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Status of implementation of the first Linear Fresnel solar thermal power plant in the Middle East – WECSP solar project in the Kingdom of Jordan

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Abstract

The WECSP solar plant is a 1 MW_e solar thermal power plant based on Linear Fresnel Reflector CSP Technology developed by French technology provider Solar Euromed. It is designed with a Rankine cycle and ultimately injects electricity into the Jordan local electricity grid. The project site benefits from favorable solar radiaton with a DNI at 2670 kWh/m^2/year. Linear Fresnel Reflector CSP Technology, thanks to its light and simple design, is the most suitable technology to provide maximized local value and ultimately reduce capital costs and LCOE of CSP technology [1]. A significant portion of the plant equipments are sourced and manufactured locally, providing know-how and employment opportunities to the Kingdom of Jordan. The project also includes a R&D part with the installation of a CSP laboratory and a knowledge transfer activity. Project stakeholders are building a solid foundation for the deployment of CSP in Jordan which has already launched a vast solar energy development program and in the Middle East where several large scale solar energy deployment programs are being implemented.

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Keywords: Concentrated Solar Power; Linear Fresnel Reflectors; Solar Thermal Electricity; Jordan; WECSP; Demonstration Projects;

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1. Introduction

The Jordan National Energy Research Center (NERC) has commissioned the implementation of a solar thermal power plant in the southern part of the Hashemite Kingdom of Jordan. This solar plant is part of a EU-funded project called “Capacity Building for Wind Energy and Concentrating Solar Power in Jordan – WECSP” established under the ENPI/EuropeAid Program [2]. The main objective of the WECSP solar project is the engineering, procurement, construction and trial operations of a 1 MWe solar thermal power plant in Jordan. This solar plant is the first solar thermal power plant to be connected to a grid in Jordan and the first solar plant connected to a grid in the Middle East based on the Linear Fresnel Reflector CSP technology.

2. Context

Jordan is one of Middle East's most active and attractive market for renewable energy and has recently increased its visibility on the global solar market thanks to favorable conditions to develop solar projects on its territory. Despite being extremely dynamic in the field of renewable energy, Jordan remains a net importer of energy, importing 97% of its total energy consumption [3]. Over 80% of this energy is imported via the Arab Gas Pipeline (AGP), which transports natural gas from Egypt to Jordan. As fuel imports have become increasingly volatile in the past few years, power shortages and blackouts are frequent and have forced Jordan to operate its power plants on expensive imported fuels. This energy spending accounts for a large part of the GDP of the country (approx. 20 % in recent years) [3]. Because solar technologies can generate electricity at a lower cost than imported fuels and without the risk of major supply disruptions, they have been domestically promoted in recent years as a stable and cost-effective power source. Jordan has therefore implemented a legal framework to support renewable energy targets. In April 2012, the country enacted the Renewable Energy and Energy Efficiency Law (REEL) [4], which requires national utility companies to purchase electricity from renewable energy projects and for the government to cover the cost of grid connection. As a consequence, transmission and distribution companies shall purchase electricity produced from solar energy facility at a rate of JD 0.135/kWh (approx. US$ 0.19/kWh) for solar thermal power plants [5]. The offtaker is one of Jordan's three distribution companies: Jordanian Electric Power Company, or JEPCO (operation in the North), Electricity Distribution Company, or EDCO (operation in the North-West and in the East), and Irbid District Electricity Company, or IDECO (operation in the North and East). However when a project connects at a high voltage level, the primary counterparty is Jordan's experienced transmission company NEPCO, which has procured and successfully executed four major conventional independent power projects in Jordan.

3. Location

The project site is located in the Governorate of Ma’an and the directorates of Arady Al Fujeij, in Jordan, east of the town of Al Khirba As Samara, and west of the town of Al Showbak (see Figure 1). The site location is about 200km south of Amman, the capital of Jordan, and about 180km north of Aqaba sea port, and accessible from both directions. The site is located in a desert area in the western part of Al Fujeij plateau, with a smooth topography. Site elevation varies from 1235m above sea level (asl) in the southwest part of the area to maximum altitude of 1270m asl in the northeast part. Altitude drops eastwards and westwards of the area. The most direct route is the main Desert Highway route, and it takes approximately three hours by car (220 km). From Aqaba it takes approximately 2 hours by car to reach the site (175 km).

