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The System Architecture of the Integrated Solar Combined Cycle (ISCC) Power Plant: The Case of Ain Beni Mathar Morocco

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Abstract

Climate change is one of the most serious threats our world faces today. The energy-supply side is the number one contributor to global greenhouse gas emissions, and responsible for almost 35% of the total emissions. In response to such facts, there have been actions to phase-out from generating electrical energy from conventional power plants that depend upon fossil fuels (mainly coal and oil) which produces steam to run the electrical generators. Among so many present-day alternatives, the Integrated Solar Combined Cycle (ISCC) power plant has emerged as one of the most efficient technologies for generating electricity, while being environmentally clean and economically viable. The basic concept of the ISCC scheme depends upon the integration of two power generation systems; the solar section that generates power by utilizing solar irradiation, and the gas-fired combined cycle section that depends upon natural gas, the cleanest among fossil fuel. This technology is credited with having low carbon emissions as well as high operational efficiency. This is due to the presence of the Heat Recovery Steam Generator (HRSG) system, which increases the overall generation efficiency in the plant to almost 50%. The first ISCC power station was inaugurated in the summer of 2010 in Morocco, known as the Ain Beni Mathar (ABM) power plant. The goal of this work is to apply the system architectural methodologies in order to better understand and analyze the performance and concept of operation of ISCC technology. We will use the world's first ISCC station as a model in this paper.

Keywords: Integrated solar combined cycle (ISCC); Ain Beni Mathar (ABM); Power plant; System architecture; Parabolic trough solar system; Natural gas combined cycle power plants

Abbreviations: ABM: Ain Beni Mathar; HRSG: Heat Recovery Steam Generator; GED: Global Environment Facility; AFDB: African Development Bank; ISCC: Integrated Solar Combine Cycle; NGCC: Natural Gas Combine Cycle; GWh: Gigawatt-Hour (1×10^9); TWh: Terawatt-hour (1×10^{12}); KV: Kilovolt (1000 Volt); ONE: Office National de l'Electricité

What is ABM?

Ain Beni Mather is a small town located in Jerada Province, the eastern side of the Kingdom of Morocco, near the Algerian border. It has a total population of slightly over 15,000 citizens as of 2010. Due to its geographic nature, mostly sunny around the year with spacious and vast lands, it was voted as the best option to have the project built on its territory, which later on named after it.

The Vision and Objectives of the ABM Project

Several goals were to be achieved by the inauguration of the ABM ISCC power plant. The project cost a total of $540 Million (5.199 Billion Moroccan Dirham), and was awarded to Abener, a Spanish energy company, to develop and construct the project. The Moroccan government's main concern in regard to establishing the ABM project was to modernize its electrical infrastructure in order to meet the extremely increasing demand on its energy grid by providing cheap and clean energy; to reduce its dependence on fossil fuel in its power plants due to the volatility and instability of oil and coal prices that affect the overall national economy; to comply with the international environmental standards Morocco ratifies when signed the Kyoto Protocol in 2002, an international environmental protection treaty adopted in late December of 1997 in Kyoto, Japan, to reduce the greenhouse gas emissions on global level [1-3]; to successfully support the implementation of its Rural Electrification Global Program (PERG) that was signed into law in 1995, to provide electric service to the rural communities of Morocco that constitute 45% of the population, which had a very low electrification rates at 63% as of June 2004; to enable the participation of the Moroccan energy companies in developing and operating the newly emerged technology that is promised to be one of the most desired and acquired schemes in power generation systems throughout the world in the near future, which will give them an economical, operational and technical experience that will allow them to be the leaders in this field [4].

