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Full-length article

Development modes analysis of renewable energy power generation in North Africa

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Abstract: North African countries generally have strategic demands for energy transformation and sustainable development. Renewable energy development is important to achieve this goal. Considering three typical types of renewable energies—wind, photovoltaic (PV), and concentrating solar power (CSP)—an optimal planning model is established to minimize construction costs and power curtailment losses. The levelized cost of electricity is used as an index for assessing economic feasibility. In this study, wind and PV, wind/PV/CSP, and transnational interconnection modes are designed for Morocco, Egypt, and Tunisia. The installed capacities of renewable energy power generation are planned through the time sequence production simulation method for each country. The results show that renewable energy combined with power generation, including the CSP mode, can improve reliability of the power supply and reduce the power curtailment rate. The transnational interconnection mode can help realize mutual benefits of renewable energy power, while the apportionment of electricity prices and trading mechanisms are very important and are related to economic feasibility; thus, this mode is important for the future development of renewable energy in North Africa.

Keywords: North Africa, Renewable energy, Wind power generation, Solar energy generation, Transnational interconnection, Optimal planning, Levelized cost of electricity.

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1 Introduction

Some countries in North Africa, such as Morocco, face the energy problems of a single energy structure, an uneven distribution of fossil energy resources, and a high dependence on imports. Energy transformation and sustainable development are the strategic demands of this region. On the other hand, renewable energy resources are abundant in North Africa; especially under the tropical desert climate, solar energy resources are extremely rich.

According to the international classification of solar energy utilization regions, North Africa is one of the regions with the strongest solar radiation in the world [1]. Fig. 1 shows the distribution diagram of annual average solar radiation intensity, and Fig. 2 shows the distribution diagram of wind speed at a height of 70 m in the North Africa region. It is the resource base of renewable energy development [2], [3]. Many countries in North Africa have formulated their own clean energy development plans in recent years. Morocco plans to further increase its target of 42% of total installed electricity capacity from renewable energy to 52% by 2030. In 2018, Tunisia announced that by 2030, its installed capacity of renewable energy would reach 4.7 GW, and 30% of its domestic energy demand would come from renewable energy. Egypt plans to generate 20% of its electricity from renewable energy by 2022.

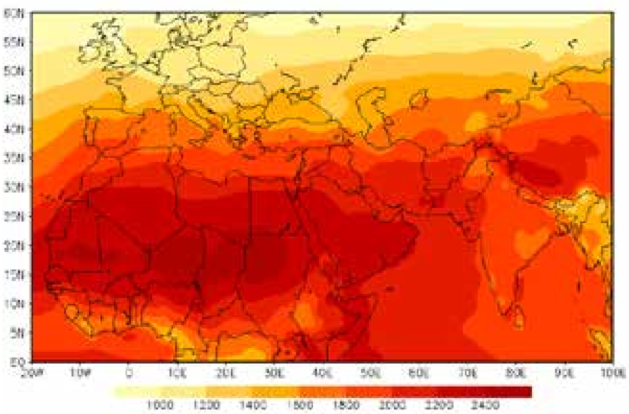


Fig. 1 Distribution diagram of annual average solar radiation intensity in North Africa region

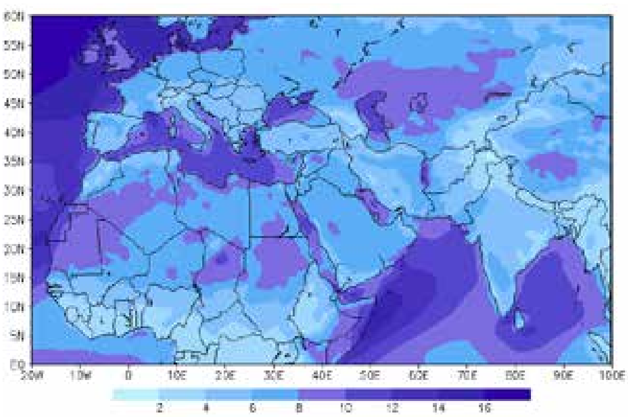


Fig. 2 Distribution diagram of wind speed (70 m) in North Africa region

Meanwhile, the technology progress and overall cost reduction of wind, concentrating solar power (CSP), and photovoltaics (PV) power generation also provide favorable conditions for the development of renewable energy power generation and energy transformation. The cost of solar energy power generation and the development trends were have been the focus of several research studies, where the technical and economic character of CSP and PV were compared [4], [5]. In [4], with solar energy development in Tunisia as a background, the development modes and the levelized cost of electricity (LCOE) were studied. Considering CSP stations with thermal energy storage (TES) and the scheduling model of wind power, the grid integrated benefits with CSP and PV combined power generation were analyzed in [6]. For other forms of renewable energy generation, the complement of wind power and CSP as well as investment costs were analyzed in [7]. The aforementioned research does not involve the optimization of the installed capacity allocation of various renewable energy power generation methods from an economic perspective. Optimal planning of a high proportion of renewable energy sources and coordinated operation with power systems has become a research focus in the field of energy and power systems in recent years [8], [9].