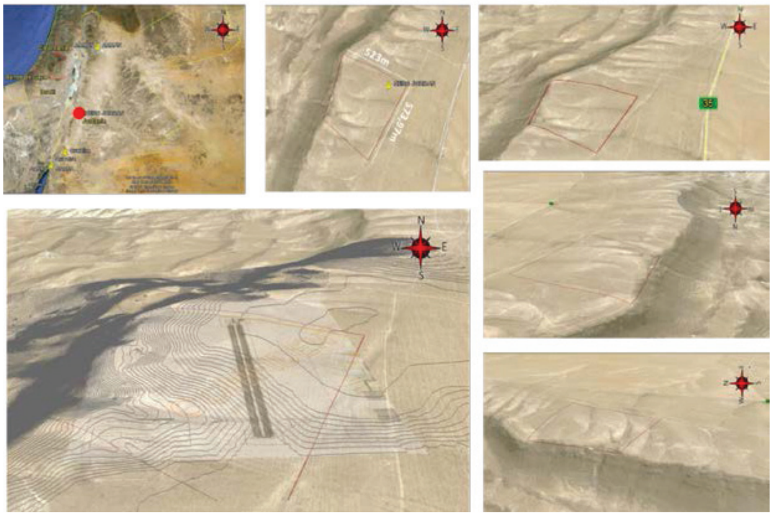

Fig 1. WECSP project location in Jordan

4. Environmental conditions

The Jordan climate is mainly Mediterranean, with a hot dry summer and mild cold winter with two short transitional periods in between. The local climate presents two principal seasons: summer season (dry season) from June to September, winter season (rainy season) from October to April. The site is located in a hilly region which is characterized by hot dry summer and cold wet winter seasons. In winter seasons (around January) these regions experience cold weather with low temperatures in January. Average temperatures vary between 9°C and 18.7°C with a mean value of 13.88°C and extreme temperatures are between -5°C and +35°C. Current POCC philosophy precludes any operation during freezing periods (rare occurrence). The average relative humidity varies from 35% to 45% in summer and from 50% to 69% in winter, as can be seen in Table 1 summarizing the project site specific parameters.

Table 1 : specific parameters of the location

DNI	Elevation	Ambient design temperature	Annual average temperature	Barometric Pressure	Average Barometric Pressure	Minimum Relative Humidity	Average Relative Humidity	Maximum Relative Humidity	Maximum Wind speed	Annual Rainfall
2670 Wh/m^2	1235 to 1270 m	-10°C / 40 °C	13.9°C	800-883 mbara	853 mbara	6%	49.3%	98%	18 m/s	250 mm

A Typical Meteorological Year (TMY) was generated for the site based on adapted satellite-derived data with an annual average DNI of 2670 kWh/m^2/year with an uncertainty of ± 7% [2]. High quality redundant solar measurements with a pyrheliometer and a Rotating Shadowband Irradiometer (RSI) are available near the site project in Ma'an at the Ma'an Development Area (MDA) since late 2010. The MDA site is located 45 km southeast of Al Fujeij at a similar elevation. Thus, it is assumed that the solar radiation characteristics at Ma'an are similar to those at Al Fujeij. The measurements at Ma'an are taken for regional adaption of the satellite-derived solar radiation data. This adaption of the satellite-derived time-series at MDA is applied to the data of Al Fujeij to reach higher quality solar radiation data. The adapted site-specific satellite time-series is used together with ground measurements of wind, temperature and humidity at Al Fujeij to create a typical meteorological year (TMY) for Direct Normal Irradiance (DNI) of the Site.

