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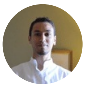

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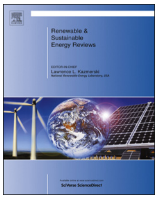

Potential of concentrating solar power (CSP) technology in Tunisia and the possibility of interconnection with Europe

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ABSTRACT

In this paper, the potentials of solar resources and the suitable factors for the deployment of concentrated solar power CSP in Tunisia were presented. This study was done in the framework of the enerMENA project which aims to prepare the ground towards a sustainable realization of CSP power plants in the North Africa and Middle-East countries. Moreover, the electrical interconnection between Tunisia and Italy and the opportunity of the exploitation of renewable energy sources such as CSP plants in North Africa by European countries, were discussed. In addition, solar radiations data and weather parameters values delivered by a specific network of solar radiation and weather data installed in the Tataouine region at the south of Tunisia, were discussed from the angle of fitting with CSP technology. Besides, simulations of 50 MW parabolic trough solar power plant based on the solar radiation and climatic data delivered by the installed station were performed. The energetic and economic performances of the Tunisian simulated plant were compared with a reference CSP plant Andasol in Spain. The results prove that Tunisia has very important solar resources suitable for the CSP deployment such as the direct solar radiation DNI. Even, the total annual production of electricity generated from the simulated field of Tataouine exceeds that of the plant of Andasol in Spain by an amount of 1793 MWhe. However, the total investment cost is more important in the case of Tataouine station in Tunisia. A concentrated solar power project becomes economically competitive in Tunisia when the majority of the plant components such the collectors structure, the mirrors and the storage system should be manufactured locally in Tunisia to minimize the transport fees and by the way create jobs and enhances the local industry to investigate in this field.

Contents

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1. Introduction

Today, our energy supply is based almost exclusively on fossil fuels. The consequences of this become clear both on the supply side and on the disposal side. The limited natural resources available will not allow supply to continue at current levels. While we use fossil resources, population growth and the worldwide pursuit of prosperity will continue to increase demand and aggravate the problem. This is being reflected in current price trends, and potential conflicts are already starting to emerge. At the disposal side, the burning of fossil fuels is not less problematic, as emissions have negatives effects on our environment and our climate. The most prominent is the greenhouse effect causing global warming, but the dangers to health caused by air pollution constitute a major threat as well. Global warming also leads to shortages of drinking water and productive land [1].

An alternative solution for these problems is solar energy, which is available, plentiful in most areas, and represents also a good source of thermal energy. Tunisia as the most of the Mediterranean region countries has a high level of solar radiation. In fact, Tunis, capital of Tunisia receives an average of 16,720 kJ/m^2/day with a total insulation period of 3700 h/year and 350 sunny days per year [2]. Despite the limited penetration of solar technologies in the industrial sector, its potential is quite large. Indeed, almost the third of the Tunisian territory constituting the south regions is formed by desert. This region, which was regarded as a wasteland for a very long time, is now considered prime real estate for power generation from solar and wind energy. In fact, the desert regions contain an abundant and inexhaustible source of clean energy, and that very large-scale solar electricity generation provides economic, social and environmental benefits, security of electricity supply and fair access to affordable and sustainable energy solutions. In addition, Tunisia is situated in the center of North Africa and in close proximity to Europe, in a strategic position to play a vital role in developing a regional wide electric grid network along and across the Mediterranean Sea. This venture would certainly make the Tunisian economy strong, and the educated Tunisian youth thrive. Tunisia would regain its position as “the trading hub of the Mediterranean Sea,” as it was once known as in Carthaginian times. This time, Tunisia would be known as the trading hub of energy, or as the provider of clean electricity produced sustainably [3]. Tapping into this potential would provide a significant solar contribution to industrial energy systems. However, in many cases the solar energy should be concentrated to attend the relatively high temperature needed by the process. In the solar thermal applications, the energy is optically concentrated before being converted into heat. The sunlight is concentrated in the focal plane, with the aim of maximizing the energy flux on the absorber surface [4]. Concentrating solar power (CSP) systems use lenses or mirrors and tracking systems to focus a large area of sunlight into a small beam. The concentrated heat is then used as a heat source for a conventional power plant. A wide range of concentrating technologies exists; the most developed are the parabolic trough, the concentrating linear Fresnel reflector, the Sterling dish and the solar power tower. Various techniques are used to track the Sun and focus light. In all of these systems a working fluid is heated by the concentrated sunlight, and is then used for power generation [5]. Unlike solar photovoltaic (PV) technologies, CSP has an inherent capacity to store heat energy for short periods of time for later conversion to electricity. When combined with thermal storage capacity, CSP plants can continue to produce electricity even when clouds block the sun or after sundown. CSP plants can also be equipped with backup power from combustible fuels [6]. In addition, For instance, a one megawatt of installed CSP avoids the emission of 688 tonnes of CO_2 compared to a combined cycle system and 1360 tonnes of CO_2 compared to a coal/steam cycle power plant. A one square mirror in the solar field produces 400 kW h of electricity per year, avoids 12 t of CO_2 emission and contributes to a 2.5 tonnes savings of fossil fuels during its 25-year operation lifetime [7]. The first commercial plants began operating in California in the period 1984 to 1991, spurred by federal and state tax incentives and mandatory long-term power purchase contracts. A drop in fossil fuel prices then led the federal and state governments to dismantle the policy framework that had supported the advancement of CSP. In 2006, the market reemerged in Spain and the United States, again in response to government measures such as feed in tariffs (Spain) and policies obliging utilities to obtain some share of power from renewable energy and from large solar in particular. As of early 2010, the global stock of CSP plants neared 1 GW capacity. Projects now in development or under construction in more than a dozen countries (including China, India, Morocco, Spain, the United States and South Africa) are expected to total 15 GW. Parabolic troughs account for the largest share of the current CSP market, but competing technologies are emerging [8]. Some studies [9–20] were interested to the explorations and comparisons between the different technologies adopted for CSP plants such as towers, linear Fresnel and parabolic trough solar collectors. Moreover, others authors studied the main components of CSP plant from different approaches and proposed some designs and suggestions to improve the overall performances of theses installations [21–27]. Beside, several studies [28–36] have investigated the potential and the opportunities to built CSP plants in different country around the word. Moreover, as of the importance given by researchers and environment friends to the intensification of the solar energy use, a strategic concept the DESERTEC [37,38] was developed. The DESERTEC concept is concerned with the sustainable supply of cost-effective electricity from renewable energy sources for the Europe Middle-East and North Africa 'EU-MENA' region. Accordingly, concentrated solar power (CSP) plants in the North African desert should supply a significant share of electricity. CSP deployment would bring substantial advantages to these countries. It will meet the rapidly growing power demand, reduce dependence on fossil fuels for electricity generation, lower carbon footprint, and promote job creation and economic development through increased opportunities for local manufacturing and technology transfer in this area.Despite the obvious suitable conditions for the development of CSP MENA countries, there are lacks in the intentions devoted to this technology particularly in Tunisia. Very few and brief studies related to possibilities of realizing CSP plants in the country were done [39,40]. Therefore, there is a gap obstructing the emergence of the technology and the related know-how transfer. More investigations and pre-feasibility studies are still needed to prepare the ground towards a sustainable realization of CSP power plants in Tunisia as well as the other North Africa and Middle-East countries.

This study was done in the framework of the enerMENA project [41] which aims to prepare the ground towards a sustainable realization of CSP power plants in the North Africa and Middle-East countries. The project is funded by the German Federal Foreign Office. It was initiated and is run by the Institute of Solar Research at the German Aerospace Center (DLR), a pioneer in this field who has shaped the DESERTEC concept. Therefore, in this paper, the potentials of solar resources and the suitable factors for the deployment of CSP in Tunisia will be presented. In addition, solar radiations data and weather parameters values delivered by a specific network of solar radiation and weather data installed in the framework of enerMENA project in the Tataouine region at the south of Tunisia, were discussed from the angle of fitting with CSP technology. Besides, simulations of 50 MW parabolic trough solar power plant based on the solar radiation and climatic data, delivered by the installed station, were performed for the Tatouine site in the south of Tunisia.

2. Methodology

In the following sections, we will present the factors suitable to the deployment of CSP plants in Tunisia such as the energy mix, the geographic and climatic factors, the possibilities of interconnection with Europe and the solar resources. Thereafter, we present the meteorological station and the site of Tataouine in the south of Tunisia. In a following step, the meteorological solar data delivered by the station of Tataouine were explored relatively to the condition of CSP fields running. Beside, the weather data delivered by the Tataouine station were used to perform modeling and simulation of a solar power plant using the "Greenius" software. Greenius (Green energy system analysis) is a software developed at the German Aerospace Center DLR (Deutsches Zentrums für Luft und Raumfahrt-ev) [42]. It is a powerful simulation environment for the calculation and analysis of renewable energy projects (solar, wind). It offers a combination of detailed technical and economic calculations necessary for the planning and installation of the electricity power projects. Additional Greenius interfaces give detailed information that supports the user to define the project in its entirety. The parameters introduced in the interfaces are preset with realistic values that allow achieving more realistic simulation results.

In our modeling and simulations of the solar plant the methodology is divided in this way:

- Analysing the actual state of CSP plants in the world to select a plant as a model to exploit its power, technological and dimensional data in the simulations.
- Collecting data: economical, geographic and meteorological data of Tunisia.
- Exploration of the meteorological data delivered by the Tataouine station.
- Simulation: using Greenius sofware and adopting the technical parameters of the Andasol Plants in Spain which have a gross electrical output of 50 MW and a thermal storage capacity of about 7.5 h at full load [43]. Even the available information relative to Tunisian conditions was introduced.
- Discussing the results: Exploring and analyzing the regime of CSP plant running as daily behavior during the four seasons of the year. The monthly and the yearly power production were also analyzed and compared to similar plant performances.

In the following section, an economic analysis was performed for the simulated plan and compared principally to the andasol plant in Spain. Finally, some conclusions were drawn.

3. Favorable factors to the deployment of CSP technology in Tunisia

As expected by many researchers [34,44], the determinant factors for the deployment of CSP in a country are the energy situation, the solar resources, the climatic and geographic conditions, availability of transmission and supporting infrastructure, water accessibility and potential for auxiliary supply. In addition, Tunisia has some particular important factors as its nearest to Europe which constitute an opportunity to be a transient zone and a way of electricity interconnection between North Africa and Europe.

3.1. Energy context of Tunisia

The Tunisian energy mix is mainly based on traditional fossil sources, as for the most of MENA Countries. Tunisia produced an average of 68.3 thousand barrels of crude oil per day in 2012. The total primary energy supply in 2011 was 9 200 ktoe, with natural gas and oil accounting, respectively, 46% and about 40% of the total (Fig. 1).

At the end of 2012, the installed capacity of the Tunisian power generating system is around 4024 MW. The generating system consists essentially of [45]

- gas turbines (1532 MW);
- 4 steam units totaling 1090 MW burning either natural gas or heavy fuel;
- the combined cycle plants of Sousse (364 MW) and Ghannouch (416 MW);
- the wind farm of El Haouaria (53 MW);
- hydroelectric power stations with a cumulated installed capacity of 62 MW.

Total domestic electricity supply was 15 957 GWh in 2012 and the Tunisian per capita electricity consumption was around 1 200 kWh.