The annual energy consumption in Morocco had tripled over a 20 year period, from 4.8 TWh in 1983 to 14.8 TWh in 2003, accounting for an annual increase of 6% per year. This percentage shows a high increase on energy demand that is above the international average levels. This is indicated as well in the overall energy per capita of Morocco which was doubled for the same period from 217 KWh to 453 KWh, an indicator of the increased standard of living during these years. In response to such an increase, the ABM project was approved in May of 1999, with construction planned to start in 2007 and to be completed in 2010 [5]. The nameplate capacity of the project is 472 MW, of which 20 MW will be provided from its solar section. An estimated 1.6 TWh of energy per year is expected to serve the Office National de l'Electricite (ONE), which runs the Moroccan power grid.

The Stakeholders Involved in the ABM Project

Stakeholders are all the beneficiaries entitled to direct or indirect benefits from the ABM project. Any actions or considerations that do not result in benefits to the stakeholders are not required for the successful implementation and operation of the project (Table 1).

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Stakeholders	Characteristics	Needs
The Government of the Kingdom of Morocco	Government of Morocco is responsible for providing well-planned yet equal opportunities and services for all of its citizens and residents.	- Modernize the state's energy infrastructure. - Reduce dependence on fossil fuel and improve the overall economy. - Contribute to climate change in accordance with Kyoto Protocol Treaty. - Increase electrification rates in rural areas.
The Moroccan citizens and residents	Consumers which drive the operations of the project. Different classification of consumers based on needs of service, including residential, industrial,… etc.	- Reduce risks of blackouts. - Receive clean, reliable and cheap energy. - Residents of Jerada Province receive direct and indirect employment opportunities. - Higher standards of living.
ONE	Highly skilled professional engineers, scientists, managers and customer service providers. Direct communication with customers requires communication as well as technical skills.	-Diversify the company's generation portfolio, increase generation capabilities. - Increase profits. - Establish leadership in new energy arena. - Ability to meet extra demand on grid.
National Contractors	Highly skilled professional engineers, scientists, managers and customer service providers. Independent service providers.	- Increase profits. - Develop skills in new energy arena. - Receive well-paid operation and maintenance contracts and business opportunities.
University research centers and institutes	Academic professors, researchers, grad and undergrad students with main interest in developing useful technologies and ascend in academic rankings	- Access to study and analyze the world's first ISCC project. - Produce quality research, excel in academia. - Receive awards, research grants, ..etc.
Borrower (GED)	International agency. A coalition of 183 countries to address and influence environmental problems and issues.	- Contribute to global environment. - Influence policies to promote sustainable development in clean energy production.

Table 1: The stakeholders of the ABM project.

Project Description

Financial instruments

The ABM source of funds is a joint effort between several parties. The estimated total cost of the project is $540 million, of which ONE covered the primary share of the overall costs of the project by both providing from its own equity contribution ($135 million), and by borrowing funds from AFDB ($390 Million). The GEF funded the remaining cost, which was estimated as 8% of the overall project costs ($43.2 Million). The rational essence of GEF funding comes from its global commitment to reduce the cost of low-carbon energy production technologies to a level of economic viability [6,7].

Performance indicators and metrics

The ABM ISCC power plant is the first of its kind in the world, so it is of great interest to several parties to measure and monitor the indicators that will provide an overall looking on the new integrated technology and evaluate its performance to build definite perceptions about its effects and benefits [6].

A. Quantitative indicators

- Total energy production (GWh/year).
- Energy production from the solar section of the station (GWh/year).
- Solar production as a percentage of total energy production in ABM power plant.
- Share of ABM energy output in total energy production (%).
- ONE staff training in various aspects related to plant technology.
- Reductions in CO_2 emissions (tons/year).
- Cost of energy from the solar section of the station (cents/KWh).
- Cost of the solar to the overall ISCC plant production as percentage.

B. Qualitative indicators

- Lessons learned during the pre-construction period, including the feasibility study, bidding process, and financing of a newly developed technology.
- Lessons learned during the actual construction of the project.
- Recording the viability of the new technology by measuring the performance and monitoring the operation of the plant for a sufficient time, specifically three years from its inauguration date.