On the other hand, most of the energy programs focus on the development of domestic renewable energy. However, clean energy flows across borders and continents to transmit electricity by transnational interconnection modes, which has important research value and strategic significance for promoting optimal planning and economic development of regional renewable energy [10], [11]. Considering the coordination of multiple types of flexible resources, the optimal planning problem of high-rate renewable energy power generation has been studied, and a power planning model with the goal of minimizing the investment cost in the life cycle was established in [12]. An optimal planning scheme for renewable energy power generation with an improvement in the flexibility index by unit investment was achieved. Some studies are from the perspective of transnational interconnections for planning clean energy power generation and transmission channels [13–15]. In [13], a scheme for the transmission of clean power to North Africa, Europe, and Southern Asia by the six Gulf states in the near, medium, and long term were proposed. It can provide a reference for renewable energy development and transnational interconnection in the North Africa region. In addition, the prospects and the innovative cross-border and cross-continent electricity trading mechanisms are presented based on three different interconnection scenarios in [16], and profit models are considered in [17].

To research optimal programming problems for renewable energy power generation in the solar resource-rich region of North Africa, three development modes are designed for Morocco, Tunisia, and Egypt. According to the national load demand, economic indexes, such as construction investment and electricity curtailment loss, are determined as the optimal objective. Although the investment cost of wind and PV power generation modes is relatively low, they lead to renewable power curtailment and load loss. This disadvantage will be solved when CSP is combined, but at a higher cost. In addition, transnational interconnection modes will promote the optimal allocation of clean energy resources with reasonable electricity trading mechanisms. This study can provide a reference for the development modes and optimal programming of renewable energy power generation in North Africa.

2 Renewable energy power generation planning model

2.1 Objective function

The energy strategic transformation of North African countries mainly focuses on resources and comprehensive economic benefits. Development modes and scales of multiple types of power generators are planned under the gradually increasing trend of power load demand, especially when the share of renewable energy in power generation is gradually increasing and some conventional coal, oil, and gas power generators are gradually retired. Hence, based on the current power structure and development planning in three countries, while maintaining the current conventional power unit installed capacity and according to the load increase trend in the future, the comprehensive cost of investment in renewable energy power generation systems and the electricity curtailment loss are taken as the optimization objective to plan wind power, PV, and CSP power generation capacity through the time sequence production simulation method.

2.1.1 Objective function for renewable energy generation planning in different countries

The objective function is given by

$$F_1 = \min\left\{(C_{\text{wind}}S_{\text{wind}} + C_{\text{PV}}S_{\text{PV}} + C_{\text{CSP}}S_{\text{CSP}})/Y_{\text{inv}} + \sum_{i=t}^{T}[E_{\text{wind\_loss}}(t)Pri_{\text{wind}} + E_{\text{PV\_loss}}(t)Pri_{\text{PV}} + E_{\text{CSP\_loss}}(t)Pri_{\text{CSP}}]\right\} \tag{1}$$

where C_{wind}, C_{PV}, C_{CSP} are the construction costs of wind power, PV, and CSP in the future planning year, respectively (yuan/kW); S_{wind}, S_{PV}, S_{CSP} are the installed capacity of wind power, PV, and CSP in the future, respectively (kW); Pri_{wind}, Pri_{pv}, Pri_{CSP} are the feed-in tariffs of wind power, PV, and CSP in the future, respectively (yuan/kWh); $E_{\text{wind\_loss}}(t)$, $E_{\text{PV\_loss}}(t)$, $E_{\text{CSP\_loss}}(t)$ are the electricity curtailment in each interval t for wind power, PV, and CSP respectively, (kWh); Y_{inv} is the life cycle of the power plant; and T is the total length of time.

The renewable power energy curtailment in each interval t is

$$E_{j\_\text{loss}}(t) = \left[P_{j\_1}(t) - P_j(t)\right]\cdot t \tag{2}$$

where j represents wind, PV, and CSP, respectively; $P_{j\_1}(t)$ and $P_j(t)$ are the theoretical output power and actual output power in the interval t, respectively.

2.1.2 Objective function of renewable energy generation planning under transnational interconnection

The objective function is given by

$$F_2 = \min\left\{(C_{\text{wind}}S_{\text{wind}} + C_{\text{PV}}S_{\text{PV}} + C_{\text{CSP}}S_{\text{CSP}})/Y_{\text{inv}} + \sum_{i=t}^{T}[E_{\text{wind\_loss}}(t)Pri_{\text{wind}} + E_{\text{PV\_loss}}(t)Pri_{\text{PV}} + E_{\text{CSP\_loss}}(t)Pri_{\text{CSP}}] + \sum_{k=1}^{N}C_{\text{Line}}Dist(k)L_{Num}(k)\right\} \tag{3}$$

where C_{Line} is the construction cost of transmission lines in the future (yuan/km·loop); $Dist(k)$ is the distance of the kth transmission channel, (km); L_{Num} is the number of loops of the kth transmission channel; and N is the number of planning transmission channels.