The country's socio-economic development, combined with policies based on the subsidization of nearly all types of energy, has led to the strong growth of energy demand in Tunisia over the

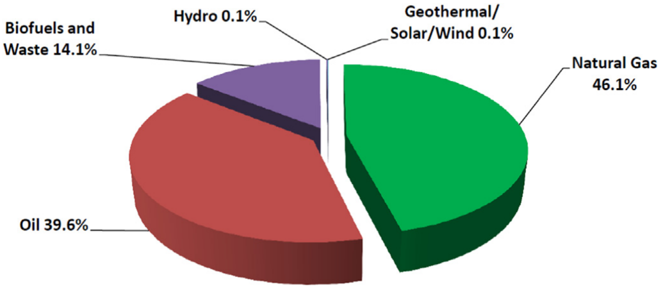

Fig. 1. Share of total primary energy supply in Tunisia.

last 20 years. Energy consumption, which was 0.9 toe per capita in 2011 (5 times lower than the EU average), increased at an average annual rate of 3.3% between 1995 and 2000, compared to an annual rate of 1.4% between 2005 and 2010 (Fig. 2).

3.2. Geographic and climatic factors

Tunisia is located at the eastern end of North Africa at the turn of the western and eastern basins of the Mediterranean, over which the country opens with a frontage of 1300 km double exposure. It is separated from Europe by a distance of 140 km at the Sicily Channel as shown in Fig. 3. With an area of 163,610 km², the country is bordered to the west by Algeria with 965 km of common border, southeast talks with Libyan border and 459 km to the north and east by the Mediterranean with 1298 km of coastline [46]. Croplands represent 4.9 million hectares. Sahara desert occupies an area of between 33% and 40% of the territory as it defines the post aridity or as landscape features.

3.2.1. Tunisia a transition zone

Given its proximity to Italy, Tunisia is in an ideal position to transfer such renewable energy directly to European markets, with much less energy loss along the way compared to its Maghreb neighbors. In addition, based on sea depth and current submarine cable technology, the feasible routes from North Africa to Europe are towards Italy and towards Spain (Fig. 4) [47]. It is in this

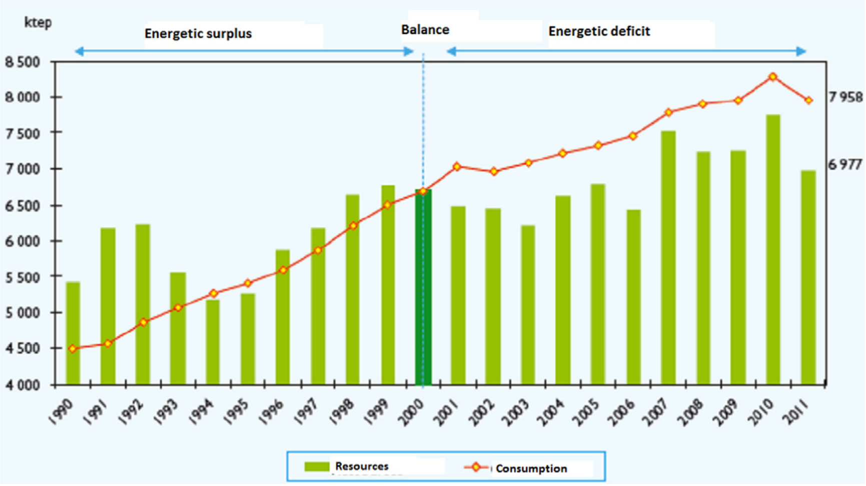

Fig. 2. Energy consumption and resources evolution in Tunisia.

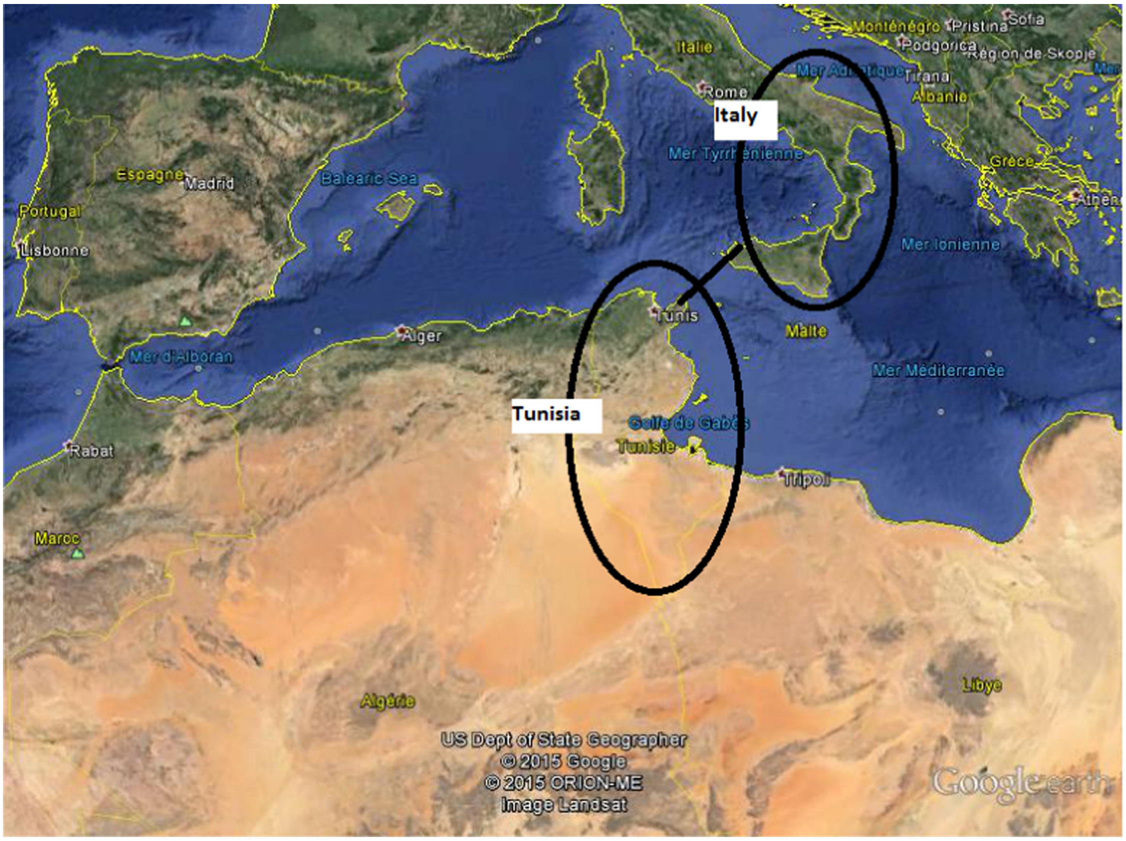

Fig. 3. Map of the geographic position of Tunisia.

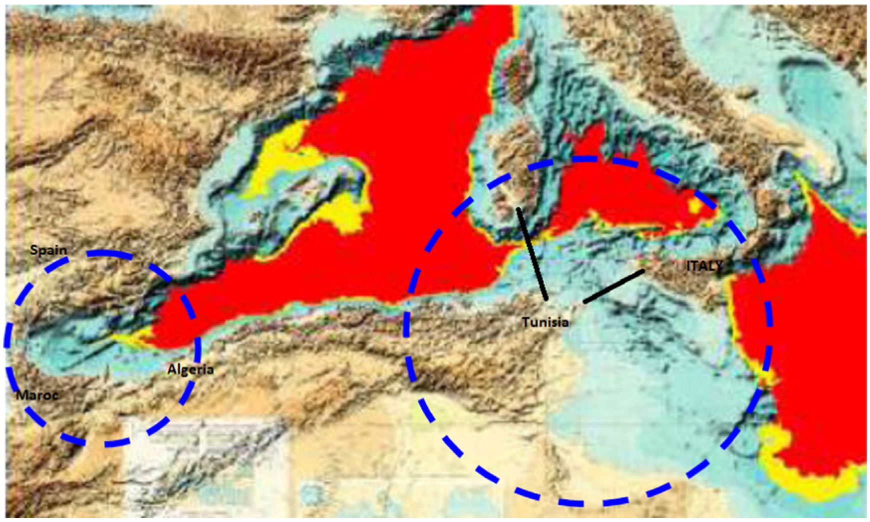

Fig. 4. Mediterranean sea depth level: the blow color corresponds to depth suitable for submarine cable technology but the red color corresponds to depth more than 3 km not suitable. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

framework and implementation of this policy, the Ministry of Industry, Energy and SMEs, the Italian Ministry for the Environment, Land and Sea and the National Agency the energy Management of Tunisia (ANME) signed a memorandum of understanding for the construction of two feasibility studies for the realization of the power interconnection project between Tunisia and Italy [48,49]. They hope to link to the Italian grid via new undersea high-voltage cables spanning the Mediterranean. A joint-venture between the society of electric and gas in Tunisia “STEG” and Italy's electricity transportation company, will see a 200-km long 1000-MW high-voltage direct current (HVDC) submarine cable link the two Mediterranean nations via El Hawaria in Tunisia and Partanna in Sicily (Fig. 3). This submarine electric link by HVDC cable will be added to the existing Transmed gaz pipeline linking Algeria Tunisia and Italy.

The power plant construction project will require the installation of an electric cable DC submarine with a capacity of 1000 MW (MW) and a length of 160 km. This cable will be resized to 1000 MW of which 800 MW will be produced from the plant and the remaining 200 MW will be reserved for renewable energy. The electrical interconnection between Tunisia and Italy will include improving the reliability of the regional power system and contribute to the creation of a regional electricity market and a green energy market. It will also provide an opportunity for the exploitation of renewable energy sources such as CSP plants in North Africa and contribute to the achievement of the objectives of the European Community for renewable energy penetration.

3.2.2. *Climate in Tunisia*

The climate of Tunisia is divided into seven bioclimatic zones, the big difference between the north and the rest of the country is due to the chain of Tunisian ridge that separates the areas subject to the Mediterranean climate of those subject to the arid climate engendered by the opening to the Sahara. Because of its location, the Tunisian climate is influenced by various types of winds: the north coast is exposed to sea winds blowing from the south of France, causing a significant drop in temperatures and increased precipitation, and south with hot, dry winds like the sirocco blowing over large stretches of desert and plains. The country also benefits from a significant rate of sunshine. Temperatures vary because of latitude, altitude and the proximity or remoteness of the Mediterranean Sea. If it could decrease by few degrees below 0 °C in winter in the mountains of Kroumirie, the temperature sometimes climbs in the summer around 50 °C in desert regions. Annual rainfall also varies by region: about 1000 mm in the north to about 380 mm and less than 300 mm in the south [50].

3.2.3. *Solar radiation resources*

The duration of the average insolation of the country is relatively high; two thirds southern countries have, in fact, an exposure time to the sun of more than 3200 h per year, with peaks of 3400 h on the south coast (Gulf of Gabes), while the minimum period of insolation in the northern third is between 2500 and 3000 h per year [46].

Monthly average sunshine duration varies from 4 to 7 h/day in winter and 10 to 12 h/day in summer, which endows the country with an interesting solar radiation. As shown in Fig. 4, solar radiation varies from 1800 kWh/m^2/year (North) to 2800 kWh/m^2/year (South). As for the global solar radiation, its daily average is between 4.2 kWh/m^2/day northwest, and 5.4 kWh/m^2/day in the far south; most of the territory (over 80%) located in the upper fringe of 4.75 kWh/m^2/day [51].

3.2.4. *Potential of direct solar irradiation DNI*

The Direct Normal Irradiance (DNI) is the most important parameter for the simulation and implementation of solar concentrated power CSP technologies.