Description of the project major components

The ABM project is the first ISCC power plant in the world [2,4]. Although both the solar parabolic trough and the NGCC generation schemes, shown in Figure 1, are not exactly new, the integration of both technologies into one station is a new concept here. The main components of the ABM project are as follow [6]:

A) Construction and operation of the plant ($520 million): The schematic design of the ABM power plant is shown in Figure 2 [8]. It includes the following main parts:

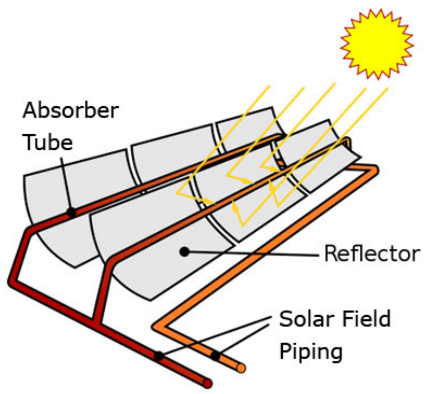

Figure 1A: Concept of CSP scheme

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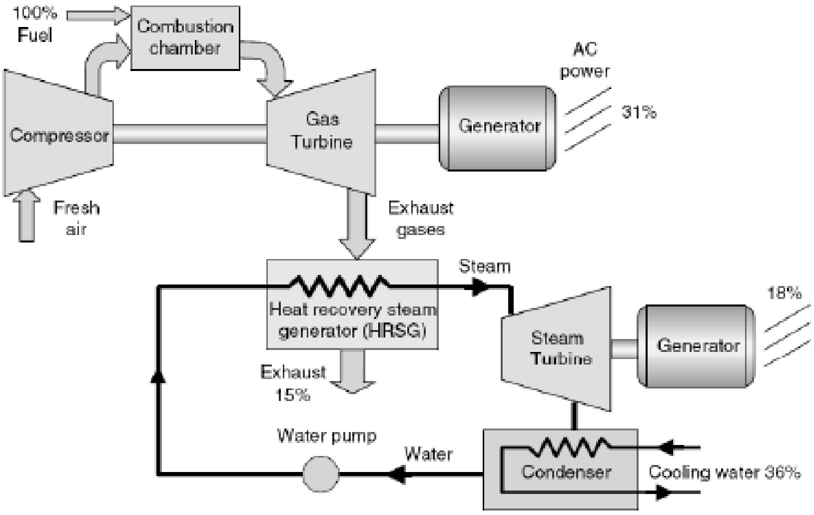

Figure 1B: Combined Cycle Scheme.

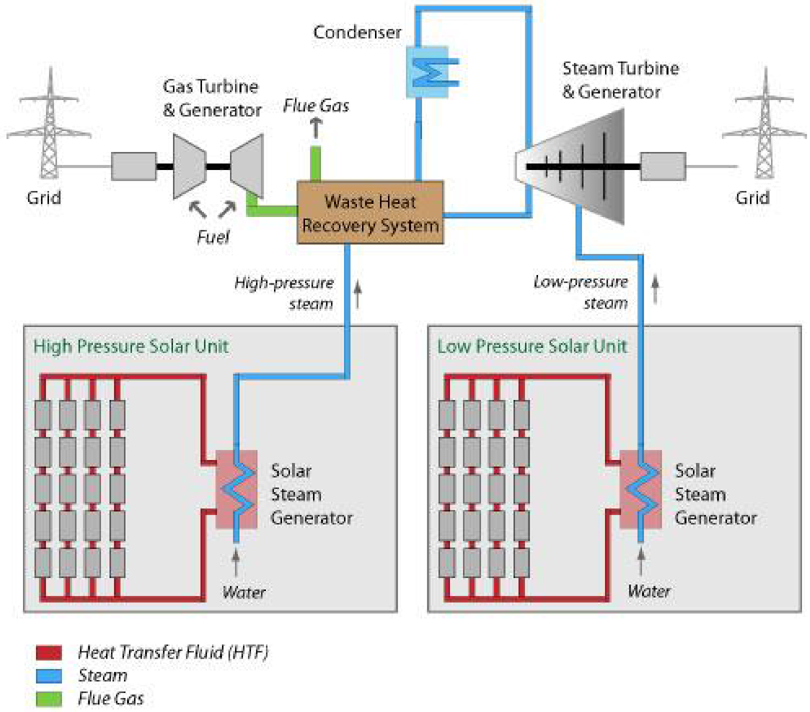

Figure 2: The schematic Design of the ABM ISCC power plant.