2.2 Constraints

1) System power balance constraint

Renewable energy power generation planning is ultimately used to meet the power and energy balance between the power supply and the system load demand. If considering transnational interconnection, power export and import should be included in the power balance constraint, which is given by

$$P_{\text{coal}}(t) + P_{\text{PV}}(t) + P_{\text{CSP}}(t) + P_{\text{wind}}(t) - P_{\text{line\_out}}(t) + P_{\text{line\_in}}(t) - P_{\text{load}}(t) = 0 \tag{4}$$

where $P_{\text{coal}}(t)$, $P_{\text{wind}}(t)$, $P_{\text{PV}}(t)$, $P_{\text{CSP}}(t)$ are the output power of thermal units, wind power, PV, and CSP at time t (kW); $P_{\text{line\_out}}(t)$, and $P_{\text{line\_in}}(t)$ are the power export and import through transmission channels at time t (kW); and $P_{\text{load}}(t)$ is the total power load at time t (kW).

2) Generation unit output power constraints

Due to unit operation characteristics and resource characteristic limits of various types of generators, the minimum and maximum output power should be constrained as

$$P_{\text{coal\_min}} \leqslant P_{\text{coal}}(t) \leqslant S_{\text{coal}} \tag{5}$$

$$0 \leqslant P_j(t) \leqslant P_{j\_1}(t) \tag{6}$$

where $P_{\text{coal\_min}}(t)$ is the minimum output operating limit of conventional units (kW); S_{coal} is the installed capacity of conventional units (kW); and $P_{j\_1}(t)$ and $P_j(t)$ are the same as defined in (2).

3) TES of CSP constraint

Generally, the CSP station is equipped with a TES system, and the capacity of the system is described as the operating hours of the CSP station according to the rated power. The real-time thermal storage capacity of the TES system should be satisfied:

$$0 \leqslant ES_{\mathrm{CSP}}(t) \leqslant S_{\mathrm{CSP}} \cdot FLH \tag{7}$$

where $ES_{\mathrm{CPS}}(t)$ is the thermal storage capacity of the TES at time t; and FLH is full load hours.

4) Constraint on the rate of power change of a synchronous generator unit

A conventional thermal power unit and CSP are connected into the power grid through synchronous generators. Affected by the inertia of heat transfer, the power change of the unit is subject to the rate of power climbing up and down.

$$\begin{cases} P_k(t+1) - P_k(t) \leqslant \Delta P_{k,\mathrm{up}} \\ P_k(t) - P_k(t+1) \leqslant \Delta P_{k,\mathrm{down}} \end{cases} \tag{8}$$

where $\Delta P_{k,\mathrm{up}}$ and $\Delta P_{k,\mathrm{down}}$ are the rate limit of power climbing up and down of a synchronous unit, respectively; k represents two types generation of coal and CSP, respectively.

5) Transmission channel constraint

The power of transmission line should be within the upper and lower limits. The transmission power of channels is defined as the transmission power of each line multiplied by the number of lines planned for the channel. The constraint condition is

$$P_{\mathrm{line\_min}} \cdot N_{\mathrm{line}} \leqslant P_{\mathrm{line}\_l}(t) \leqslant P_{\mathrm{line\_max}} \cdot N_{\mathrm{line}} \tag{9}$$

where $P_{\mathrm{line\_min}}$ and $P_{\mathrm{line\_max}}$ are the minimum and the maximum transmission power of the transmission line, respectively; N_{line} is the number of lines for transmission channel planning; $P_{\mathrm{line}\_l}(t)$ is the transmission power at time t; and l represents export or import.

2.3 Economic feasibility assessment

LCOE is a very useful and important index in assessing economic feasibility or a comparison of power system projects involving both generation and transmission. LCOE is usually described as the present value of the total cost of the project divided by the present value of the electricity generated [18], [19].

$$LCOE_{\mathrm{RE}} = \frac{I_{\mathrm{RE}} + \sum_{n=1}^{N} \frac{OM_{\mathrm{RE}}}{(1+r)^n}}{\sum_{n=1}^{N} \frac{E_{\mathrm{RE}}}{(1+r)^n}} \tag{10}$$

where I_{RE} is the initial investment cost of the renewable energy project; OM_{RE} is the operation and maintenance cost, which, for simplicity, is 0.2% of fixed asset investment; E_{RE} is the annual electricity generated by renewable energy; r is the discount rate; and N is the life cycle of the renewable energy power generation system.

3 Design of development modes

3.1 Study case parameters

3.1.1 Power system parameters

The planning year is set as 2030, and the installed capacity of conventional units in power systems is the same as the recent capacity and will remain unchanged. Based on the current annual load level and the load growth trend of each country, the annual load characteristics of each country in 2030 are estimated.

1) Morocco

According to the 2016 annual report of the Arab Union of Electricity, the installed power generation capacity in Morocco was approximately 8260 MW, including 161 MW from solar energy generation, 898 MW from wind power generation, 1770 MW from hydropower generation, and 5443 MW from other conventional power sources [20]. The hydropower generation will reach approximately 2970 MW by 2030. Therefore, in the design of the planning case, the installed power generation other than wind and solar energy is calculated as 8400 MW.

The power load demand was 6300 MW in 2017, and based on the forecast of the Arab Union of Electricity, the load will increase to 11240 MW and 14000 MW in 2027 and 2030, respectively. According to the annual load characteristic curve and maximum load in 2030, the 8760-h load curve for Morocco in 2030 can be constructed as shown in Fig. 3.