In Tunisia, as expected in Fig. 5 [52], the highest values were measured in the southern regions and in some mountainous areas of central west of the country. In the North, we can identify sites with direct radiation reaching the DNI of 2100 kWh/m^2 per year while in the South, we can attempt the value of 2400 kWh/m^2 per year. Some researchers [29,53] suggested the threshold value of 2000 KWh/m^2/year for the annual DNI for solar thermal power generation. Therefore, the most area of the center and the south of Tunisia have annual DNI suitable for the CSP plant running.

3.2.5. *Available lands*

CSP plants require large areas of land for deployment of solar field, power block and storage component. Requirement of land may vary according to the CSP technology used and the extent of storage with the plant. The required land is expected to be available in abundance (and perhaps at reasonable cost) in arid and semi-arid areas of the country with high DNI [44]. As the center and the south regions of Tunisia are semi-arid and arid with about 40% of the country territory are desert, there are very large waste land. Most of these lands are with slope less than 2% and therefore suitable for CSP plants.

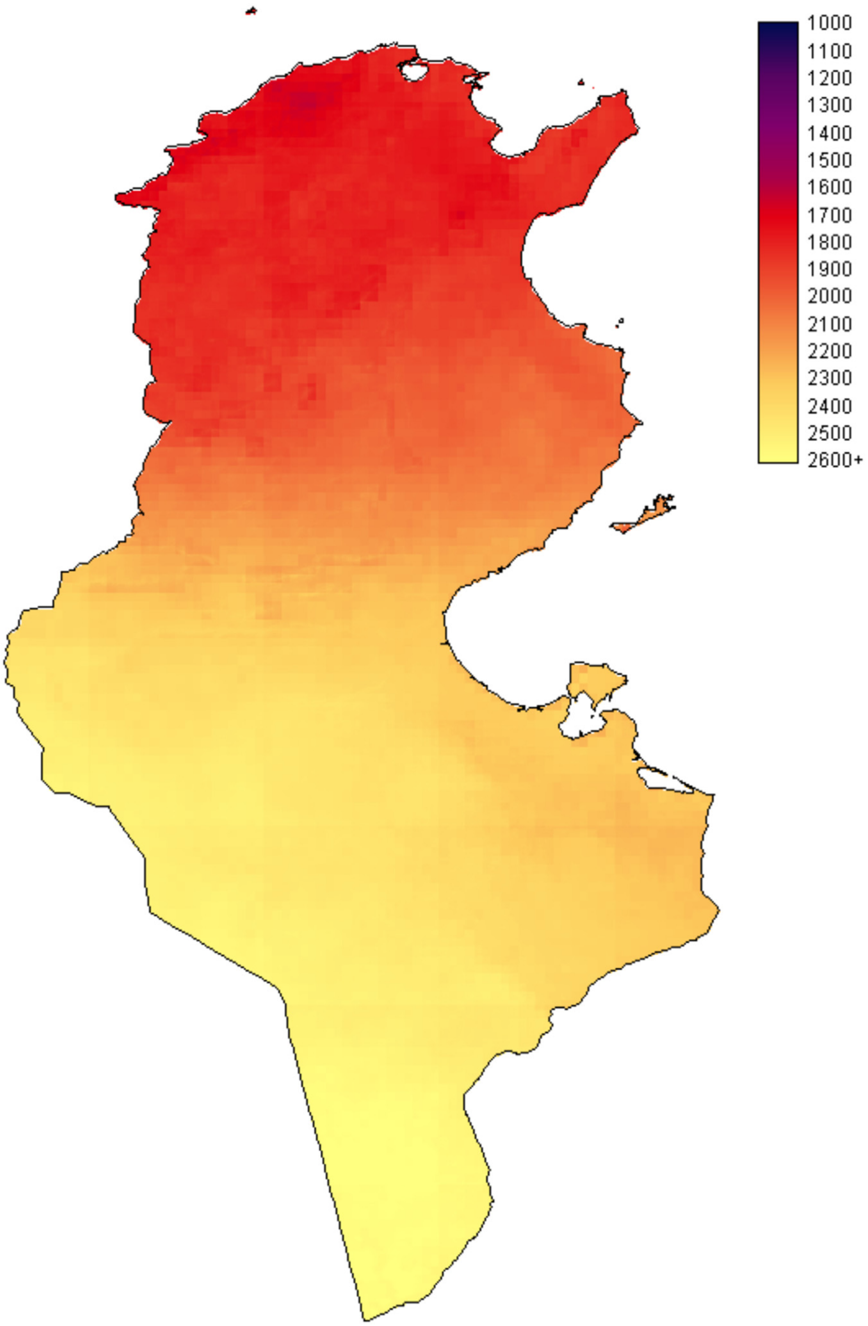

Fig. 5. Solar map of Tunisia with average daily sum of direct normal irradiation per square meter (kWh/m²/year).

3.3. *Availability of transmission and supporting infrastructure*

CSP systems would require appropriate transmission infrastructure for evacuation of electricity produced [53,54]. In Fig. 6, is represented a map of the electricity production and transport network in Tunisia. The majority of the Tunisian regions is connected to the grid. The voltages levels used for the high-voltage network are 400, 225, 150 and 90 kV and the network consists mainly of overhead lines except in the capital, where for planning considerations and servitude, certain routes are underground. The Tunisian system is interconnected with the Algerian network with two lines of 90 kV, a line 150 kV, two 225 kV lines, a new 400 kV interconnection is underway commissioning. Two 225 kV interconnections with the Libyan network are built and currently not functional. The Tunisian Society of Electricity and Gaz “STEG” uses the power line carrier (PLC) for the needs of electric tele-driving system, currently it generalizes the use of guard cables with fiber optics for its data transmission system, in particular after commissioning the new national dispatching.

During construction and subsequent operation of plants, suitable roads are required so that heavy construction and maintenance machinery can reach the site. The Tunisian road network, as shown in Fig. 7, consists in its entirety of approximately 19,412.6 km roads of which 13,139.8 km paved. In addition, the rail network consists of 2165 km of track of which 1991 km are for all kind of transport and 673 km for freight only. Thus, the transport network covers the majority of Tunisia territory; even the southern regions are accessible.

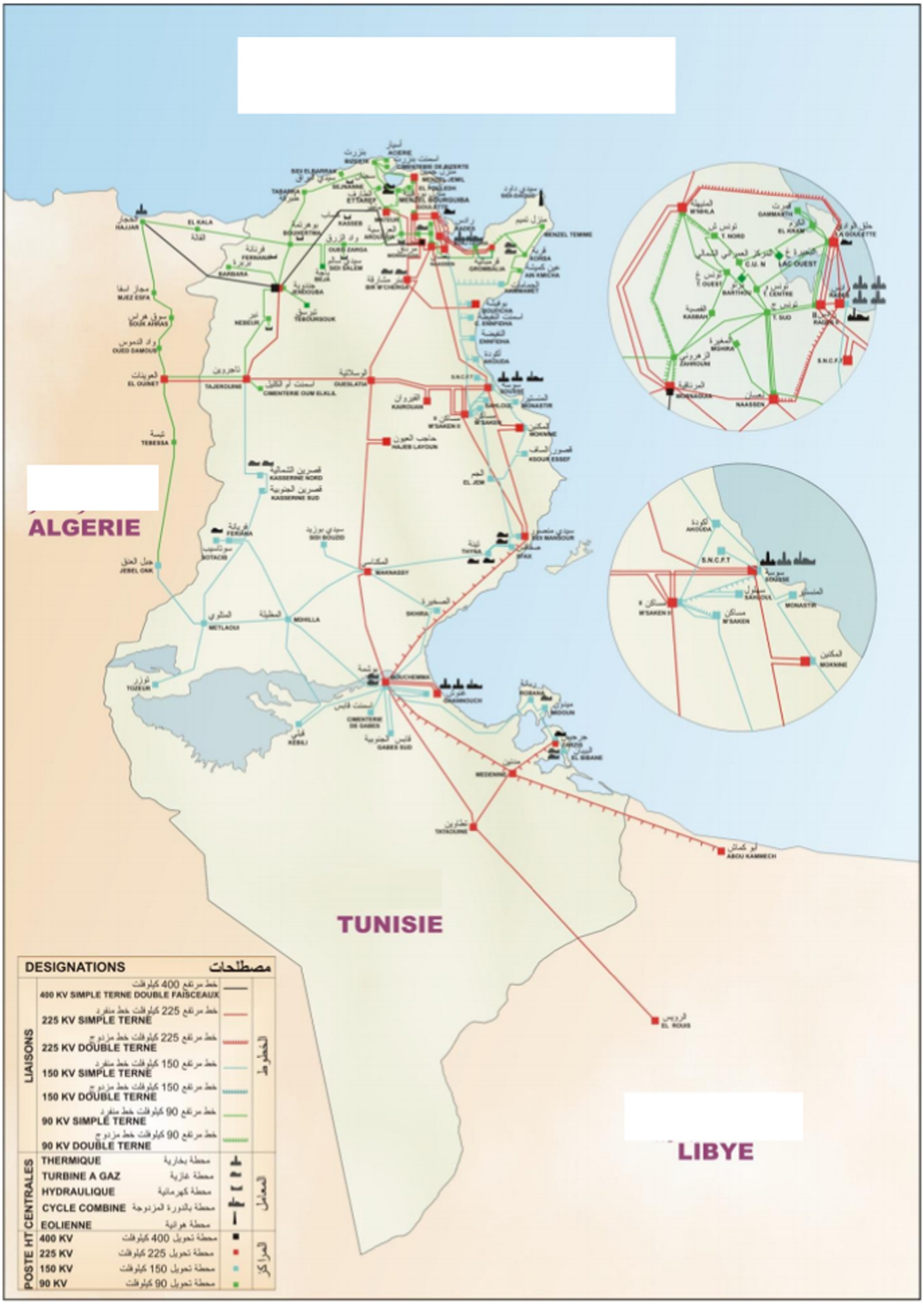

Fig. 6. Network of production and transport of electricity in Tunisia [40].

Moreover, Tunisia has an important port infrastructure formed by more than 10 great seaports spread over 1300 km of coasts from Bizerte in the north to Zarzis in the south. Actually there are 23 shipping lines that connect Tunisia to main Mediterranean ports and allow, among other connections, a daily departure flows to Marseille in France and Genoa in Itally. As for the current status of airport infrastructure is characterized by the presence of 9 international airports distributed over the Tunisian territory.

Fig. 7. Network of roads in Tunisia.

3.4. Water availability

The country has about 4.6 billion m^3 of mobilized water: 60% flows on the surface, 40% are underground but 80% of water resources are located in the north of the country while 70% of groundwater in the south. The country also has ground water to the north and a huge potential constituted by fossil aquifers to the south. Tunisia is equipped with 29 traditional dams, 221 earth dams and 741 mountain lakes, 5200 deep drilling and 130,000 surface drilling. The distribution of drinking water is ensured by the national society of water exploitation and distribution (SONEDE). For remote sites in its network, SONEDE cannot connect to its central water distribution network, in which case the user must obtain permission from the Ministry of Agriculture to carry out the necessary drilling to meet the needs of the facilities industrial water. For the CSP plant, from the total water requirement, 90% of water is for cooling and remaining 10% is for mirror washing and other purposes [55]. Availability of water could be a challenge in some of the arid areas and, if feasible, dry cooling technologies may have to be used at such locations with some compromise on efficiency of power block [44]. For Tunisia, if the CSP plant will be installed in southern regions, it's better to adopt dry and the availability of water will be sufficient for mirror washing and other needs.

