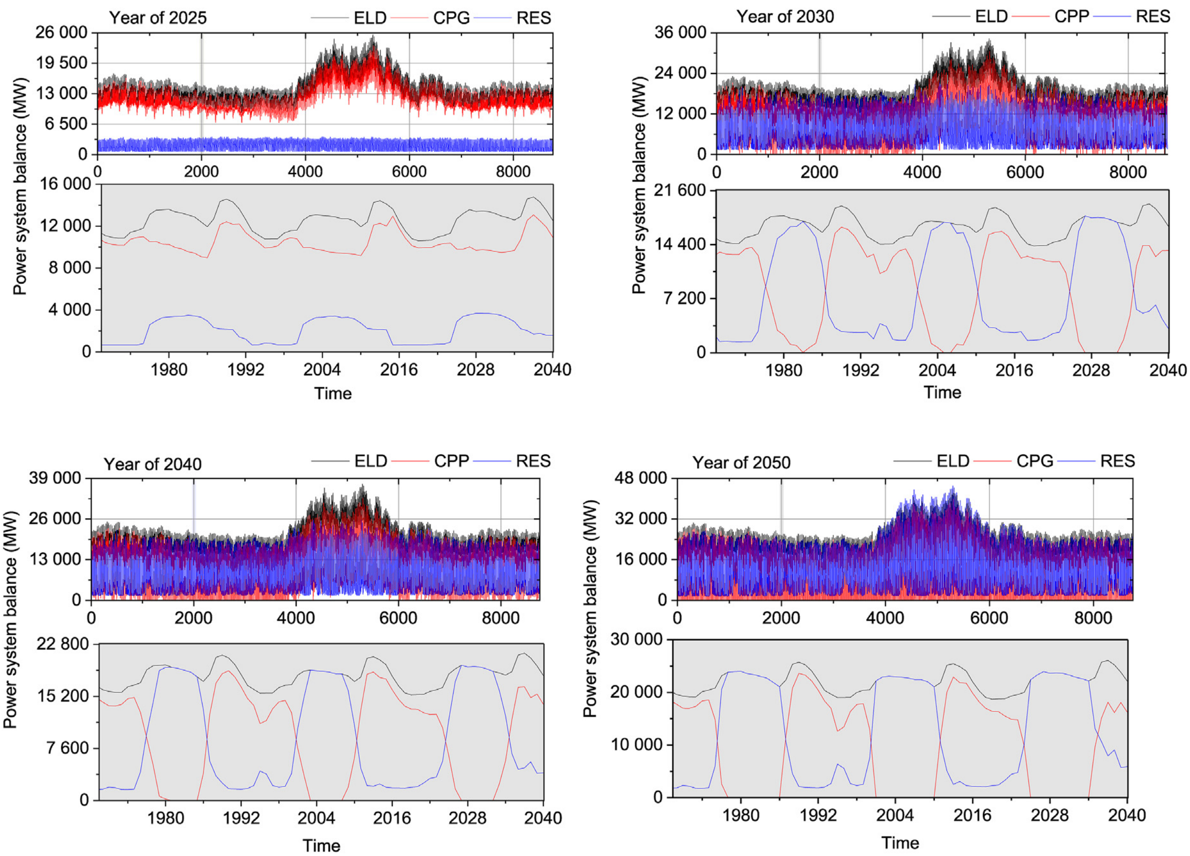

Fig. 14. Yearly power system balance of the years 2025, 2030, 2040, and 2050.

Table 8
Results of NPPs impact.

REPS without NPPs	REPS with NPPs						
	Percent of electricity demand	REPS	Electricity from RES	TACs	AICs	CO_2 emission	CPG
%	%	%	TWh	M$	M$	Mton	GW
50	37.0	44.4	96.3	8013	4411	31.04	35.6
60	45.3	52.4	113.8	10734	6155	24.68	34.5
70	53.2	59.0	128.0	16879	10016	19.20	33.2
75	59.9	64.4	139.7	22632	13660	14.91	32.6

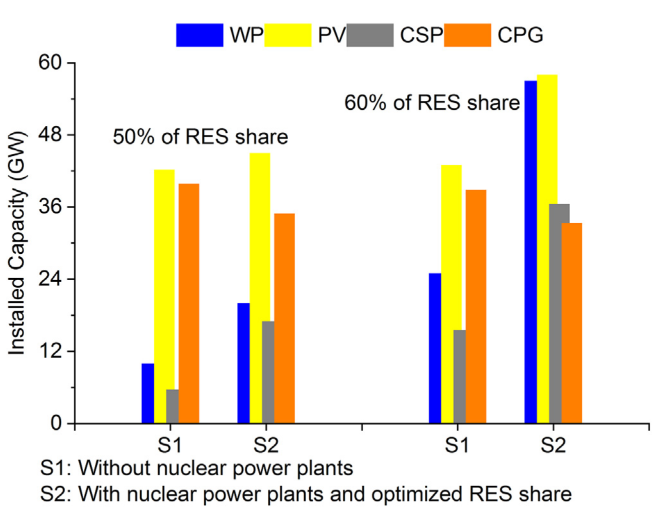

Fig. 15. Installed capacity with and without NPPs according to various shares of RES.

is reduced. This revealed that our proposed MOCSA approach can be well used for energy transition pathway.