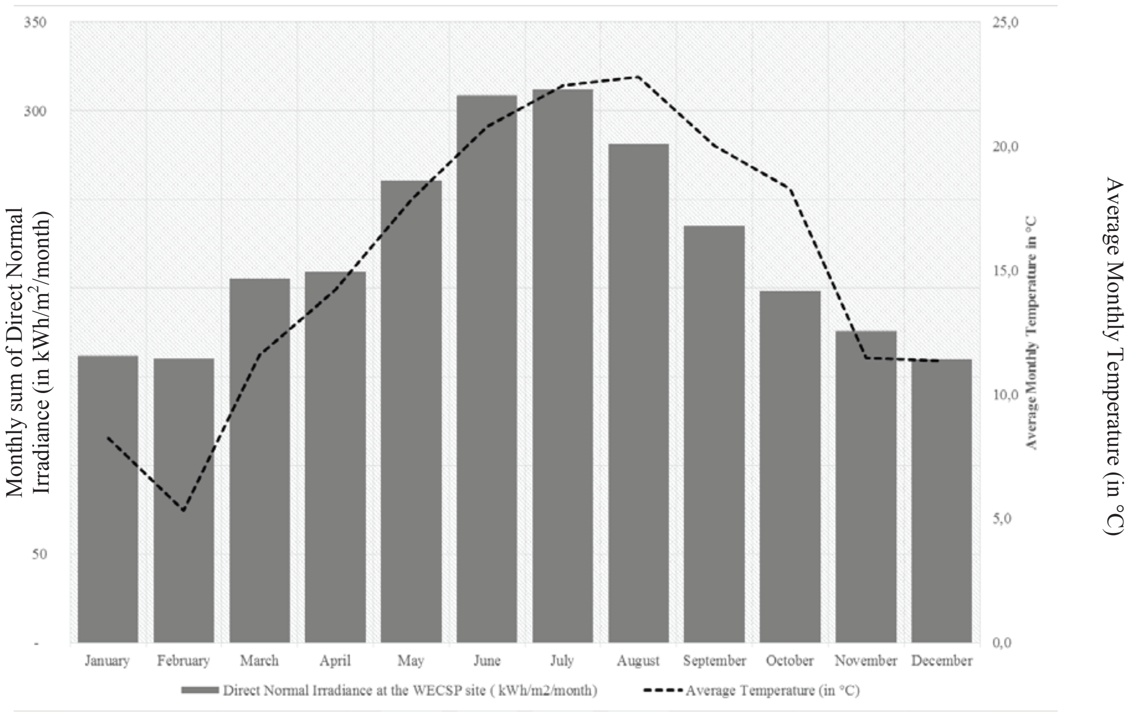

Fig 2. Solar radiation and Temperature Profile (source : TMY)

The TMY was derived from long-term site-specific satellite-derived data at the Al Fujeij covering 18 years of data (from 1994 to 2012), which was adapted with ground-measured data using the concatenating method described in Hoyer-Klick et al. (2009) [6]. MDA solar measurements were used for comparison and slight regional adjustment of satellite data following Schumann et al. (2011) [11]. According to this method, various months are selected from the adapted long-term satellite time-series in such a way that they represent long-term monthly averages as good as possible. These selected months are then concatenated so as to create a complete year. The annual average is approaching the long-term average better than 1 % and each monthly average meets the long-term monthly average better than 5 %.

5. Plant design

5.1. General

The plant relies on a Rankine cycle, comprising a Solar Boiler as heat source, a steam turbine as converter and an air-cooled condenser as heat sink. The plant enables the conversion of solar energy into thermal, then into mechanical energy and finally to electricity. The main equipments are organized in four major entities, as well as auxiliaries: the Solar Boiler ensures the collection and conversion of solar energy into thermal energy (steam); the Steam Turbine Generator converts thermal energy into mechanical energy and mechanical energy into electricity; the Cooling system cools the residual steam at the outlet of the turbine, collects the condensate and distributes the flow in the system. Finally, the Feedwater system pressurizes the condensates, and feeds the Solar Boiler with feedwater at the required temperature and pressure.