3.5. Potential for auxiliary supply

Though CSP systems can be designed as standalone systems, in many situations, arrangement of an auxiliary backup may be necessary [56]. In Tunisia, the total length of crude oil, petroleum and natural gas pipeline network in Tunisia was about 3292 km. Major pipelines in the country include the Trans-mediterranean Pipeline, the Transmed Pipeline (Tunisia Section) and the Gabes-Tunis Pipeline. These pipelines have lengths of 775.00 km, 740.00 km and 319.50 km respectively [40]. In addition, a gas pipeline of 370 km long and 24'' of diameter is actually under construction in the south of Tunisia (Fig. 8). The pipeline's routes crosses four Governorships, Tataouine, Mednine, Kebili and Gabes. The gas pipeline will be used to channel the gases treated at the Nawara concession, in the Tunisian South. These gases will be conveyed via this gas pipeline towards the Gabes treatment station [57]. Therefore, many regions in the center and in the south of Tunisia are well suited to the installation of hybrid CSP plants.

4. Description of the site and the meteorological station of Tataouine (Tunisia)

As part of the valuation and qualification of Tunisian solar sites, several weather stations are being installed, which will allow to obtain more precise estimates of the solar resources. A weather station has been installed as part of the cooperation between the research center of Energy in Tunisia CRTEn and DLR German Aerospace Center in the framework of enerMENA project. The station currently allows the collection of solar radiations data and whether parameters in the Tataouine region a southeastern city of Tunisia (Table 1) located at 531 km from the capital Tunis (Fig. 9). It is bounded by the governorates of Kebili and Medenine to the north, by Libya to the east and by Algeria to the west. It has significant solar resources with direct irradiation index 6 $kWh/m^2/day$. The average temperature is 22° C and the annual rainfall varies between 88 and 157 mm.

The installed meteorological station is a network of high-precision for solar resources measurements. It is based on a "SOLYS 2" two-axis sun tracker which is a positioning platform used to point specialized instruments at the sun's movement across the sky. An integrated Global Positioning System "GPS" receiver automatically configures location and time data. The sun tracker provides a stable mounting for the pyrheliometer and moves horizontally (azimuth) and vertically (zenith) to follow the solar arc. Stepping motors controlled by a micro-processor drive through belts or gears to provide movement with the desired torque and accuracy. An on-board program requires accurate longitude, latitude, altitude, date, and time information for the measurement site. It then calculates the current position of the sun and points the pyrheliometer and shading assembly towards it [58]. The weather station has the following facilities:

- Two Kipp & Zonen pyrheliometers to measure the direct normal irradiation (DNI).
- A pyranometer for measuring global horizontal radiation (GHI).
- A pyranometer associated to a shading device to measure the diffuse horizontal radiation (DHI).
- Hygrometers to measure the relative and the absolute humidity.
- Sensors to measure the ambient temperature.
- Anemometers to measure wind speed and indicate its direction.
- Pressure sensors.

The data delivered by the station (Fig. 10) are sent every day to the Center of Research and Technologies of Energy in Borj Cedria Tunisia "CRTEn" and to the German Aerospace Research Center DLR" via Internet. The obtained meteorological data are bilaterally shared and jointly analyzed with project partners. Moreover, the data is available for all parties working on CSP related R&D activities in the region. It can be used also for the preparation of feasibility studies, project performance calculations, support of project financing and solar power plant operation monitoring.

4.1. Exploring of meteorological solar data delivered by the station of Tataouine relatively to CSP fields running

The station is used to deliver specific data relating to solar radiation as the direct normal radiation DNI, the diffuse and global horizontal radiation and meteorological data such as ambient temperature, pressure, wind speed and humidity. These parameters are determinant for the operating of CSP fields. The efficiency of a solar power plant depends a lot on the intensity of direct solar radiation (DNI) and climatic factors which may influence the DNI such as humidity, wind speed must be considered. Also factors such as temperature and wind speed can influence the heat loss especially at the receivers (vacuum tube for example).

As an example, the intensity of the direct solar radiation should be more than 700 W/m² value used for nominal power from solar thermal collectors in official statistics.

In this section, four representative and typical weeks were selected, one from each season, to analyze the evolutions of the weather conditions and theirs sustainability for the operating of CSP fields such as the direct solar radiation, the ambient temperature, the humidity and the wind speed.

During the winter week (Fig. 11), the direct normal radiation has exceeded the value of 700 W/m^2 for only four days from seven. As the field of solar concentrators requires direct solar radiation above 700 W/m^2 to operate the solar loop, the use of solar energy will be limited to four days in the week. The ambient temperature varied between 5 and 25 °C, these low values have a great influence on the performance of solar power plants and in particular the performance of absorber tubes or solar receiver. The wind speed exceeded the value of 5 m/s for

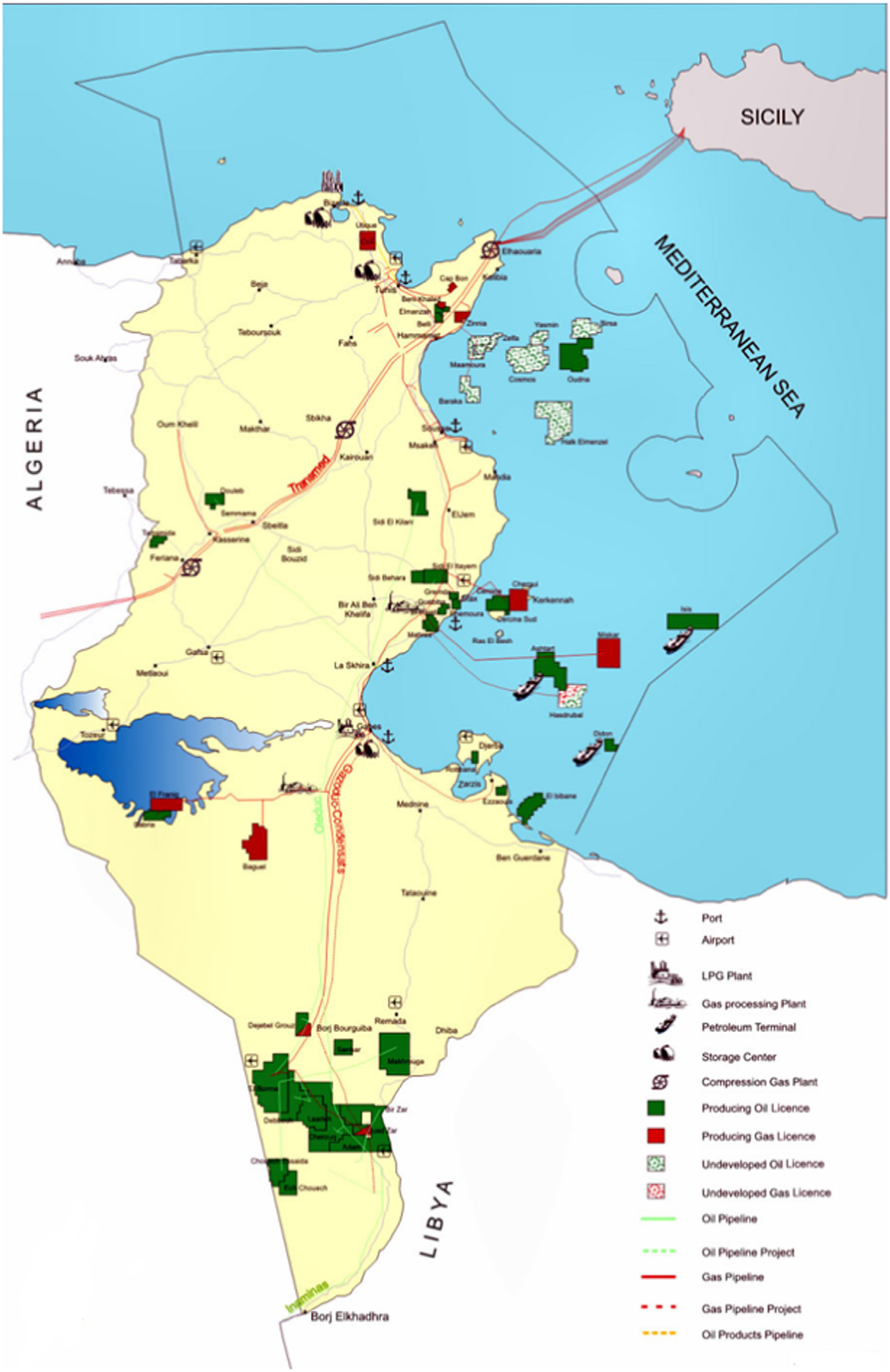

Fig. 8. Tunisian oil and gas production and transport Infrastructure.

5 days and it exceeded 9 m/s for 2 days. The wind speed has remained around a value of 5 m/s for 5 days except that in two days, it has had an increase in a value between 9 m/s and 15 m/s. These values remain acceptable for the running of a solar power plant in terms of stability of the collector's structures.

During the week of spring (Fig. 12), the direct normal radiation has exceeded the value of 700 W/m^2 for 5 days. Ambient temperature ranged between 20 and 30 °C and the wind speed has exceeded the value of 5 m/s for 5 days with a maximum value of 10 m/s.

In the summer week (Fig. 13), the direct normal radiation has exceeded the value of 700 W/m^2 for all days. The ambient temperature ranged between 10 and 35 °C and the wind speed was below the value of 5 m/s during the majority of the time.

Table 1
Characteristics of the site of Tataouine.

Site name	Tataouine (Tunisie)
Latitude	32.9741°N
Longitude	10.48513°E
Altitude	210 m
Time zone	1 (UTC+1 h)
Area	38,889 km^2
DNI	2,170,871 W/m^2

During the autumn week (Fig. 14), the direct normal radiation has exceeded the value of 700 W/m^2 for 5 days. The ambient temperature varied between 10 and 29 °C and the wind speed exceeded the value of 5 m/s for 4 days with a maximum value of about 9 m/s. In addition, this period is characterized by a strong non-linear behavior of the DNI daily curve where small forecast errors result in large errors in hourly DNI values.

Fig. 15 shows the variations of the relative humidity during the four representative weeks. We note that the humidity rises at night and decrease during the daytime. The higher values are recorded during the winter and the lower values are attempted in the summer week. During the daytimes, the relative humidity was between 15% and 50% during the four weeks. These relatively low values are appropriate for the operating of the CSP field.

Figs. 11–14 show that weather conditions are suitable in the summer for the operation of solar power plants, they are acceptable during the spring and autumn while the use of solar energy is minimal during the winter season.

According to Fig. 15, we notice that the relative humidity is low enough during the day during almost the entire year, which is an important support for the site to be considered as a suitable area for installation of solar fields concentration 'CSP'.

Fig. 9. Position of the Tataouine site on the map of Tunisia.

Fig. 10. Photos of the solar meteorological station installed in Tataoine in the south of Tunisia.

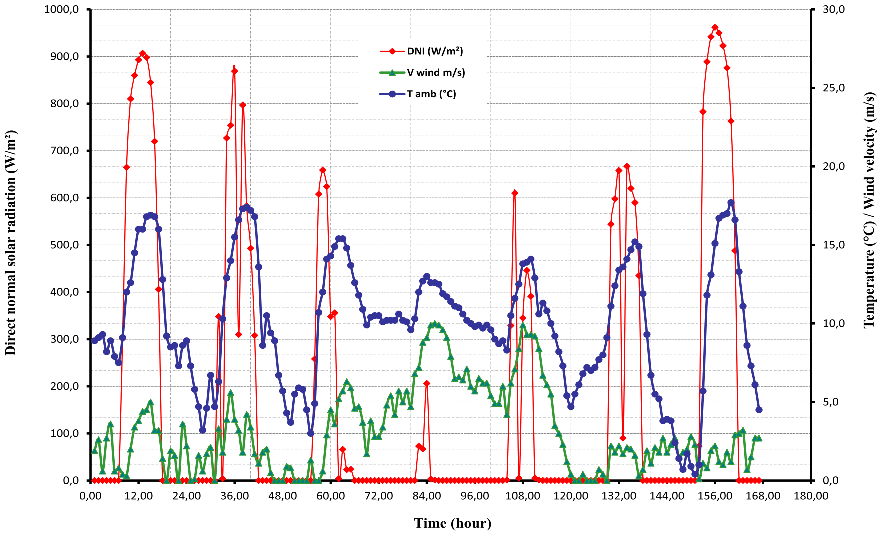

Fig. 11. Evolutions of the direct normal solar radiation, the ambient temperature and the wind velocity during one representative week of winter in the Tataouine station in Tunisia.