2) Egypt

The installed power generation capacity in Egypt was approximately 39,103 MW, including 140 MW from solar energy generation, 747 MW from wind power generation,

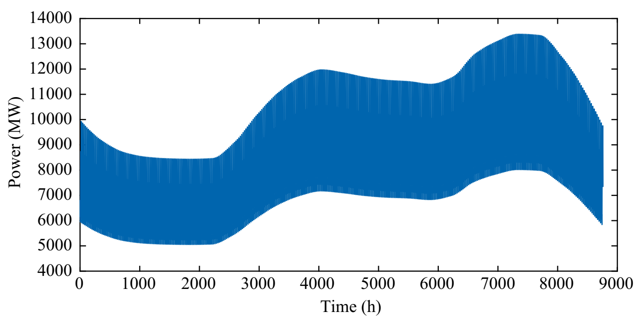


Fig. 3 Yearly load characteristic of Morocco in 2030

2800 MW from hydropower generation, and 35,416 MW from other conventional power sources [20]. In the design of the planning case, the installed power generation from sources other than wind and solar energy is calculated as 36,000 MW.

The power load demand was 29,200 MW in 2016, and based on the load forecast, the maximum load will reach 52,231 MW and 54,200 MW in 2027 and 2030, respectively. The daily peak load occurred in the morning peak and evening peak periods in Egypt, and during Ramadan, the daily peak load is only from 7 to 9 p.m. The peak load of the annual load characteristic is in July and August [21]. The yearly load curve for Egypt of 8760 h in 2030 can be constructed as shown in Fig. 4.

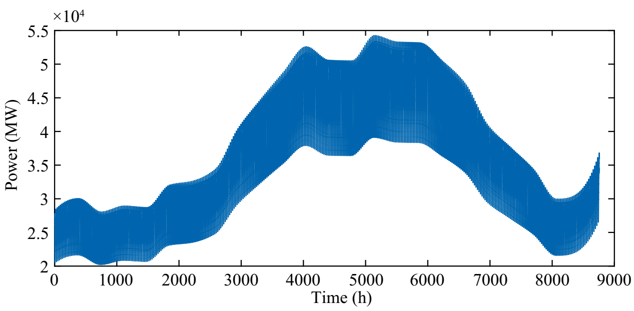


Fig. 4 Yearly load characteristic of Egypt for 2030

3) Tunisia

The installed power generation capacity in Tunisia was approximately 5513 MW, including 37 MW from solar energy generation, 240 MW from wind power generation, 62 MW from hydropower generation, and 5174 MW from other conventional power sources [20]. In the design of the planning case, the installed power generation from sources other than wind and solar energy are calculated as 5236 MW.

The power load demand was 3400 MW in 2016, and based on the load forecast, the maximum load will reach 5870 MW and 6795 MW in 2027 and 2030, respectively. According to the daily load characteristic and the yearly variation characteristic of the daily peak load in [22], the annual load characteristic of Tunisia is the same as that of Egypt. Hence, the yearly load curve of 8760 hours in 2030 of Tunisia can be constructed as shown in Fig. 5.

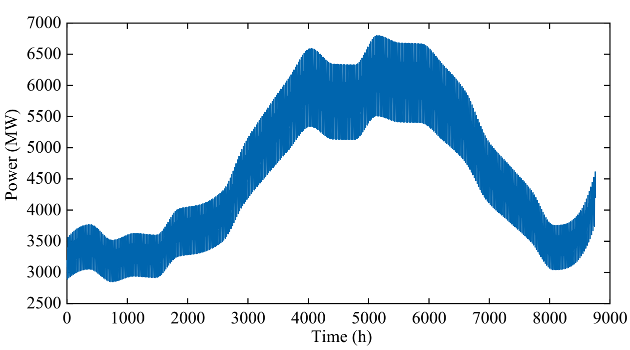


Fig. 5 Yearly load characteristic of Tunisia for 2030

3.1.2 Construction investment of renewable energy power generation

The construction cost and LCOE as well as the development trend of PV and CSP were analyzed in [4],[23]. According to the wind and solar energy power generation projects in North Africa in recent years, such as the Noor CSP stations in Morocco [24], the construction investment of various countries in North Africa in 2030 are forecasted as shown in Table 1.

Table 1 Cost forecast of renewable energy power stations in three countries of North Africa in 2030

Country	Morocco	Egypt	Tunisia
Construction cost of PV station(yuan/kW)	2000–3000	3000	2000–3000
Feed-in tariff of PV(yuan/kWh)	0.5	0.5	0.45
Construction cost of CSP station(yuan/kW)	28000–30000	30000	20000
Feed-in tariff of CSP (yuan/kWh)	0.8	0.9	0.68
Construction cost of Wind Farm(yuan/kW)[25]		3000	
Feed-in tariff of Wind (yuan/kWh)		0.35	

3.2 Development and planning of each country independently

3.2.1 Mode 1: Wind and PV power generation planning

Based on the parameters set in section 3.1, the installed conventional power generation cannot meet the maximum load demand. This case consists of planning wind and PV power generation to realize a power balance with the constraint from section 2.2. The planning results are shown in Table 2.