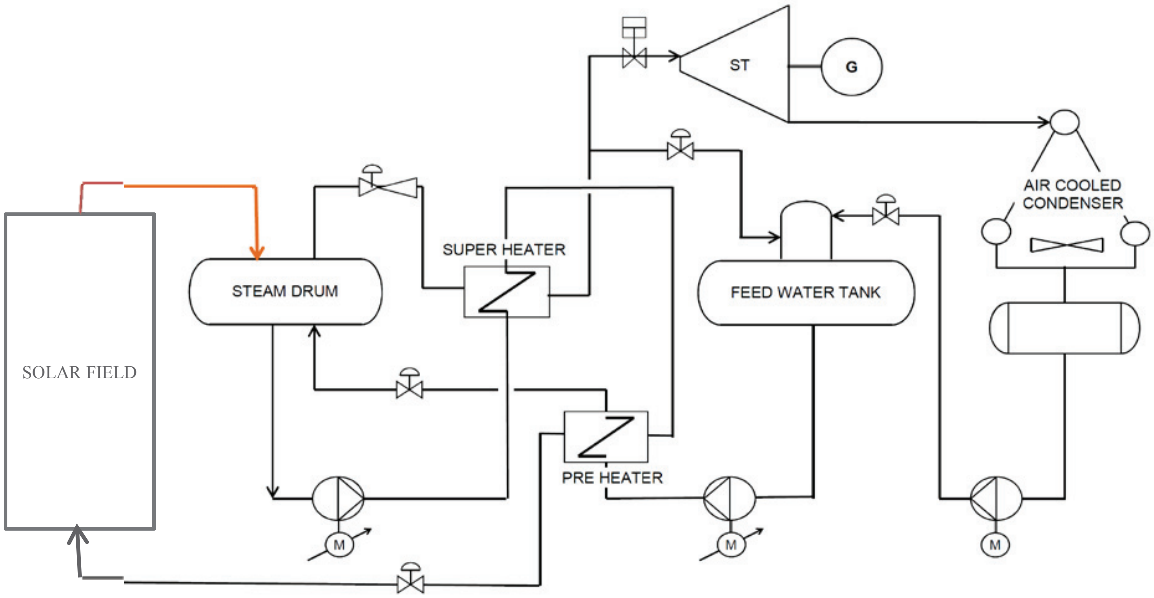

Fig 3. Schematic Process Flow Diagram

5.2. Plant design methodology

The minimum power output is fixed at 1000 kWe and the main design optimization criteria is the capital investment cost for the power plant. The general sizing methodology consists of iterations on the plant design variables:

1. based on steam and condensate parameters, evaluation of nominal and partial-load efficiencies:
   a. through dedicated software Thermoflex®,
   b. through verification against potential supplier actual capabilities,
2. selection of a set of ACC design variables (ambient temperature vs. power consumption),
3. evaluation of several solar field aperture areas,
4. calculation of the auxiliary consumption (pumps, ACC, solar field tracking system, etc.),
5. integration of gross electrical production and parasitic consumption,
6. iteration on solar field aperture area until the production target is reached,
7. evaluation of capital investment cost for the whole plant.

A further iteration is made on the selection of steam cycle parameters, until a minimum cost is reached for the project.

5.3. Solar field optimization

Once the steam cycle and solar field aperture are selected, several possibilities occur as for the configuration of the solar field. Indeed, the following items can be adjusted such as solar field orientation, number of loops, length of each loop, and circulation principle within the loops. The considerations, which are taken into account in order to select the best configurations, are the following:

- mass flow rate: given a predefined enthalpy increase in the solar field, the length of each loop will automatically induce the mass flow rate in each loop. Loops that are too short will lead to low mass flow rates, which can infer phase stratification inside the absorber tubes, leading to thermal shocks and overheating. On the other hand, loops too long will require important mass flow rates, and thus high steam velocities, which can lead to high pressure drops, fast erosion, water hammers, etc.