5. Simulation of a solar power plant at the site of Tataouine in the south of Tunisia

5.1. Current status of CSP technology deployment

By 2013 the operational CSP capacity reached 3631 MW and there is 1307 MW under construction according to the NREL (US National Renewable Energy Laboratory) [59]. Fig. 16 shows the distribution of these capacities by technology and by magnitude of the electric power of the CSP plants. One can notice that the most adopted technology is parabolic trough with 76.6% then the Tower by 15.3% and with Fresnell with 8.1%. Moreover, most of the CSP plants have a capacity of 50 MW. Even, in the same location we can found 3 or 4 plant with same capacity of 50 MW like Andasol 1 to 3 or Extresol 1 to 3. After this analysis, we chose to simulate a parabolic trough plant with a capacity of 50 MW under the conditions of the south of Tunisia. The technical parameters of the Andasol-1 plant installed in Spain were used.

The solar field consists of north–south aligned parabolic trough loops with a thermal oil flow which temperature is about 293 °C at the inlet and 393 °C at the outlet (Fig. 17). The size of the solar field is selected such that with good weather conditions (high DNI, low wind and low incidence angle) nominal electric power is generated and the thermal storage is charged with full thermal load. For the design conditions in the south of Spain this requires a solar field with an aperture of 510,120 m^2 or 624 collector assemblies of

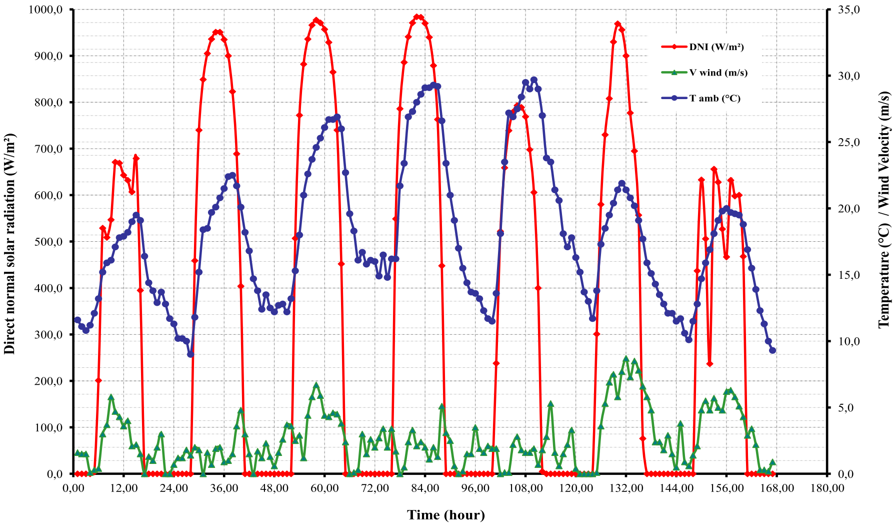

Fig. 12. Evolutions of the direct normal solar radiation, the ambient temperature and the wind velocity during one representative week of spring in the Tataouine station in Tunisia.

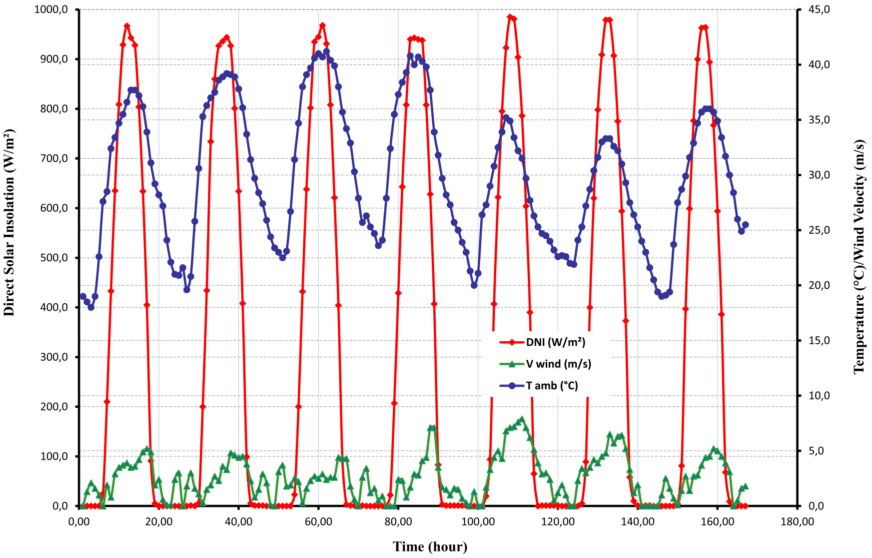

Fig. 13. Evolutions of the direct normal solar radiation, the ambient temperature and the wind velocity during one representative week of summer in the Tataouine station in Tunisia.

150 m length and 5.7 m aperture width each. Technical specifications of the modeled solar plant are summarized in Table 2 [43,60].

5.2. Exploration of the solar plant simulation results

To study the variations of different flows and powers that come into play during the operation of the simulated solar power plant, we chose two representative days from each season. The monthly and yearly performances were also discussed.

The considered amounts of energy at various stages of the solar plant are

- Hdn: the intensity of direct solar radiation DNI multiplied by the apparent surface of the reflectors. This value can be interpreted as the solar energy available for the solar collectors.
- Qabs: amount of heat absorbed by the vacuum tubes receiver.
- Qcol: amount of heat at the output of the collectors (Qabs-thermal losses in absorbers).
- Qfeild: amount of heat at the output of solar concentrators field (Qcol-heat loss from pipes).
- Qout: amount of heat available for the production of steam.
- DQ storage: variation of the heat stored quantity.

Wel s: Net electric power obtained from solar energy only.

During the summer representative days (Fig. 18.), the energy available at the apparent concentrator area Hdn reaches the value of 350 MWh at 9:30 am. The maximum value obtained at noon was about 430 MWh. At 20:00 after sunset, the available solar energy vanishes. The amount of heat absorbed by the evacuated tube Qabs was about 230 MWh at 9:30 h, then rushes a maximum of 300 MWh around noon and vanishes at 20:00 h. The heat that will be used for the production of steam at the boiler Qout varied from 200 MWh at 8: 30 am to 270 MWh at noon. The net electricity production began at 8: 30 h in the morning then from 9:00 pm until 20:00 h it remains almost constant at the value of 45 MWhe. From 21:00 h the electricity production drops by 10 MWhe to stabilize around the value of 35 MWhe during 7 h and then stops. In that case, the solar power plant produces electricity in full mode (45 MWhe) during 11 h and in average mode during 8 h (35 MWhe). The average regime corresponds to the production from the storage tanks that can guarantee 8 h of power bloc

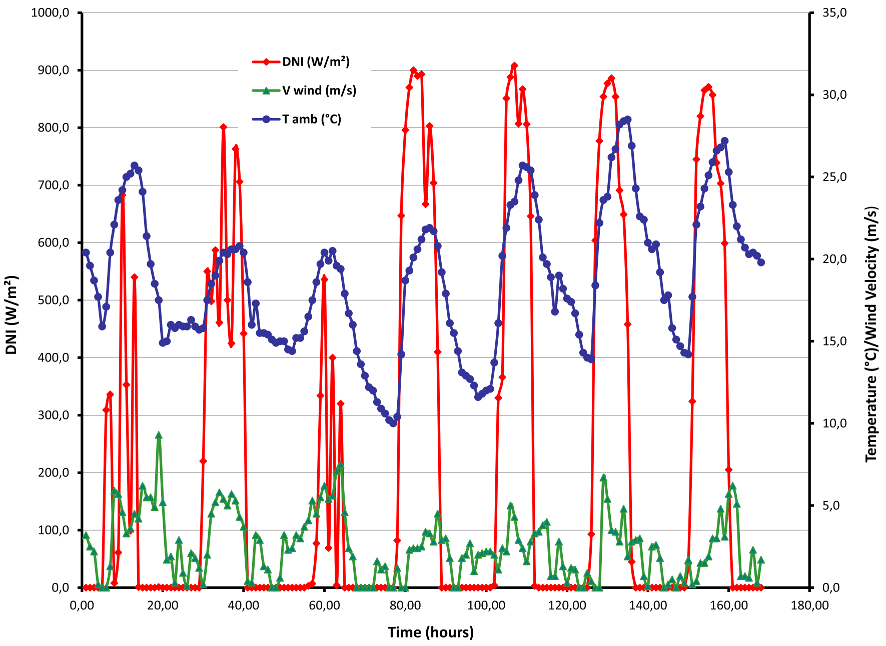

Fig. 14. Evolutions of the direct normal solar radiation, the ambient temperature and the wind velocity during one representative week of autumn in the Tataouine station in Tunisia.

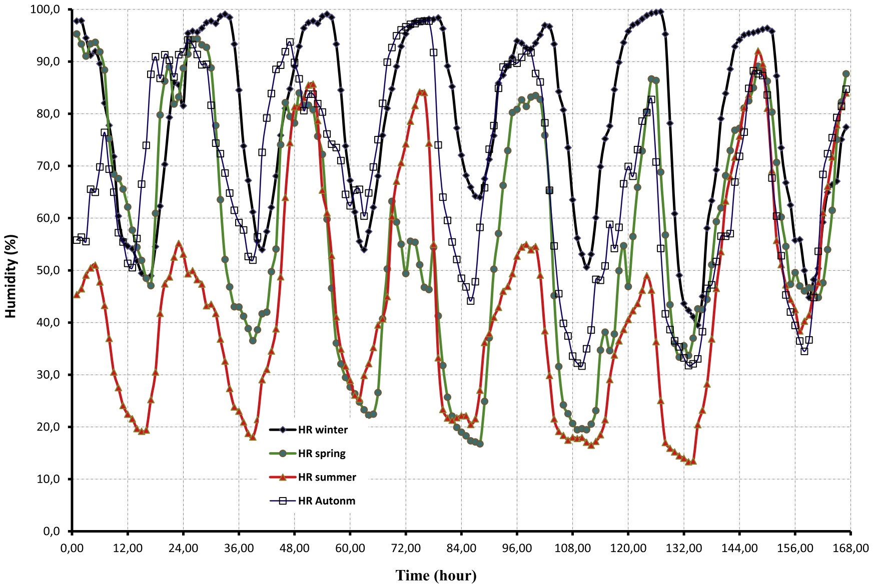

Fig. 15. Evolutions of the relative air humidity during four representative weeks from winter, spring, summer and autumn.