- The solar field of the station, which utilizes the solar concentrated thermal scheme to generate power using the parabolic trough technique, illustrated in Figure 1A. The concept is to inject an easy-to-vaporize fluid into a tube to be heated by the sunlight that is reflected on the tube by mirrors (reflectors). The heated fluid turns into steam at high temperature and pressure through the solar steam generator (the vaporizer), which then piped through the turbines of the station. The capacity of the solar section of ABM is 20 MW with an estimated annual production of 40 to 55 GWh a year, installed on an estimated area of 183,000 m^2.

- NGCC section, which increases the flexibility and dispatchability of the station by producing efficient power via burning natural gas in gas turbine. The NGCC section includes the gas turbine that is run by the produced steam, including steam from the solar field, and is connected via common shaft to the electrical generator that produces energy. The ABM consists of two generators with capacity of 155 MW per each, to increase reliability and dependability of the plant.

- HRSG, which characterizes the NGCC from its competing technologies by improving efficiency of the generation via the exploitation of the exiting steam from the first turbine to run another turbine that also drives another generator. This element raises the generation efficiency from 32~35% to almost 50% [9,10], and is shown in Figure 1B.

B) Transmission lines and substation ($25 million): The ABM power plant is interconnected to the rest of the Moroccan grid via two high voltage transmission lines; both rated 225 KV, existing from the substation after stepping up the voltage from the generation level (11 to 25 KV) to its transmission level. There is an additional 60 KV transmission line that's used as a backup power line to the auxiliaries of the ABM power plant, providing emergency power from ONE's nearest substation in the area.

C) Access road ($3.8 million): A road needed to be constructed in order to connect the ABM plant with main transportation systems of the area. Its purpose was to ease the construction process (which required moving heavy equipment and apparatus), and to facilitate the commute of both employees and visitors.

D) Boreholes and wells ($0.35 million): ONE received the approval to construct two boreholes in the area nearby the station for the purpose of operation and maintenance of the plant, including the cleaning process for the solar reflectors, a process needed to maintain high efficiency in the generation process. However, they are limited to consume 3.1 Million m^3 per year.

E) Gas pipeline ($9.22 million): A 13 km gas pipeline is constructed for the supply of the natural gas between the ABM power plant and the nearby Maghreb-Europe pipeline.

F) Land acquisition ($0.87 million): ONE has acquired a total of 203 hectare to build the ABM power plant, including the areas needed for the gas pipeline.

G) Social consideration ($2.3 million): It is ONE's responsibility to reduce the overall impact of the project on both the nearby community and the involved work personnel. It includes providing public awareness sessions and outreach, increasing employment opportunities to local citizens, and building recreational facilities.

H) Consultation and management services ($5.1 million): For the purpose of ensuring and reporting proper construction and operation of the project, including specifying, monitoring, highlighting and implementing the quantitative and qualitative key performance indicators.

The Architectural Framework of the ABM Project

Tradeoff analysis

Clean energy vs. safety of wildlife: Solar power facilities can adversely affect the wildlife in the areas of its installation [11,12]. Furthermore, fatalities have been recorded in such areas for burnt birds and change of behavior related to the migration of species which raises fears on the safety of wildlife inhabitants in the Moroccan desert that already contains endangered species. It is interesting that the total CO_2 reduction over the lifespan of the ABM project (25 years) is estimated to be 575,000 tons [6], which nominates the ISCC technology to be considered "environmentally clean and efficient", but clearly it is not the case for the other inhabitants of our world, should we include them in the definition of the word "environment".