- pressure drop within the solar field: head losses are higher for higher mass flow rates, and also for wider solar fields where header pipes (mainly at the steam outlet) have to run a long distance. Along with high mass flow rates, pressure drops lead to high parasitic consumption for the circulations pumps, which is to be avoided,
- optical end losses: given the one-dimensional tracking of the solar field, low sun positions (mainly in winter) lead to important end losses at the inlet or outlet of the solar field. These become relatively larger for shorter lines than for longer lines, and compensation measures (extra receiver lengths) can become prohibitive for short lines,
- flow regimes: in certain circulation patterns, and given the two-phase flow, the flow regimes can become hard to control and pose problems with regard to Solar Boiler operation. For example, elbows are not recommended for two-phase flow circulation, since they can lead to high pressure drops and local overheating.
- land topography: the land topography also has an impact on the chosen solar field configuration and circulation pattern. Indeed, wise configuration choices can limit the cost impact of the earthworks and/or facilitate the maintenance, while local or global slopes can be beneficial or detrimental to the good flow circulation.

5.4. Process description

5.4.1. Solar boiler

The Solar Field is the key equipment of the Solar Boiler. Using concentrated sunlight, it turns subcooled pressurized water coming from the Steam Island circulation pumps into saturated steam, driven to the steam drum. The Solar Field consists of three parallel loops each 470m-long for a total aperture area of approx. ~ 12 000 m².

Fig 4. Example of LFR Solar Field Module

The Solar Boiler is fed by a feedwater tank, through feedwater pumps, which pressurize and drive the deoxygenated condensates to the steam drum. This feedwater is also used to cool the recirculated water, through a feedwater preheater, thus reducing the necessary mass flow and heat losses in the solar field, and minimizing the design constraints for the expansion system at the solar field inlet. Another approach would have been to mix the feedwater and circulation water at the inlet of the solar field: this approach has been eliminated since it reduces the reactivity of the system in case of a low steam drum level. This issue is solved by feeding the steam drum directly.

In normal operation, the Solar Field supplies wet steam to the Steam Island under the following conditions:

- wet steam pressure: 28 bar abs
- wet steam temperature: 230°C (sat.)
- wet steam vapor mass fraction: 80%

In order to maintain a good controllability of the working steam characteristics, the solar field shall be providing saturated steam, through the recirculation principle, in which wet steam is separated into dry steam and saturated liquid water, the former being sent to the Power Block and the latter being recirculated through the solar field. Then, in order to supply superheated steam to the steam turbine, the flash effect is being used, by reducing the pressure of the dry saturated steam and going through a heat exchanger with the recirculated water. The superheating thus obtained must be sufficient to ensure a low humidity (< 8%) at the steam turbine outlet.

Saturated Steam from the Solar Field is collected in the steam drum or steam separator. Steam and liquid water are separated in this drum. Saturated steam pressure from the steam drum is reduced in a reducing valve and then superheated in a super-heater and the superheated steam is sent to the Steam Turbine. The saturated water is pumped to the Solar Field via the circulating pumps (2x100%). This water is sub-cooled in the heat exchanger, which at the same time preheats the water entering the Solar Boiler by heat recovery. A continuous blow down of the steam drum is made in order to keep the required process water quality. The blowdown stream is discharged to the atmospheric tank.

The feedwater tank / deaerator used for de-aerating the make-up water from the water treatment unit, feeding the steam drum via the feedwater pumps and collecting the condensate from the condensate tank is kept under slightly higher pressure than atmospheric in order to avoid air suction and resulting oxygen contamination.

The Steam Island converts saturated steam at around 28 bar abs (inside the steam drum) into superheated steam at 14 bar abs / 225°C, after steam passing through a superheater (external or internal) and pressure reducing valve. Given the variability of the solar resource, the Solar Boiler and Steam Turbine seldom run on nominal conditions. The Steam Turbine will work under sliding pressure mode (flow rate to be reduced). Sliding pressure is also occurring in the Steam drum and the pressure ratio is adjusted between saturated steam in the steam drum and superheated steam going to the Steam Turbine in order to keep the superheating of +25°C at least. The turbine is controlled in sliding mode during main load variations.