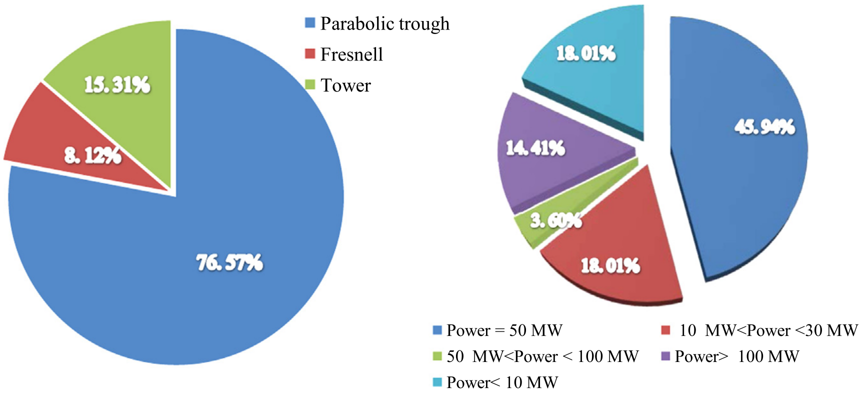

Fig. 16. Distribution of the worldwide installed CSP capacities (operational and under construction) by technology and by magnitude of the electric power block.

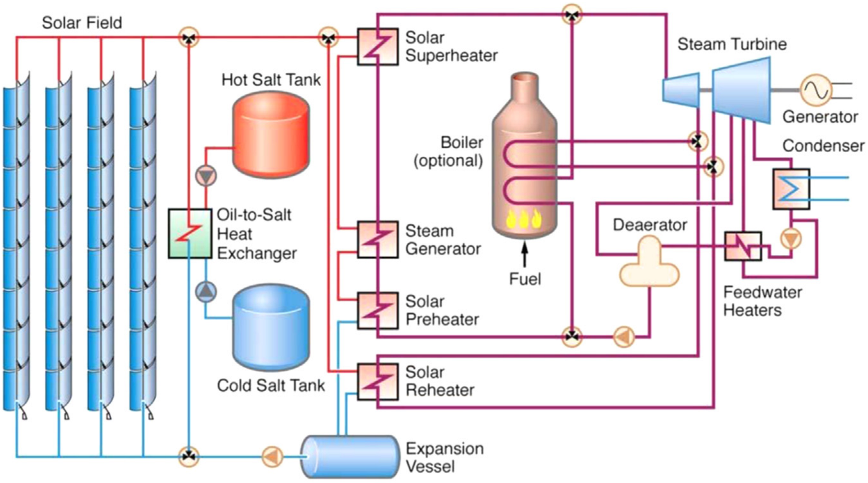

Fig. 17. Scheme of the simulated CSP plant.

Table 2
Technical data of the reference plant.

Designation	Value or intensity with the corresponding unit
Nominal capacity	50 MW
Overall area of the field (land use)	190 ha
Aperture area of the solar reflectors	510,120 m^2
Length of one collectors	148.5 m
Aperture width of a collector	5.77 m
Focal length	1.7 m
Absorber tube diameter	0.0655 m
Raw spacing	17.3 m
Distance between collectors	1 m
Number of raw in the field	156
Optical peak efficiency	0.75
Heat loss factor from piping	15 W/m
HTF temperature at field entrance	293 °C
HTF temperature at field exit	393 °C
Pipe length in loops	6807 m
Pipe diameter in loops	0.0525 m
Storage capacity	95,000 MWh_{th}
Full load storage hours	7.5 h
Loss per hour from the storage system	395.8 KWh
Relative losses in 24 h from the storage system	1%

running after sunset. The quantities of Qcol heat, Qfield, Qout, vary simultaneously from 7:00 am to 19: 30 h. They reach maximum values at 13: 00 pm. During periods that present an important DNI (between 9: 00 am and 15: 00 h), the differences between these three variables was of the about 15 MWh. These differences are caused by the thermal losses through the HTF pipes. The curve of the heat stored dQstorage shows the phases of charging and discharging of the storage system. dQstorage was positive when the solar field provided power to the storage system during the day when sunlight is sufficient. It was negative during the discharge phase when the storage tank provided power to the boiler to produce steam. The discharge period lasts from 20:00 h to 4:00 h of the following day in the morning during which the variation of dQstorage was 100 MWh. Thus, the storage system extends the operation of the plant 8 h after sunset.

During the days of spring (Fig. 19.), the energy available at the solar collectors Hdn reached the value of 410 MWh around noon. This value becomes zero at 19.30 h after sunset. The amount of heat absorbed by the evacuated tubes Qabs was about 240 MWh at 13:00 pm and was canceled at 19.30 h. The heat that will be used for the production of steam Qout reaches a maximum value of 200 MWh to 13: 00 AM. The production of electricity starts around 10 am and remains almost constant at the value of 45 MWhe up to 19:00 h and then it drops to the value of 32 MWhe and remains constant until midnight (00:00) then vanishes. Thus, the solar power plant produces electricity in full power mode during 9 h and in an average mode from the storage system during 4 h.

During autumn days (Fig. 20.), the energy available at the apparent solar collectors reaches its maximum of 420 MWh around noon. The overall behavior is similar to that of the Spring. The solar power plant produces electricity in full regime (45 MWhe) during 9 h and the storage system provides electricity production for 6 h in the medium mode.

During the winter (Fig. 21), we noticed random drops in the curves of Hdn. These falls have influenced the thermal and electrical profitability of the solar plant. Adverse weather conditions (the presence of wind and cloudiness) are at the origin of these disturbances. Although the maximum values of Hdn are recorded near noon (from 11:00 to 15:00), we see a decrease in amounts of heat Qabs, Qcol, Qfield and Qout. Similarly electricity generation decreases slightly during this period. This decrease may be caused by the south–north orientation of the collectors in addition to the low solar incidence angle during the winter.

During the first day, although the curve of Hdn shows no disturbance, the production of electricity does not exceed 6 h. The electricity generation time is further reduced if the Hdn curve exhibits disturbances such as the case of the second day. In addition, we note that the stored quantity is very low, which does not allow the storage system to generate electricity after sunset.

5.3. *Electric energy output*

The net power production which is the final electrical power that is ready to be fed to the grid is shown in Fig. 22. The high production corresponds to the summer months in addition to two months from spring and one from autumn. The electricity productions were more than 1000 MWhe from April to September. The low production correspond to the months of winter (December, January and Febrary). This was caused by the solar resource availability for the parabolic trough which exhibits a strong seasonal dependence. Beside weather conditions, the solar resource availability is dependent relative to the seasonal “cosine” effect due to low sun elevation angle in winter, which is more pronounced for single-axis tracking parabolic trough collectors' configurations.

The annual performance data of the simulated solar plant in the region of Tataouine at the south of Tunisia are presented in Table 3. The annul electricity that the plant could sold to the grid

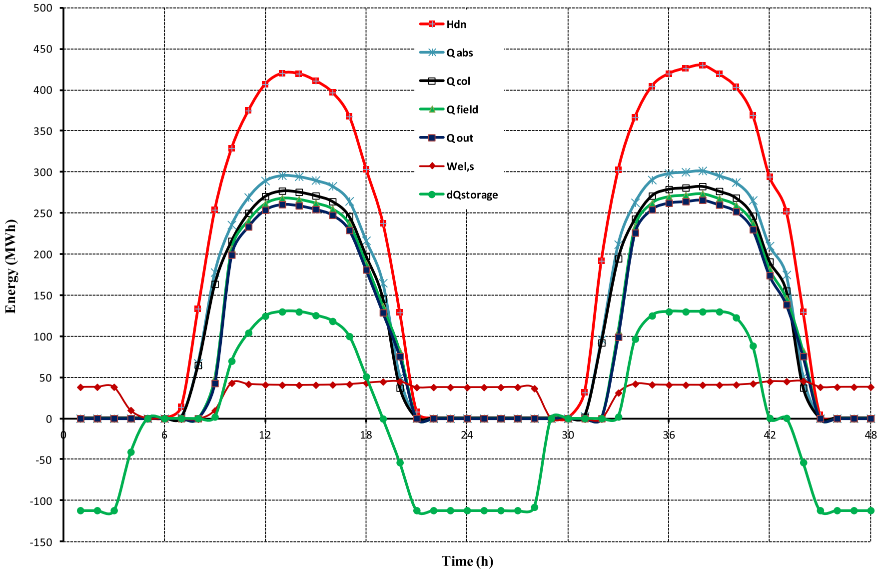

Fig. 18. The considered amounts of energy at various stages of the solar plant during two representative days from Summer: Hdn: solar energy available for the solar collectors. Qabs: amount of heat absorbed by the vacuum tubes receiver. Qcol: amount of heat at the output of the collectors. Qfeild: amount of heat at the output of solar concentrators' field. Qout: amount of heat available for the production of steam. DQ storage: variation of the heat stored quantity. Wel s: Net electric power obtained from solar energy.

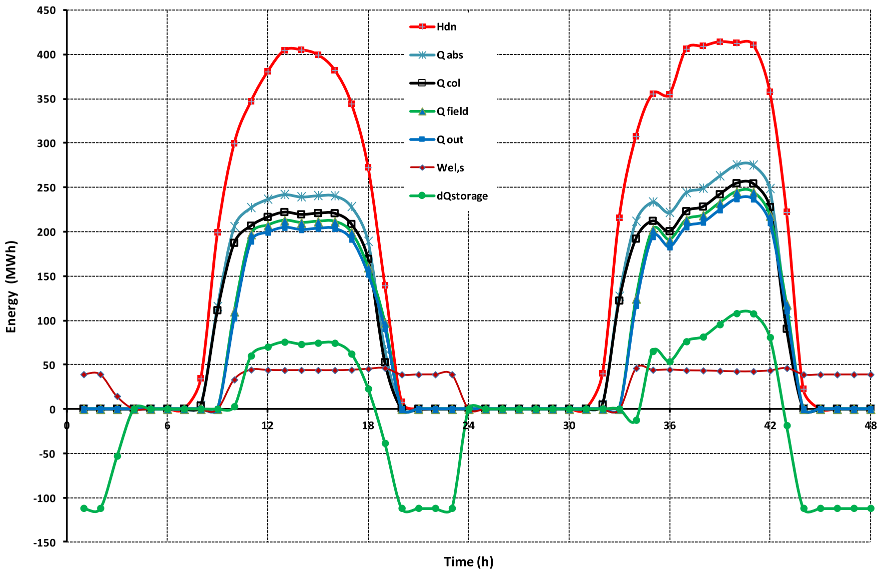

Fig. 19. The considered amounts of energy at various stages of the solar plant during two representative days from Spring: Hdn: solar energy available for the solar collectors. Qabs: amount of heat absorbed by the vacuum tubes receiver. Qcol: amount of heat at the output of the collectors. Qfeild: amount of heat at the output of solar concentrators' field. Qout: amount of heat available for the production of steam. DQ storage: variation of the heat stored quantity. Wel s: Net electric power obtained from solar energy.

was about 114,219 MWhe. The mean thermal efficiency of the plant was 39% and average value of the solar to electric conversion efficiency was about 15%. The number of the full load running hours was 2548 h while the number of hours corresponding to the operations at medium regime from the storage system was 1024 h. Moreover, the prevented CO_2 emissions was about 78,811,110 kg/year if a concentrated solar plant is used instead of an equivalent fossil fuel thermal electric plant.