Due to the uncertainty and randomness of wind power and PV power generation, the wind power will curtail at some time through the time sequence production simulation, and curtailment rates are all approximately 10%, with Egypt at 19.2%. On the other hand, renewable energy power generation cannot guarantee power supply, resulting in load loss. For example, the maximum load loss in Egypt is close to 30% of the annual maximum load.

The cost of load loss and wind power curtailment amounts to billions, or even tens of billions, of yuan for countries with heavy electricity load. Therefore, when the power supply fails to meet the load demand of the system, it is difficult to ensure the reliability of power supply by only planning wind power and PV renewable power sources.

Table 2 Planning results of wind and PV power generation for three countries of North Africa in 2030

Country	Installed capacity of wind power (MW)	Installed capacity of PV(MW)	Total installed capacity of RE† (MW)	Total investment cost of RE(yuan, billions)	Rate of RE electricity curtailment(%)	Cost of RE electricity curtailment (yuan, billions)	Maximum load loss (MW)	Cost of load loss (yuan, billions)	Total cost (yuan, billions)
Morocco	9000	3830	12,830	34.7	9.0%	0.8	4883	4.6	40.1
Egypt	83,000	5051	88,051	264.1	19.2%	7.7	15,631	24.7	296.5
Tunisia	2491	1748	4239	11.0	9.7%	0.3	1250	1.0	12.3

† renewable energy

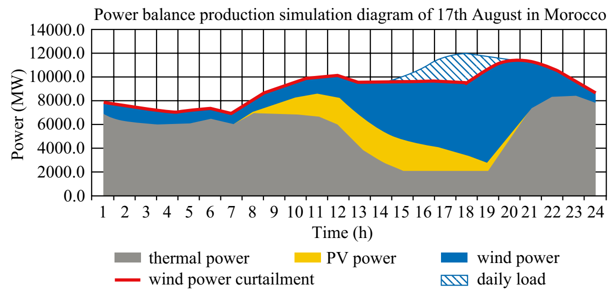
Typical days of power system balance operation simulation in Morocco and Egypt are shown in Fig. 6.

It is seen from the three figures that wind resources are rich for Morocco on August 17th, and that wind power is curtailed after 2 p.m., although the conventional units are reduced to the minimum technical output power. In the evening of November 3rd, wind and solar resources are not sufficient, and the conventional units reach the maximum output power; however, the total power supply still cannot meet the load demand, which leads to a load loss. On the same day, Egypt experienced both curtailment and power failure in the early morning and overnight.

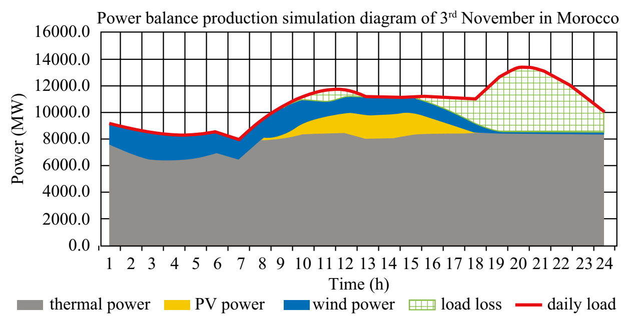
3.2.2 Mode 2: Wind/PV/CSP power generation planning

Compared with PV, CSP can significantly smooth the output power through TES, and it can improve utilization time and generated energy. CSP can enhance the regulation performance of stations to satisfy the power system demand after dark or when the power grid requires peak load regulation. However, in terms of economics, CSP power generation is still in the demonstration stage. The overall construction cost of CSP stations is high and investment varies widely among countries with different technical routes and project scales. Hence, the primary goal is to ensure the reliability of power supply; thus, wind, PV, and CSP combined development modes can be adopted. This not only plays the role of energy storage for CSP, but also takes advantage of the relatively low cost of wind power and PV to improve the overall economic feasibility of multiple renewable energy combined power generation.

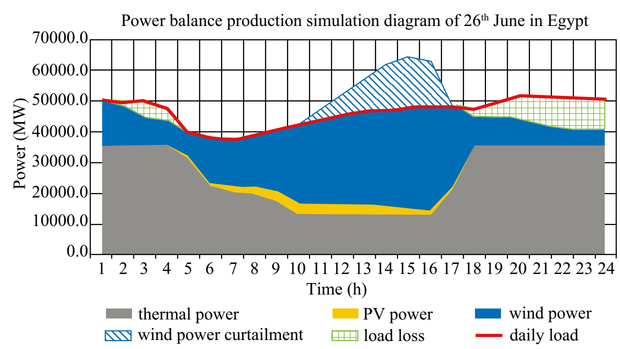
The plan case parameters are the same as those in section 3.2.1, and CSP is added to the planned power supply. The value for full load hours is 9 h for the CSP station. The planning results are shown in Table 3.