Solar loss vs. increase size of turbine: During times of the year where solar irradiation is vast enough, the amount of steam that is generated from both the solar section as well as the HSRG of the plant can get to high levels that it cannot be accommodated by the current installed turbines, thus resulting in excessive amounts of steam which is wasted. There are ways to take advantage of this excess of heat, mainly by installing larger turbines. However, in addition to the required high cost to implement this option, this would adversely affect the overall generation efficiency during the days where solar irradiation is at or below average level, due to the fact that machines operate at higher efficiency when they are operating near their full-rated capacity. Therefore, it's about choosing between forsaking abundance amounts of energy during certain times in the year, versus fortifying the efficiency during normal operation days [13].

New technology vs. well-defined technology: The ABM ISCC plant, as the first project of its kind, is about reducing the cost of power generation and operation while maintaining a reliable, clean and efficient source of energy. To ONE, it was an investment that was merely based upon calculation and expectation, not on experience or real performance realization. It is a difficult tradeoff, investing hundreds of millions on an indefinite type of technology, but by now, ONE has gained the privilege of making the right decision. The ISCC scheme has started to attract more developers around the globe, indicating the success of the ABM project.

Quality attributes

Configurability: The ABM ISCC has the ability to operate in two modes: as power booster mode where it keeps the generation of the NGCC constant during normal operation, and as fuel economy mode, when there is vast steam generated from its solar section, thus saving the natural gas for later use [14,15].

Efficiency: Both parts of the ABM project are considered efficient methods to generate electricity. Actually, NGCC is indeed the most efficient scheme to produce power, with its generation output efficiency reaching an overall 50% [10].

Sustainability: The concern about deterioration to the environment was one of the main drivers of the ABM project. While there is no direct emission from the solar section of the station, natural gas is considered a cleaner fuel than oil and coal in the category of fossil fuel. It emits 50 ~ 60% less carbon dioxide to the environment than coal, and 20% less than oil [16].

Reliability and availability: Due to the virtue of integrating two of the most efficient schemes in power generation into one power plant, this project has the ability to conduct its operation during several severe scenarios. Although its output would not be as large as the NGCC section, the solar station still has the ability to provide as much as 20 MW of energy in case of a sudden shut-down of the gas supply. Not to forget that the station is interconnected to one of the most protected pipelines in the region, the Maghreb-Europe pipeline, which ensures a continuous supply of natural gas.

Replicability: The ABM provides ONE with a golden opportunity to be a leader in this new arena of technology. As a result of the success of the project, ONE now has all the desired attributes including knowledge in design, construction, operation, and experienced personnel to replicate such a project in other countries around the world [17].

Risks and risk mitigation

The prices of fossil fuel: The project was mainly approved and constructed due to the high prices of oil, which constitute one major fuel that Morocco uses in its power plant. The main price of fuel to pay in the ABM project is for natural gas only, which has a relatively and historically low price tag. However, the price is considered volatile and may affect the economic operation of the plant in the case of a sudden increase in prices over the years. It should be noted that Morocco is the largest fossil fuel importer in Africa, and such project could both be harmful in the case of volatility of gas prices and beneficial in the concept of phasing-out from dependence on the much more expensive fuel, the oil.

Site selection: There have been several suggested sites to have the plant built upon. Although the village of Ain Bani Mathar is not the place in Morocco with the most solar irradiation, it was chosen mainly due to its lowest levelized tariff cost which yielded the highest rate of return to the project.