5.4. Comparison with Andasol-1 and other CSP plants with similar capacity

A comparison of the simulated plant of Tataouine in the south of Tunisia with the Andasol plant in Spain was performed. On the histogram of Fig. 23, we have illustrated the monthly changes and the annual output of solar power in both regions Andasol (Spain) and Tataouine (Tunisia). We note that electricity production of Andasol plant is more important than that of the simulated solar plant of Tataouine during only the two months of April and June. However, the total annual production of electricity generated from the simulated field of Tataouine exceeds that of the plant of Andasol in Spain by an amount of 1793 MWhe. Even, from the histograms of the figure (Fig. 24), the number of running hours in full load and in medium regime, corresponding to the operation from the storage system, was more important in case of Tataouine simulated plant except for the two months of April and June. In Fig. 25, the monthly number of hours with intensity of the direct solar irradiation DNI more than the value of 700 W/m^2, recommended for the running of the concentrated solar plant, was considered. As expected, this number was more important during

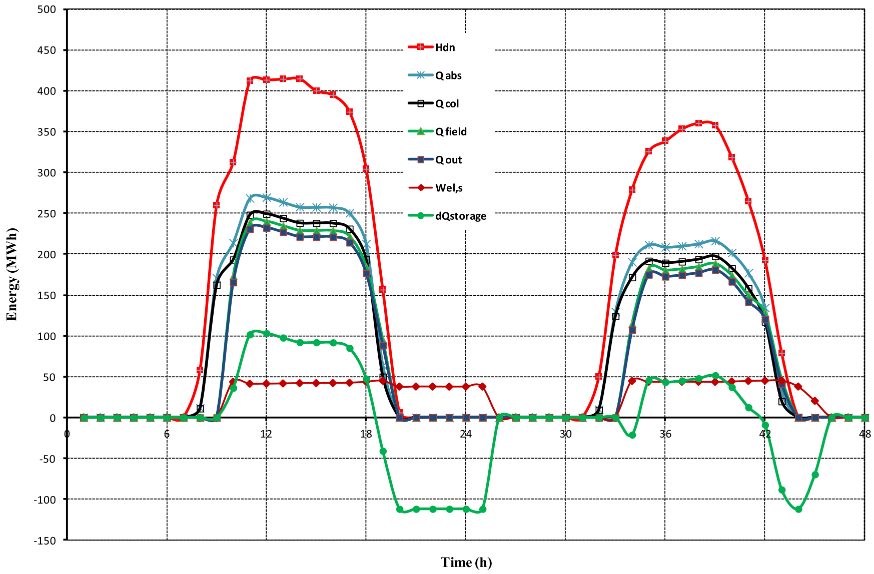

Fig. 20. The considered amounts of energy at various stages of the solar plant during two representative days from Autumn: Hdn: solar energy available for the solar collectors. Qabs: amount of heat absorbed by the vacuum tubes receiver. Qcol: amount of heat at the output of the collectors. Qfeild: amount of heat at the output of solar concentrators' field. Qout: amount of heat available for the production of steam. DQ storage: variation of the heat stored quantity. Wel s: Net electric power obtained from solar energy.

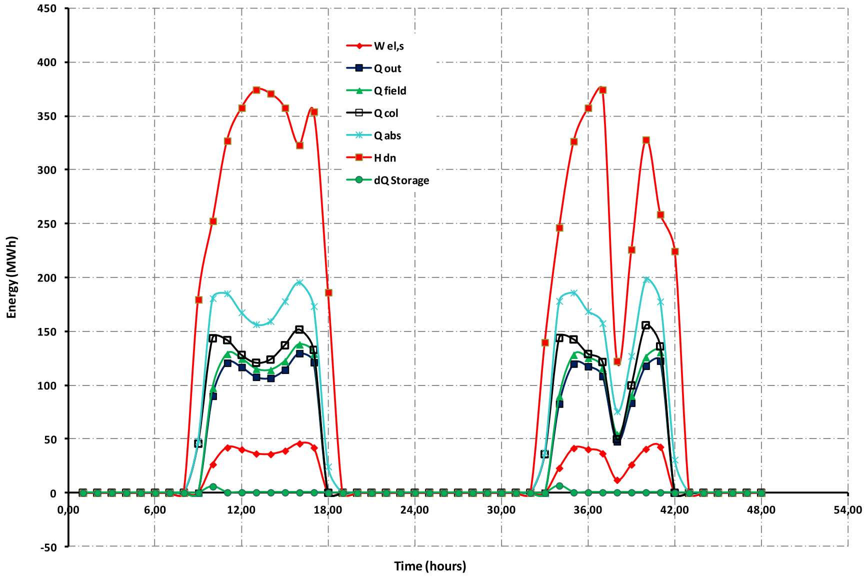

Fig. 21. The considered amounts of energy at various stages of the solar plant during two representative days from Winter: Hdn: solar energy available for the solar collectors. Qabs: amount of heat absorbed by the vacuum tubes receiver. Qcol: amount of heat at the output of the collectors. Qfeild: amount of heat at the output of solar concentrators' field. Qout: amount of heat available for the production of steam. DQ storage: variation of the heat stored quantity. Wel s: Net electric power obtained from solar energy.

the entire year except for the two month of April and June. Due to the location of Tataouine region which constitute a pre-Saharan area, the DNI in months of April and June is influenced by the occurrence of winds accompanied by sandstorms. Theses winds causing soiling and dust occurs generally in the region in this period corresponding to the transition between the spring and summer seasons. Despite its influence on the DNI, which is not very important, the effects of dust and soiling on the components of the solar concentrator field such as mirrors and absorber tubes must be studied before the installation of solar fields in southern Tunisia. The overall thermal and electrical efficiencies for the two plants are shown in Fig. 26. The thermal and the electrical efficiencies of the Andasol plant were more important than that of the simulated solar plant of Tataouine during only the two months of April and June. The maximum overall thermal and electrical efficiencies were respectively 55% and 18% for Tataouine plan, while theses values were 52% and 16% for the Andasol plant and occurred during the month of June.

Table 4 gives the basic data of some CSP plants with equivalent capacity of 50 MW and using the Parabolic Trough technology [61]. The Puertollano and the Solnova 1 to 3 plants have less yearly expected electricity generation than the other plants. However, these plants have better overall efficiency (18.8%) because they use less solar field aperture area (less mirrors). The Solnova plants use only about 58% of the mirrors used by the Andasol plants. The simulated plant of Tataouine in Tunisia uses the same technical parameters and the same aperture area of the Andasol-1 plant. As given in Table 3, its yearly electricity production with 160,219 MWhe is in the third rank after La Dehesa and La Florida plants. Nevertheless, the overall efficiency of 15% is better than the

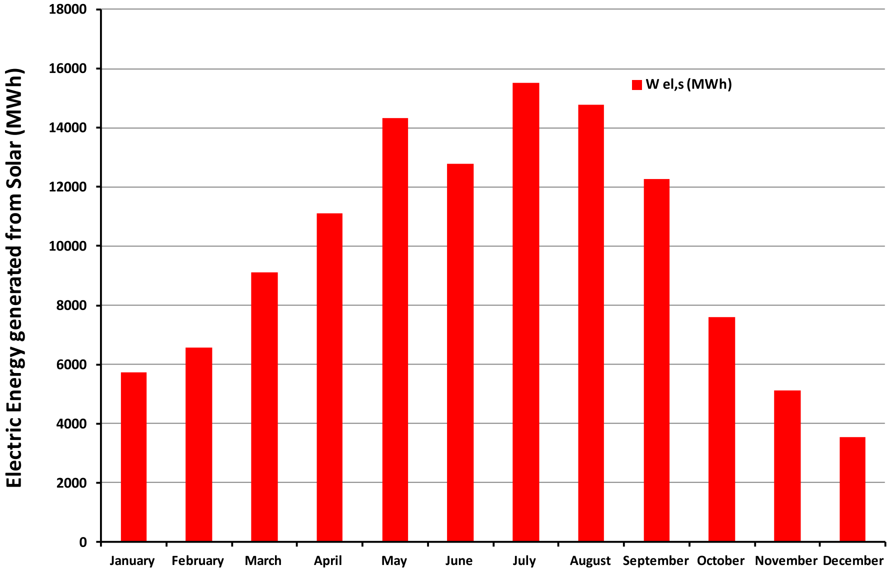

Fig. 22. Monthly electrical net power generated from the simulated CSP plant in Tataouine in the south of Tunisia.

Table 3
Annual performance data of simulated solar plant in Tataouine Tunisia.

Description	Value
Annual solar irradiation on the field	1,048,488 MWh
Thermal efficiency	Peak 67% Annual 39%
Annual electricity sold to the Grid	160,219 MWhe
Solar to electric efficiency	Peak 22% Annual 15%
Full load hours	2548 h
Operation from the storage	1024 h
CO_2 savings compared to fuel plant	78,811,110 kg/year

Andasol 1-3, the Extresol 1-2 and Palma del Rio II and less than the efficiencies of the Puertollano and the Solnova 1 to 3 plants.

6. Economic study

The economic study aims to determine the intrinsic profitability of a project regardless of its financing. It allows the planner to schedule its solar project and to have an overall idea about the possible constraints to minimize the risks. It is generally difficult to give an overview on investment costs of solar thermal power plants. First, as the study of [62] shows the literature data strongly depend on the chosen technology and specific configuration of the analyzed plant. In addition, the economic parameters of the plants are often deduced from information from the solar thermal industry and not of independent sources. Even more difficult is the assessment of costs in the future. Unlike the photovoltaic industry or the wind, the application the concept of learning curves to determine the future costs of power plants remains problematic for solar thermal because the growth of this market is always difficult to predict.

The economic feasibility of an electricity generation project can be evaluated by various methods, but the LCOE is the most frequently used when comparing electricity generation technologies or considering grid parities for emerging technologies [63]. LCOE calculates the cost of solar electricity during the whole lifetime of the systems. The levelized cost of energy is the cost of electricity generated considering several aspects. It includes the initial capital, discount rate, as well as the costs of continuous operation, fuel, and maintenance [64]. In this work, we will use the formula used for calculating the LCOE of renewable energy technologies proposed by IRENA [65]:

$$LCOE = \frac{\sum_{t=1}^{t=n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{t=n} \frac{E_t}{(1+r)^t}} \tag{1}$$

$$E_t = E_0\left(1 - \frac{DR}{100}\right) \tag{2}$$

where

- *LCOE*: the average lifetime levelised cost of electricity generation.
- I_t: investment expenditures in the year t which includes the following costs: land cost, solar thermal collector system, thermal energy storage, power block system, labor cost, road construction, connection transmission line, substation. The investment costs of CSP systems in range between 4.2 USD/W and 9 USD/W [66]. In this work we use the average value to estimate the LCOE.
- M_t: operations and maintenance expenditures in the year t; the operation costs of CSP systems are relatively low. However, in this work, supplementary costs related to the effect of geographic and climatic desertic conditions such as soiling and dust are considered. An annual O&M cost of 3% of the investment cost is used instead of 2% proposed by Hernández-Moro et al. [67].
- F_t: fuel expenditures in the year t; generally negligible for most of renewable power plant.
- E_t: electricity generation in the year t.
- E_0: electricity produced in the first year of the installation, 160,219 MWh.
- r: discount rate; 10% [66].
- n: life of the system. In this study we consider a lifetime of 25 years.
- DR = Degradation factor: for CSP systems, an annual output drop of 0.2% has been considered [67] mainly as a result of the degradation of the turbines.