(a) Morocco, August 17th



(b) Morocco, November 3rd



(c) Egypt, June 26th

Fig. 6 Production simulation diagrams for typical days in Morocco and Egypt

Table 3 Planning results for wind, PV, and CSP power generation in three countries of North Africa in 2030

Country	Morocco	Egypt	Tunisia
Installed capacity of wind power (MW)	2740	8409	545
Installed capacity of PV(MW)	6313	2058	1571
Installed capacity of CSP(MW)	6672	23352	1338
Total installed capacity of RE (MW)	15726	33819	3456
Utilization hours of wind power	2050	1263	2109
Utilization hours of PV	1416	1583	1401
Utilization hours of CSP	3467	3893	3516
Rate of RE power generation curtailment(%)	1.3%	0.14%	0.04%
Maximum load loss (MW)	0	0	0
Total investment of RE(billions)	207.67	731.96	31.54

From the results, the total installed capacity of renewable energy is approximately 53 GW, and the total investment cost is approximately 971.17 billion yuan. For this case, the rate of wind and PV power curtailment in all countries is significantly reduced, and there is no load loss after CSP is added in planning.

The power system balance operation simulation of three consecutive days of peak load period in Egypt is shown in Fig. 7. It is seen in the figure that CSP gives full play to its regulating ability with TES systems, especially at night, when PV does not output power and wind power is low.

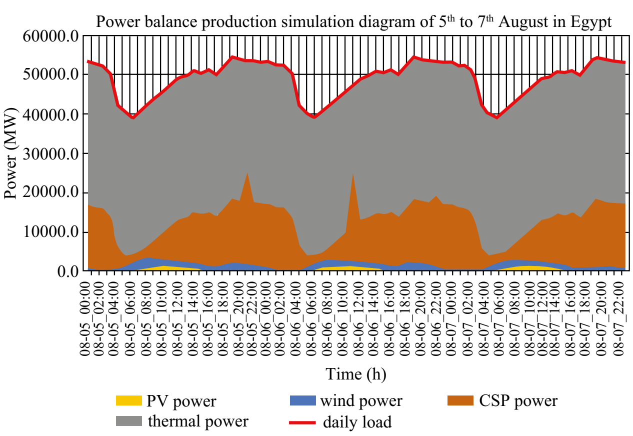


Fig. 7 Production simulation diagram for typical days in Egypt

This mode can realize the real-time balance of the power system and ensures the reliability of the power supply. Meanwhile, renewable energy curtailment is reduced. However, the high construction cost of CSP stations leads to a dramatic increase of total investment cost for renewable energy power stations.

3.3 Transnational interconnection planning

According to the energy development plan of each country in the North Africa region, the development of renewable energy in all countries after 2030 has reached a certain scale. The installed growth rate of traditional thermal power units, such as coal, oil, and gas, will slow or stop. Some thermal power units will be retired. Due to the limitations of domestic market space and development capacity, some countries will face a bottleneck in the scale of renewable energy development around 2030. Under this background, countries in North Africa can promote the overall development of renewable energy and drive the strategic transformation of energy in various countries by strengthening transnational interconnection, thus realizing mutual complementarity between clean energy power and load centers.

Morocco, Tunisia, and Egypt in North Africa are three countries with relatively stable political situations and favorable economic development. Morocco leads the way in solar energy power, while Egypt's electricity load is several times that of the other two countries. Egypt is considered as a power importing region, while Morocco and Tunisia are renewable energy power exporting regions in the transnational interconnection planning mode. The distance between Morocco and Egypt is approximately 3400 km; thus, it could consider adopting the ±1100 kV UHVDC transmission mode with a transmission capacity of approximately 10 GW. Tunisia is approximately 2300 km from Egypt, and it can adopt the ±800 kV UHVDC with 6–8 GW transmission capacity. It can realize the Morocco–Egypt (M-E), Tunisia–Egypt (T-E) interconnection.

For mode 3 planning, the objective function is given by (3) in section 2.1, and the loop number of the transmission channel is a decision variable of planning. The planning results are shown in Table 4.

Table 4 Planning results of interconnection between three countries of North Africa in 2030

Country	Morocco	Egypt	Tunisia
Installed capacity of wind power (MW)	10,299	8550	6051
Installed capacity of PV (MW)	4094	100	100

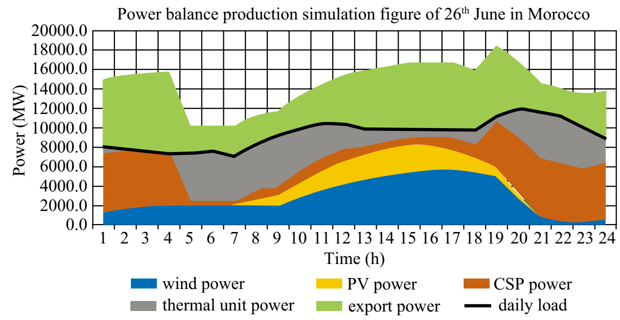
continue

Country	Morocco	Egypt	Tunisia
Installed capacity of CSP (MW)	6200	0	16,798
Rate of RE power generation curtailment	0%	0%	0%
Utilization hours of wind power	2690	1971	2603
Utilization hours of PV	1949	2068	2010
Utilization hours of CSP	4237	0	4400
Total installed capacity of RE (MW)	20,593	8650	22,949
Investment of RE in each country(billions)	209.86	25.95	354.31
Total investment of RE(yuan, billions)		590.12	