Passing from 50% to 75% of REPS, needed installing more renewable energy, whereas a slight reduction in the conventional power plants will be experience.

Renewable energy production will have an important impact on CO_2 emissions. Although during the period 2025–2045, there will be a slight increase of CO_2 emissions due to the increase of the electricity demand and the deployment of conventional power plants; from 2045 onwards CO_2 emissions will decrease even if we consider the 50% renewable scenario.

As can be see, the contribution of the CPGs in hourly balancing demand and supply continue to be important players during all horizons, following by PV plants and CSP.

With high share of variable renewable energies, the stability of a power system can be threatened, and this needs more reinforcement in the existing grid infrastructures as well as on interconnection that link Algeria with Tunisia and Morocco grids.

The North Africa region, mainly Morocco, Tunisia and Algeria countries, prospects development large scale of RES, mainly on

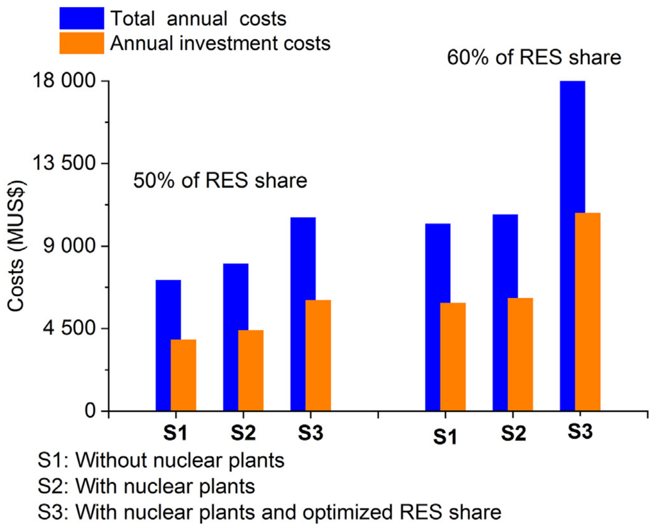

Fig. 16. TAC and AICs: 50% and 60% REPS scenarios.

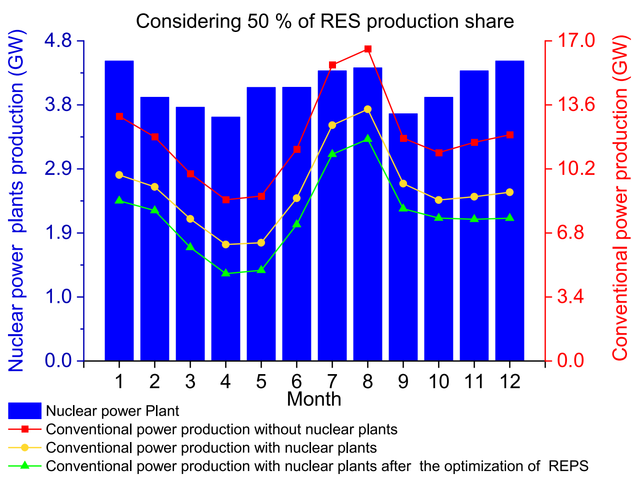

Fig. 17. CPG and NPPs productions considering 50% REPS.

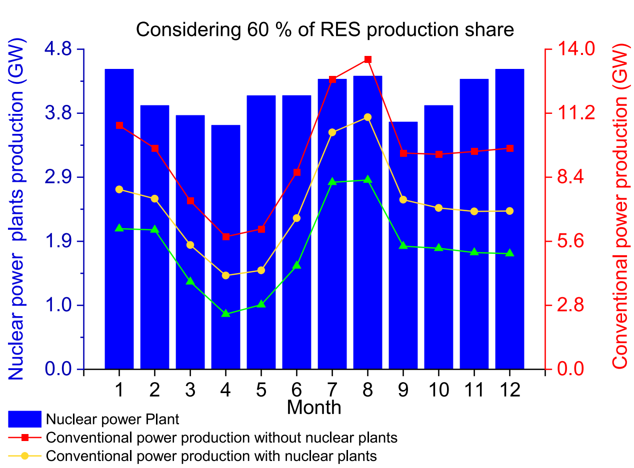

Fig. 18. CPG and NPPs productions considering 60% RES share.

solar and wind power technologies. Morocco sets the target of achieving 52% of electricity installed capacity by 2030, where 30% of electricity generation capacity was set by Tunisia government [36–38].