5.4.2. Power block

The Steam Turbine is a key equipment of the Power Block. It is fed by superheated live steam coming from the Solar Boiler, and converts the steam thermal energy into mechanical energy then into electrical energy through the generator. Given the relatively small power output required by the project, a single-stage steam turbine has been preferred, mainly for economic reasons. Such units, with such a small size, cannot accept saturated steam as a working medium, since humidity-related corrosion cannot be tackled at such a low turbine size. Besides, small steam turbine units are limited in the acceptable expansion, and therefore in the acceptable inlet/outlet pressures. In order to maintain a reasonable efficiency, and given the restrictions applying to the Solar Boiler, a low outlet pressure is preferred to a high inlet pressure: this is achieved through a condensation steam turbine (vs. a backpressure steam turbine, where the turbine outlet pressure is higher than the atmospheric pressure). Therefore, the steam turbine shall be running on superheated steam at an intermediate pressure level, with vacuum condensation at the exhaust, and with no intermediate extractions.

Vacuum steam (0,1 bara) coming from the Steam Turbine exhaust is sent to an air-cooled condenser. An oil supply unit provides oil for the lubrication of the turbine/generator parts. In case of a turbine trip or Solar Boiler overproduction, the steam production from the Solar Boiler is directed to the bypass system directly to the air-cooled condenser. The water needed for spraying in the steam duct come from the condensate tank. This desuperheating is necessary in order to cool down the high-temperature steam going to the Air-Cooled Condenser.

Under normal operation, the Solar Boiler supplies live steam to the Steam Turbine under the following conditions:

- live steam pressure: 14 bar abs,
- live steam temperature : 225°C.

5.4.3. Air-cooled condenser

The vacuum steam from Steam Turbine exhaust is discharged to the Air-Cooled Condenser where it is condensed. The condensate is flowing by gravity to the condensate tank. The condensate is then sent to the feedwater tank via pumps. The incondensable gases are evacuated towards the vacuum liquid ring pumps. At the turbine outlet, the low-pressure steam leaves at:

- low-pressure steam pressure: 0.1 bar abs,
- low-pressure steam temperature: 45.8°C (sat.),
- low-pressure steam vapor mass fraction: 95%.

The design ambient temperature is 20°C, and the design ambient pressure is 850 mbar. Given the variability of the solar resource and that the Steam Turbine run on sliding pressure mode, the Air-Cooled Condenser accommodate for varying mass flow rates, thanks to variable frequency drives on the fans.

5.4.4. Generator

The generator is sized to evacuate the normal and peak power output of the Steam Turbine over the complete range of site ambient conditions and at rated casing and stator cooling water, pressure and temperature. The Maximum Continuous Rating (MCR) of the generator corresponds to the maximum kVA, kW and minimum associated over-excited power factor that it is guaranteed to deliver continuously. Generator rating is on the basis of continuous operation with guaranteed temperature, or temperature rises, not exceeding those given in IEC 34-1. The generator is capable of satisfactory continuous operation at rated kVA and power factor at any voltage from 95% to 105% of rated voltage and within a frequency range of 47.5 to 51.5 Hz even if frequency and voltage variations occur simultaneously, without exceeding safe temperature rises, but not necessarily in accordance with the standards established for operation at rated voltage and frequency. The generator unit is capable of withstanding 3 phase short circuit at the generator terminals when operating at rated kVA and power, 5% over voltage and with rated excitation for 3 seconds. The generator phase and neutral side terminals is brought out through seal of bushings. The bearings are lubricated by oil from the turbine lube oil system. Generator collector end bearings are insulated to prevent arcing damage to the Babbitt as a result of circulating shaft current. Resistance / thermocouple type temperature detectors are provided where the highest temperatures are expected. On-line shaft leakage current monitoring system is provided to detect any leakage current through the shaft. Abnormal leakage current triggers an alarm in the control room. Generator auxiliary systems like cooling, excitation, steam handling system, etc., are monitored and controlled from the main control system.