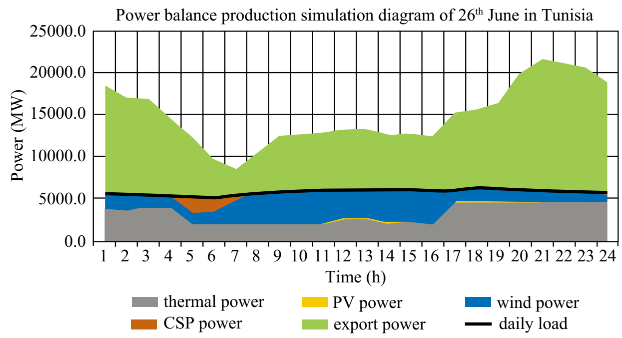
Transmission channel	Morocco–Egypt	Tunisia–Egypt
Loop number	1	2
Utilization hours	4500	4711
Transmission electricity(GWh)	45,000	75,371.3
Maximum transmission capacity (MW)	10,000	8000
Cost of transmission line (yuan/km·MW)	510	1650
Total investment of transmission channels (yuan, billions)	78.06	

In this mode, the total installed capacity of renewable energy is approximately 52.2 GW, and the total investment is approximately 668.18 billion yuan. In the results, the planning construction of wind and solar power in Morocco and Tunisia can realize the mutual benefit of renewable energy power through the transnational interconnection mode. While meeting the load demand of the three countries and ensuring a high level of utilization hours, it does not only reduce the curtailment rate of renewable energy, but also provides an optimal distribution and installed capacity of renewable energy in each country, and a reduction of the total investment of renewable energy power stations. This mode can be used as an important means of renewable energy development and energy interconnection development in North Africa.

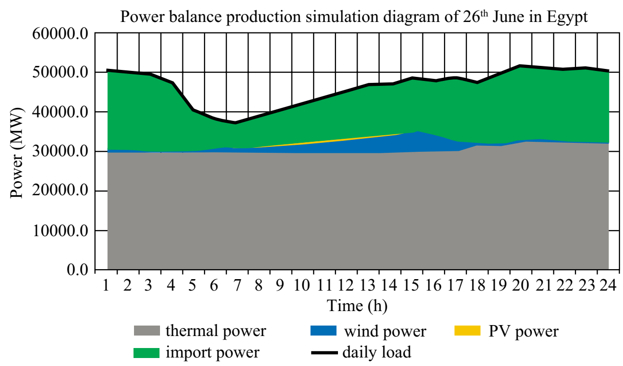
Fig. 8 shows the power system balance production simulation diagram for a typical day in the three countries.



(a) Morocco: June 26th



(b) Tunisia: June 26th



(c) Egypt: June 26th

Fig. 8 Production simulation diagram of three countries in North Africa

It can be seen from the figures that in the early morning and evening of June 26th, Tunisia mainly supplies power to Egypt through the power transmission channel, while Morocco supplies power to Egypt during the day, so as to meet the load demand of Egypt while meeting the domestic load demand through the electricity exchange.

3.4 Levelized cost of electricity

From the planning results of modes 2 and 3, we can use (10) to calculate the LCOE of renewable energy power generation in each country to compare the economic development. The discount rate is 8% and the life cycle of the renewable energy power generation system is approximately 25 years. The LCOE of renewable energy power generation and transmission channels is shown in Table 5 (unit is yuan/kWh).

Table 5 LCOE of modes 2 and 3 in each country and channel

	Morocco	Egypt	Tunisia	M-E	T-E
Mode 2	0.53	0.67	0.38	—	—
Mode 3	0.33	0.15	0.36	0.042	0.087

With the transnational interconnection, the LCOE of renewable energy power generation in each country is reduced, due to the optimal allocation of three types of renewable energy and the high utilization times, especially in Egypt. On the other hand, as the electricity import country, Egypt should pay the cost of renewable energy electricity generation and transmission to buy the imported electricity. This electricity price may be higher than the domestic price. Therefore, this development mode is not more economical for Egypt than developing independently, but this mode is better for Morocco and Tunisia.

4 Conclusion

In response to the demand of the North Africa energy transformation, three types of renewable energy power generation—wind power, PV, and CSP—were considered as planning objects. An optimal renewable energy power generation planning model was established and applied to plan the power scales of three types renewable energy generation in Morocco, Egypt, and Tunisia through the time sequence production simulation method. We can conclude the following:

(1) North Africa is rich in solar and wind energy resources and very suitable for developing solar and coastal wind power. In the future, with installed growth of traditional thermal power units slowing or stopping, only wind and PV power generation will be installed, leading to renewable energy power curtailment and load loss due to resource randomness and uncertainty. Thus, it is impossible to guarantee power supply reliability of the system. On the other hand, the investment cost of this development mode is relatively low when a certain range of power curtailment and load loss is allowed.