Currently, the Algeria is linked with Morocco and Tunisia grids and there is no interconnection between Algeria and Europe. The interconnection between Algeria and Morocco consists of two high overhead lines of 400 kV and two of 220 kV. In fact, the transit is limited to 300 MW from Morocco to Algeria and 600 MW from other side and is expected to increase to 1000 MW in the horizon of 2030. Concerning the interconnection between Algeria and Tunisia, there are currently five lines (two 90 kV lines, one 150 kV line, one 225 kV line, and one 400 kV line). However, all 90 kV and 150 kV lines will be decommissioned in 2030 and will be substituted by new 400 kV AC overhead line with 1000 MW of net capacity transfer. In 2030, two new HVDC submarine cables are planned to link Algeria with Italy and Spain grids. Each HVDC interconnection will have a capacity of 1000 MW.

Enhancing interconnection lines between these countries, in net transfer capacity and topology promotes RES integration and guarantees security of supply both at the regional and Europe-Mediterranean level. In fact, better utilization of the interconnection under high share of RES can promote and well regulate the reserves of the conventional power generations that help in reducing unnecessary of conventional reserves.

5. Conclusion

Energy transition towards large share of intermittent RESs in Algeria is facing a huge challenge. The main purpose of this paper is to design the various options offered to the Algeria's energy system to deploy 75% REPS by 2050.

EnergyPlan coupled to MOCSA and LCOE model were key tools to design and analyse all the options. The combination of the RES potential maps (wind and solar) and the LCOE order shows that developing large-scale PV power plant is the best option compared with other renewable and non-renewable options. Wind energy is the second best option to implement the energy transition.

However, PV and wind energies are intermittent sources of energy and are not available all day round particularly during night-time for solar. It is indeed particularly important to maintain power system stability and adequate reserve margins. Fossil fuels power plants will still be required by 2050 to overcome with these constraints.

Due to its low LCOE, NGT200 remains a key technology option until 2030, which will exclude NGT100 from future development plan. NGCC power plants remain dominant for all the horizon time study.

Despite geothermal technology has a low LCOE, their contribution to the electricity supply will be marginal due to lack of potential. Further efforts on R&D on geothermal in Algeria is a prerequisite before considering an increase of geothermal in Algeria's electricity mix. Furthermore, other end uses (heating) of geothermal must be considered.

According to EnergyPlan results, meeting Algeria's renewable energy plan objective of 27% share of renewable production by installing 22 GW of renewable capacity by 2030 will cover more than 36% of ELD (165 TWh) and contribute in reducing CO_2 emissions from 48 million tons in 2025 to 39 million tons in 2030. This will require nearly 2.2 billion dollars of annual investment costs and 4.9 billion dollars of total annual costs.

Achieving a 75% of REPS by 2050 will require 238 GW of total installed renewable capacity. This capacity will allow the generation of 163 TWh. The proposed energy strategy shows that PV will become the main energy source with more than 43% of total installed capacity of the electricity mix. Wind energy installed capacity will reach 34% and CSP 9% in 2050. Remaining capacity of 14% will be met by gas power plants. However, such transition might face economic constraints given the high level of investment required.

Achieving 50% of renewable share by 2050 requires installing a total of 59 GW renewable capacity of which 42 GW of PV, 10 GW wind, 5.6 GW CSP, 0.2 GW geothermal, 1 GW of waste power and 0.5 GW for cogeneration. This installed capacity will generate 108 TWh and will require substantial investment costs totalling 39 billion dollars.

Other considerations to achieving 75% REPS or more are necessary to investigate, these include defining:

- New concept of energy demand by considering heat and cooling demands, and demand-side response.
- Energy storage technology.
- Green future based on local integration of RET, by investigating regional renewable energy share.
- High economic growth, which supports high interconnection development in the grid that requires novel infrastructure planning approaches.
- Well-adopted markets design.
- Need to adopt new operation rules of the electricity system.
- Operating the electricity system smartly and cost-effectively.

CRediT authorship contribution statement

Saida Makhloufi: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **Smail Khennas:** Data curation, Formal analysis, Investigation, Writing – original draft. **Sami Bouchaib:** Resources, Data curation. **Amar Hadj Arab:** Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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