6. Laboratory

Solar Euromed is also responsible for the supply, delivery, transportation, construction, installation, commissioning and training of a CSP laboratory and research equipment. This facility is set up in order to perform various measurements related to CSP materials and parameters. The indoor Laboratory consists of an Optical measurement area and another area for CSP specific measurement, general equipment and traveling standard weather station storage. Outside, two other areas shall be dedicated to the solar radiation reference measurement station and to the outdoor exposure stand. Several testing equipment is provided with the Optical Measurement Area, including a UV/Vis/NIR spectrophotometer to measure optical parameters of samples and a mobile reflectometer shall be used to measure the reflectivity of the primary reflectors. The CSP specific measurement storage area include inclinometer sensors, an attachable flow meter sensor, a digital camera, a portable data logging electric meter, a portable data logger, a mechanical Total station, and temperature measurement equipment. Two meteorological stations are also provided: a solar radiation reference measurement station (including pyrheliometers, pyranometers, solar tracker, Absolute Cavity Radiometer (ACR) to calibrate the various thermopile sensors, Rotating Shadowband Irradiometer (RSI), visibility sensor, temperature and humidity probe, rain gauge, air pressure).

7. Construction and local content creation

The Plant construction is broken down in sub-systems as per the following diagram:

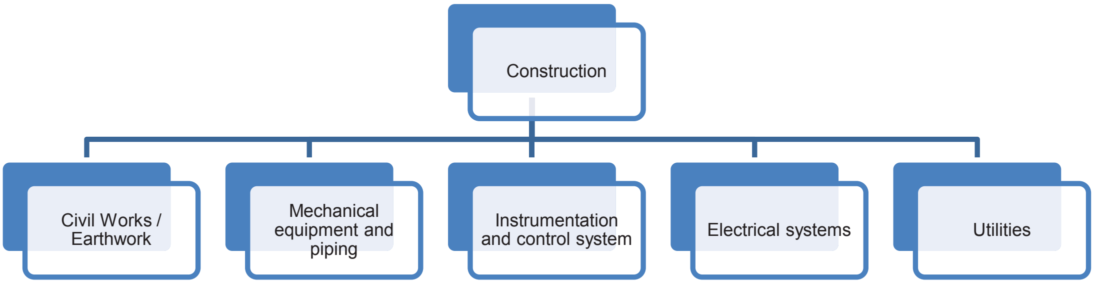

Fig 5. Scope of work

The duration of the construction phase is approx. 14 months with a completion date in the fourth quarter of 2015.

The project was subject to a tender open to several CSP technologies (i.e Parabolic Trough, Linear Fresnel, Power Tower) [2]. In 2013, Jordan's Higher Council of Science and Technology (HCST) on behalf of NERC awarded French CSP Technology provider Solar Euromed, to implement the project based on LFR technology. Solar Euromed is an award-winning innovative solar CSP private company specialized in the design, manufacturing, installation and maintenance of solar thermal boilers that concentrate sun rays to produce steam for thermal power plants or industrial facilities. Solar Euromed's LFR technology provides significant benefits to such solar thermal power plant projects : reduce its cost with the use of a simplified solar collector [7], minimize its environmental impact [8], and maximize its local content [9].

LFR technology, thanks to its light and simple design, is the most suitable technology to provide a maximized local value and ultimately reduce capital costs of CSP technology [9]. During the construction of the project, a large portion of the Solar Field components shall be sourced and manufactured in Jordan, thus providing know-how and incremental employment opportunities to the Kindgom. Detailed studies were performed to assess whether local companies were able to perform relevant activities for this Project. LFR Technology mainly relies on Aluminum and Steel metallurgy, piping and pressure vessels technology and assembly of metallic structures. Such industrial techniques are well mastered in Jordan and a large number of companies were identified with such capabilities. The realization of this Project shall also bring to Jordan the know-how in high precision metal-glass curvature components manufacturing as well as special coating tubes assemblies and welding. Besides, Jordan industrial companies have a strong experience on which Solar Euromed shall rely: steel and aluminum design, manufacture and transformation, a strong know-how in the design and manufacture of tanks, water storage, and piping for traditional boilers. Solar Field components are assembled onsite with the assembly of the primary reflectors onsite or in a local factory thanks to a flexible assembly line system, the assembly of the collector sections on site right before installation, and pipe assembly in a weld workshop on site. With supervision of the Contractor's team on site, all other erection and installation works shall be provided by Jordan companies: piles' implantation, civil works, mounting and erection of steel structures, mounting of the receiver sections, welding works and X-ray scanning of the receiver, piping and tanks erection and connection, temporary workshop mounting and dismounting, sheds installation, instrument installation, etc.. Finally, all activities related to the Power Block shall be realized via local companies thus increasing the local experience for specific CSP projects.