(2) CSP with TES can make up for the uncertainty of wind and solar resources on account of its flexible regulating ability. Wind and solar energy power generation, including CSP, can ensure the reliability of power supply, and reduce the curtailment rate of renewable energy. Meanwhile, this mode can replace a part of conventional thermal power units to satisfy load increase demand, and it is useful for achieving a high proportion of clean energy power generation development goals. However, with an increase in the amount of CSP, the investment of power station construction will greatly increase.

(3) The transnational interconnection mode can promote the optimal allocation of clean energy resources at the large regional level, so as to realize the mutual benefit of clean energy power. However, the economic feasibility from the LCOE perspective is not suitable for every country, and the apportionment of electricity prices and trading mechanisms are very important for each country. Hence, this mode will be one of the important choices of energy development and transformation in North Africa and the world in the future if an economical and reasonable electricity trading mechanism is established.

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References

[1] Huang X (2009) International solar energy resource and tendency of solar thermal power generation. Huadian Technology, 31(12):1-3

[2] Moncef B, Eddine T, Mahmoud B, et al (2016) Potential of concentrating solar power (CSP) technology in Tunisia and the possibility of interconnection with Europe. Renewable and Sustainable Energy Reviews, (56):1227-1248

[3] Hermann S, Miketa A, Fichaux N (2014) Estimating the renewable energy potential in Africa. IRENA-KTH working paper, International Renewable Energy Agency, Abu Dhabi

[4] Zhao L, Zhu L, Wang W, et al (2018) Economic analysis of solar energy development in North Africa. Global Energy Interconnection, 1(1):53-61

[5] Desideri U, Zepparelli F, Morettini V, et al (2013) Comparative analysis of concentrating solar power and photovoltaic technologies: Technical and environmental evaluations. Applied Energy, 102:765-784

[6] Chen R, Sun H, Li Z, et al (2014) Grid dispatch model and interconnection benefit analysis of concentrating solar power plants with thermal storage. Automation of Electric Power Systems, 38(19):1-7(in Chinese)

[7] Xu H, Yuan Y, Zhang X, et al (2013) Wind-solar complementarity and cost analysis of new solar-wind hybrid thermal power plant. Water Resources and Power, 31(3):240-243(in Chinese)

[8] Yao L, Zhu L, Zhou M, et al (2017) Prospects of coordination and optimization for power systems with high proportion of renewable energy. Automation of Electric Power Systems, 41(9):36-43
[9] Ma J, Zhao D, Qian M, et al (2017) Reviews of control technologies of large-scale renewable energy connected to weakly-synchronized sending-end dc power grid. Power System Technology, 41(10):3112-3120
[10] Liu Z (2016) Research of global clean energy resource and power grid interconnection. Proceedings of the CSEE, 36(19):5103-5110(in Chinese)
[11] Liu Z (2015) Global energy internet. China Electric Power Press, Beijing
[12] Xu T, Lu Z, Qiao Y, et al (2019) High penetration of renewable energy power planning considering coordination of source-load-storage multi-type flexible resources. Journal of Global Energy Interconnection, 2(1):27-34(in Chinese)
[13] Wu J, Gao C, Xiao J, et al (2018) Research on the power grid interconnection scheme between GCC countries and neighboring countries. Journal of Global Energy Interconnection, 1(5):549-557(in Chinese)
[14] Lu Z, Li H, Qiao Y (2018) Wide-area interconnection grid planning for clean power integration considering the effect of country risks. Journal of Global Energy Interconnection, 1(1):23-31(in Chinese)
[15] Huang C, Wang C, Li H, et al (2019) Analysis of basic conditions of the power grid interconnection among Xinjiang, Pakistan, and five Central Asian countries. Global Energy Interconnection, 2(1):54-63
[16] Huang K, Zhou Y, Qu H, et al (2018) The study on cross-border and cross-continent electricity trading mechanisms. Journal of Global Energy Interconnection, 1:234-241(in Chinese)
[17] Li J, Gao G, Ma L, et al (2019) Analysis of profit models for cross-border power interconnection projects. Global Energy Interconnection, 2(5):458-465
[18] Frank K, Goswami D (2007) Handbook of energy efficiency and renewable energy. CRC Press, Boca Raton
[19] Li X, Zhao X, Li J, et al (2015) Analysis of life-cycle levelized cost of electricity for tower solar thermal power. Automation of Electric Power Systems, 39(7):84-88
[20] Arab Union of Electricity (2016) Statistical Bulletin
[21] Elgazzar M, Hemayed E (2016) Electrical load forecasting using Hijri causal events. 2016 Eighteenth International Middle East Power Systems Conference (MEPCON), Cairo, pp 902-906
[22] Mahmoud M, Jaidane-Saidane M, Hizaoui N (2008) The use of mixture of generalized Gaussian for trend analysis of the load duration curve: Summer and winter load variability in Tunisia. 2008 43rd International Universities Power Engineering Conference, Padova, pp 1-5
[23] International Renewable Energy Agency (2019) Renewable power generation costs in 2018
[24] CSPPlaza (2016) Electricity price of several typical representative CSP power stations in 2015. http://www.cspplaza.com/article-6512-1.html
[25] Yang J (2018) Analysis of global wind power project cost trend. http://news.bjx.com.cn/html/20180417/892121.shtml

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