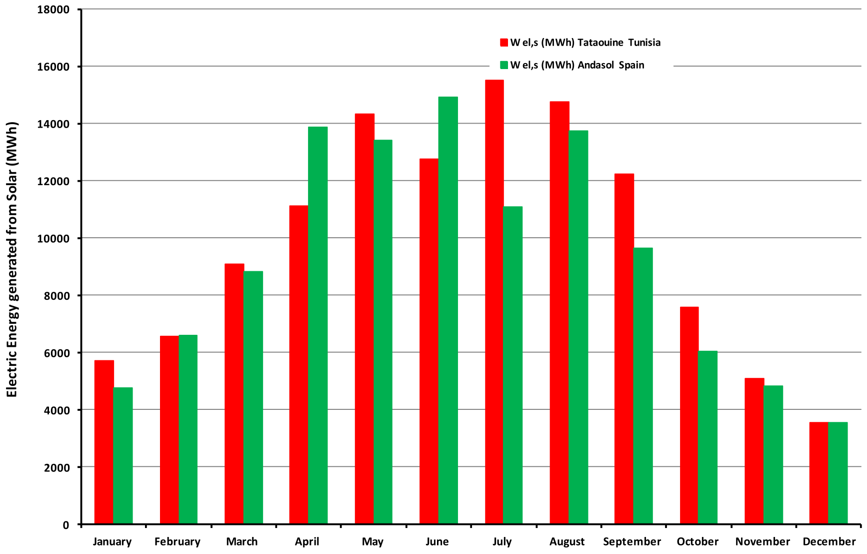

Fig. 23. Monthly electrical net power generated from the two simulated CSP plants: Tataouine in Tunisia and Andasol in Spain.

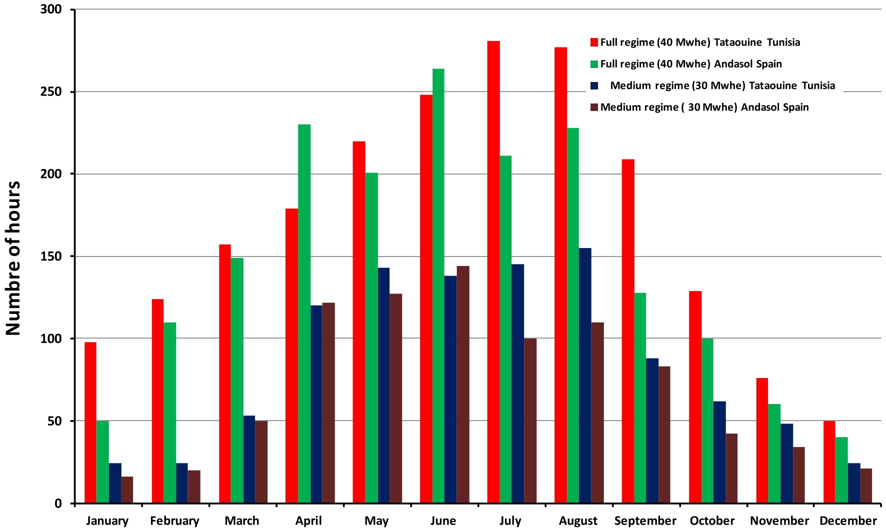

Fig. 24. Distribution of the number of running hours at full load and medium regime from the storage for the plant Andasol in Spain and the simulated solar plant in Tataouine in the south of Tunisia.

The LCOE of the proposed power plant is estimated to 0.23 €/kWh. However, the total investment cost of the proposed power plant is estimated to 261.25 million €. Beside, this economic study refers to the values published by [68], a one recent publication dedicated to the cost of solar thermal power plants in Tunisia. Table 4, gives a comparison between the costs of the simulated plan at the Tataouine site in Tunisia and the reference plan Andasol in Spain. The direct cost of the major components is calculated based on land area, power rate, thermal storage size, and field collection area. The indirect cost is derived from the direct cost.

We noticed that the total investment cost is more important in the case of Tataouine station in Tunisia. The advantage of Tataouine site compared to that of Andasol is that the price of land (desert) is very small (about 0.057 Euro/m²). However, the cost of installation in the site of Tataouine is higher than that of Spain. The increase in cost is caused essentially to the amount of transportation as the equipment will be imported. In addition to the actual price of electricity from fossil resources is less important in Tunisia which increases the damping time of the project. Moreover, there isn't any legislation or procedure by the Tunisian government to account the cost of the reduction of CO2 emission and the environment benefits when renewable energies like CSP plants are used.

A concentrated solar project becomes economically competitive in Tunisia when the price of fossil electricity increases. Even the majority of the plant components such the collectors structure and supports, the mirrors and the storage system should be manufactured locally in Tunisia to minimize the transport fees and by the way create jobs and enhances the local industry to investigate in this field.

7. Conclusions

This study was done in the framework of the enerMENA project which aims to prepare the ground towards a sustainable realization of CSP power plants in the North Africa and Middle-East countries. Therefore, in this paper, the potentials of solar resources and the suitable factors for the deployment of CSP in Tunisia were presented. In addition, solar radiations data and weather parameters values delivered by a specific network of solar radiation and weather data installed in the framework of enerMENA project in the Tataouine region at the south of Tunisia, were discussed

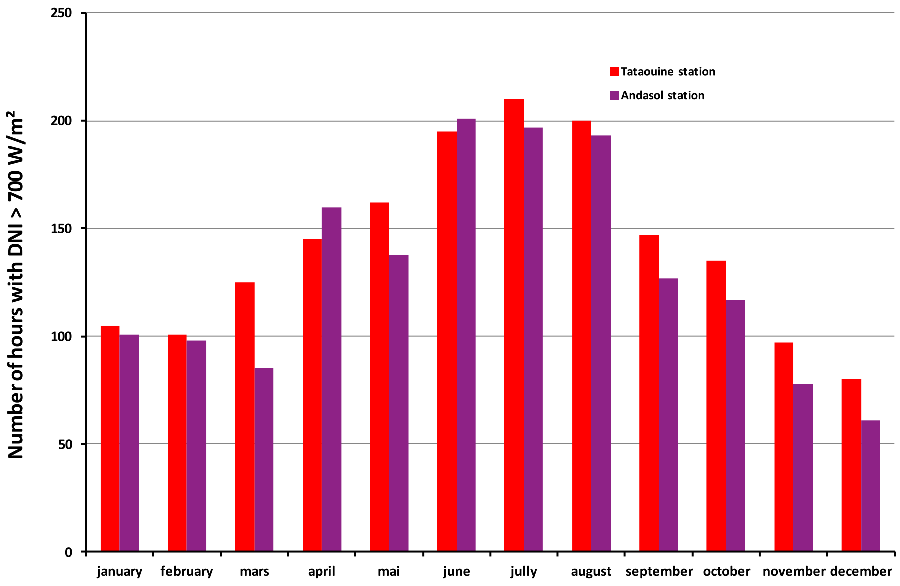

Fig. 25. Monthly number of hours with DNI > 700 W/m², suitable for running CSP plants at the meteorological stations, Tataouine in Tunisia and Andasol in Spain.

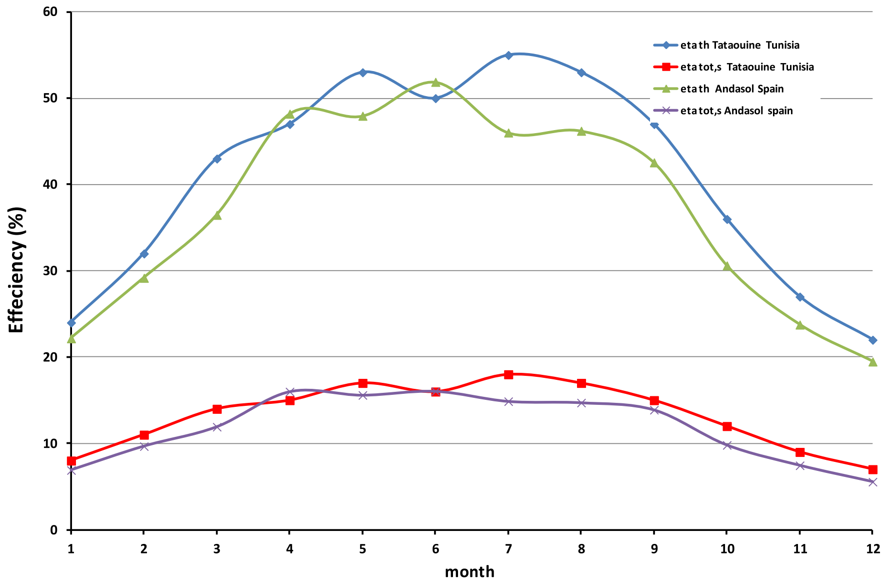

Fig. 26. Overall thermal and electrical efficiencies of the two plants Tataouine in Tunisia and Andasol in Spain.

from the angle of fitting with CSP technology. Besides, a simulation of 50 MW parabolic trough solar power plant based on the solar radiation and climatic data delivered by the installed station, were performed for the Tatouine site in the south of Tunisia. The results prove that Tunisia has very important solar resources suitable for the CSP deployment such as the direct solar radiation DNI. In addition, given its proximity to Italy, Tunisia is in an ideal position to transfer electricity produced by CSP plants in North Africa and contribute to the achievement of the objectives of the European Community for renewable energy penetration. Moreover, the data delivered by a network of high-precision for solar resources measurements installed in Tataouine in the south of Tunisia, shows that weather conditions are suitable in the summer for the operation of solar power plants, they are acceptable during the spring and autumn while the use of solar energy is minimal during the winter season. The simulation of a 50 MW CSP plant in the region of Tataouine shows that the annul electricity that the plant could sold to the grid was about 114,219 MWhe. The mean thermal

Table 4
Data on sum operational parabolic trough power plants with 50 MW capacities.

Plant name	Incident solar energy (KWh/m²/year)	Land area (acres)	Solar field aperture area (m²)	Electricity generation expected (MWh/year)	Overall effeciency (%)
Andasol I	2136	494	510,120	158,000	14.5
Andasol III	2136	494	510,120	158,000	14.5
Extresol-1	2168	494	510,120	158,000	14.2
Extresol-2	2168	494	510,120	158,000	14.2
La Dehesa	–	–	552,750	175,000	–
La Florida	–	–	552,750	175,000	–
Alvarado I	2174	334	–	105,200	–
Manchasol 1	2208	494	510,120	158,000	–
Palma del Rio II	2291	–	–	114,500	14.0
Puertollano	2061	371	287,760	103,000	17.3
Solnova 1	2012	–	300,000	113,520	18.8
Solnova 3	2012	–	300,000	113,520	18.8
Solnova 4	2012	–	300,000	113,520	18.8

Table 5
Costs of the simulated plan at the Tataouine site in Tunisia and the reference plan Andasol in Spain.

	Andasol plant	Tataouine simulated plant
Total investment costs (IC)	238,697,620€	261,250,000€
Major component cost	178,000,000€	187,500,000€
Operation period	25 yrs	25 yrs
Payback period	11.5 yrs	14 yrs
Conventionel electricity price	0.125€/kWh	0.078€/kWh
Leverized electricity costs LEC	0.203€/kWh	0.23€/kWh

efficiency of the plant was 39% and average value of the solar to electric conversion efficiency was about 15%. The number of the full load running hours was 2548 h while the number of hours corresponding to the operations at medium regime from the storage system was 1024 h. Moreover, the prevented CO_2 emissions was about 78,811,110 kg/year if a concentrated solar plant is used instead of an equivalent fossil fuel thermal electric plant. The comparison to a reference plant Andasol in Spain exhibited that the electricity production of the simulated Tataouine plant is more important for all the year except only the two months of April and June. Even, the total annual production of electricity generated from the simulated field of Tataouine exceeds that of the plant of Andasol in Spain by an amount of 1793 MWhe. However, the total investment cost is more important in the case of Tataouine station in Tunisia. A concentrated solar project becomes economically competitive in Tunisia when the majority of the plant components such the collectors structure and supports, the mirrors and the storage system should be manufactured locally in Tunisia to minimize the transport fees and by the way create jobs and enhances the local industry to investigate in this field (Table 5).

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