8. Capacity building benefits

Transferring knowledge, skills and international best practices in the field of solar energy is a primary focus of the outreach activities of the WECSP project. Through the execution of the WECSP plant, project stakeholders are building the foundation for the deployment of the CSP in the country and region with an industrial integration program, through the establishment of a local supply chain for the components of the innovative LFR technology and the installation of a production line for the assembly of the solar block components, and the development of Research, Development and Innovation activities that could take place on the project site related with solar technology topics, allowing technology transfer and sharing opportunities to rise. Construction training will be hands-on during the Construction phase with international experienced staff providing vocational trainings and documented information during the course of the various work flows. An O&M training program has been tailored for the project and is designed to start with a large overview of CSP technology and its various processes, before starting specific trainings for each major components. The operation of a power plant is taught during an initial training course and operation, general design and maintenance trainings are provided. Hands-on training on the field will take place at the end of the training program to allow engineers and workers to fully experience all cases of operation. Courses will include different levels of complexity to allow engineering staff and students to understand the process while workers can concentrate on technical specifications and practical handling. After operation, maintenance is the second core guideline of the training program dedicated to teach the overall maintenance philosophy as well as the practical details for each type of component. A second training is scheduled after a year of operation. The first week of the training program will be a summary of the first training; the second week will be dedicated for improved analysis and operation, as well as technical discussions. Courses on operation modes and efficiency will be part of the hands-on program during the second week, the aim will be to better understand the links between the controlled parameters that govern the plant operation. As the second training is scheduled shortly before the final acceptance of the commissioning phase, a special course will teach the different operations to be conducted during the commissioning.

9. Scalability and replicability in the region

As one of Middle East's most dynamic market for renewable energy, the Kingdom of Jordan has launched an independent power producer (IPP) direct proposal program for solar energy. In this program, the government has set capacity targets to be met (approx. 600 MW) [4]. The program is organized in sequential bidding rounds, two of which have already taken place. In the first round, approximately 200 MW of solar projects mainly based on PV technology were approved. In the second round, consisting of 200 MW of solar projects, private companies who have prequalified are currently preparing their final bids due in July 2014. The third round will get underway as of August 2014. The WECSP project will strengthen the capacity and tighten the involvement of local, regional and global companies specialized in Development, EPC, O&M for CSP projects to be involved in the subsequent bidding rounds. The project was also specifically designed to be exclusive of ORC Power Generation equipment despite the small power, mainly to ensure replicability using a power generation technology representative and suitable for scale-up solar projects in Jordan. As Jordan has increased its visibility in the global renewable market, major international parties now look upon Jordan as an ideal entry market to expand in other Middle Eastern countries including GCC countries such as Saudi Arabia and its visionary program to introduce 54 GW of renewable energy power in the next 10 years [9].

10. Conclusion

This paper has presented the design of the 1 MWe WECSP solar project based on Linear Fresnel Reflector CSP Technology developed by French technology provider Solar Euromed [10]. It has provided key insights on the benefits and advantages of Linear Fresnel technology for the demonstration of the viability of CSP technology in Middle Eastern conditions of operation. It also has described the execution of the project and presented the importance of such pioneering initiative for the definition of the Jordan Energy Strategy roadmap and the introduction of renewable energy in the Kingdom of Jordan. Finally, it has presented that the WECSP successful execution is a strong enabler for the scaling-up and replication of such solar CSP solutions in the Middle East.

Acknowledgements

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