Technological choice and bidding process: There was a risk and uncertainty analysis involved in the bidding process for choosing the developer of the project. Usually, the contract is to be awarded to the lowest bidders, which is not the case in this situation where the lowest bid may not be the best choice to achieve the project's goals due to limitation in technical experience of the bidder. In addition, at the time of the bidding, the concentrated solar power (CSP) technology still had an undeveloped worldwide market with limited number of suppliers. This is has contributed to the reduction of the preliminary capacity from 45 MW to 20 or 30 MW as ONE requested in the bidding process, since only GEF fund was allocated to cover the cost of developing the solar field of the ABM project [4]. In addition, during the past decade, the CSP power plant was considered a highly complex one due to several factors that play major role in evaluating its feasibility of success. Such factors include high capital cost that was still uncompetitive comparing with the conventional generation methods, availability of water resources near the plant, presence of well-educated and highly qualified engineers, contractors and technology suppliers, and sufficient monetary support from financial institutions [18].

Cancellation risk of GEF funds: During the pre-construction phase, specifically in the summer of 2007, GEF expressed dissatisfaction and threatened to cancel its shared funding of the ABM project. This is due to changes in the project conceptual design, where ONE had reduced the capacity of the solar field from preliminary 45 MW in 1999 to almost half at 20 MW in 2007. This was also due to bidding process uncertainty. However, a report including analysis assessing the reasons for this reduction has been sent from ONE and was eventually approved and ratified by GEF.

Lessons learned

This project is the first of its kind, not only in Morocco or Africa, but in the entire world. Therefore, it offers a great tool of education in regard with several aspects. Some of the noted lessons from the ABM project include:

1. Morocco's successful experience with the ABM project is a main driver to encourage the investment of ISCC, which has been so far considered a promising technology. Other countries that start to follow Morocco's steps in acquiring ISCC plants include: Algeria, Saudi Arabia, India, Iran and Egypt.

2. Satisfied from results of the ABM project, Morocco has announced its intention to build another five ISCC projects with a total capacity of 2,000 MW [17].

3. The introduction of new types of technologies can be promising in many ways, and the ISCC project has proved such a statement is true. This will open the doors not only for the African countries to show interest in renewable energy or ISCC technology, but also to take the lead in the implementation of other undeveloped ideas in different fields of science and technology.

4. The optimal selection of sites for any project plays a major role in its success. In the case of the ABM power plant, 29 families were compensated fairly to relocate in order to take advantage of the ideal location which is very close to underground water resources, access to a transmission line and nearby substation, within miles of one of the largest gas pipelines in the region, and of course rich in solar reserves [17].

5. Prices of various kinds of technologies are prone to sudden increase or decrease. The technological advancement in the case of renewable energy source assures the latter. For concentrated solar power technology, the cost of levelized generation ($cent/KWh) has been reduced around 40% from 20 to 12 Cents/KWh in the period 2000-2015 [19].

6. Human integration with new technologies has proved faster development to these technologies as well as the introduction of newer and enhanced ones. Furthermore, most of the revolutionary discoveries in science and technology in recent decades are direct results of human interaction and understandings of subsequent related systems.

Conclusion

This paper provides a system architecture approach to better understand and analyze the Integrated Solar Combined Cycle (ISCC) technology. The architectural framework applied in this work considers the Ain Beni Mathar (ABM) power plant, located in the eastern side of the Kingdom of Morocco, as a model to study. ABM was the first power plant of its kind in the world, which has raised its importance and attracted attention from several parties to measure the project performance indicators in order to formulate conceptions and conclusions about the technology. After defining the stakeholders of the project, we illustrated the function of its major components and the key performance and metrics required to measure the qualitative and quantitative aspects of the project.

Application of different system architecture techniques have been utilized in this work with respect to the ABM project that, as a newly emerged technology, have a lot of uncertainties. Such applications include: applying the tradeoff analysis required to weigh different attributes in order to reach optimal and informed decisions, identifying key quality performance measurers which have contributed to the success of the ABM project, highlighting several risks associated with the project that could have adversely affected its successful implementation and operation, and brainstorming for valuable lessons learned from the world's first ISCC project. The main conclusion drawn from this project is that the technology of ISCC has truly proven to be a viable and clean solution for a sustainable future, regardless of the doubts that humans tend to have regarding newly developed innovations.

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