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Thesis Title

**Study and analysis of the energy transition of the Timokten
Adrar cement plant GICA to a hybrid PV gas turbine system**

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DEDICATION

**What could be more than being able to share the best moments of your life with the beings
you love.**

**I have the great pleasure of dedicating this modest work : To the dearest person in my life;
my mother my dear father.To my brothers To my sisters.**

To all my family: uncles, aunts, cousins and cousins

**And without forgetting all My friends with whom I shared about my student life and to
everyone I know.**

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NOMENCLATURE

Symbol	Designation	Unit
(P_{PV})	Photovoltaic power output	kW
(P_{GT})	Gas turbine power output	kW
(P_{Load})	Electrical load demand	kW
(E_{PV})	Energy generated by PV system	kWh
(E_{GT})	Energy generated by gas turbine	kWh
(E_{Load})	Electrical energy demand	kWh
(G)	Solar irradiation	kWh/m ² /day
(H)	Solar radiation on horizontal surface	kWh/m ²
(T)	Temperature	°C or K
(T_{amb})	Ambient temperature	°C or K
(η_{PV})	PV module efficiency	%
(η_{GT})	Gas turbine efficiency	%
(η_{el})	Electrical efficiency	%
(CF)	Capacity factor	%
(P_{min})	Minimum turbine output power	kW
(P_{max})	Maximum turbine output power	kW
(F)	Fuel consumption	m ³
(SFC)	Specific fuel consumption	m ³ /kWh
(E_{fuel})	Fuel energy input	kWh/year
(SOC)	State of charge of battery	%
(C_{bat})	Battery capacity	kWh
(E_{in})	Battery charging energy	kWh/year
(E_{out})	Battery discharging energy	kWh/year
(L_{bat})	Battery losses	kWh/year
(NPC)	Net present cost	\$
(COE)	Cost of energy	\$/kWh
$(O\&M)$	Operation and maintenance cost	\$/year
(CO_2)	Carbon dioxide emissions	kg/year or t/year
(AUC)	Area under the consumption curve	kWh
(m)	Mass flow rate	kg/s
$(\dot{m}_a)$	Air mass flow rate	kg/s
$(\dot{m}_f)$	Fuel mass flow rate	kg/s
$(\dot{m}_g)$	Combustion gas mass flow rate	kg/s
(h)	Specific enthalpy	kJ/kg
(Ex)	Exergy	kJ
$(\dot{E}_X)$	Exergy rate	kW
Symbol	Designation	Unit
(Ex_d)	Exergy destruction	kW
(PR)	Pressure ratio	-

(P)	Pressure	bar
(V)	Voltage	kV or V
(f)	Frequency	Hz

ABBREVIATIONS

Abbreviation	Meaning
PV	Photovoltaic
GT	Gas Turbine
BESS	Battery Energy Storage System
HOMER	Hybrid Optimization of Multiple Energy Resources
DSM	Demand Side Management
ToU	Time of Use
SCADA	Supervisory Control and Data Acquisition
VSD	Variable Speed Drive
HRSG	Heat Recovery Steam Generator
AC	Air Compressor
CC	Combustion Chamber
NPC	Net Present Cost
COE	Cost of Energy
RES	Renewable Energy Sources

GENERAL INTRODUCTION

GENERAL INTRODUCTION

The industrial sector is one of the largest consumers of energy worldwide and plays a significant role in greenhouse gas emissions. Among industrial activities, cement manufacturing is particularly energy-intensive due to the large electrical and thermal energy requirements associated with crushing, grinding, clinker production, and material handling processes. As concerns about climate change, energy security, and sustainable development continue to grow, industries are increasingly encouraged to adopt cleaner and more efficient energy solutions.

In Algeria, the cement industry represents a strategic sector for economic development and infrastructure growth. However, the heavy dependence of cement plants on conventional fossil-fuel-based energy sources results in high operating costs and considerable environmental impacts. Consequently, the integration of renewable energy technologies has become an attractive option for improving energy efficiency, reducing fuel consumption, and decreasing carbon emissions.

The Adrar region, located in southern Algeria, possesses one of the highest solar energy potentials in the world, characterized by high solar irradiation levels and long sunshine durations throughout the year. These favorable climatic conditions create significant opportunities for the deployment of photovoltaic systems in industrial applications. In this context, the GICA Timokten cement plant represents an ideal case study for evaluating the feasibility of integrating renewable energy into an energy-intensive industrial process.

The main objective of this work is to investigate the potential contribution of a hybrid energy system combining photovoltaic generation, battery energy storage, and the existing gas turbine to support the electrical demand of the Timokten cement plant. The study aims to evaluate the technical, economic, and environmental benefits of renewable energy integration while maintaining the reliability and continuity of industrial operations.

To achieve the objectives of this study, the dissertation is organized into three chapters. The first chapter presents an energy analysis of the Timokten cement plant, including the description of the production process, the evaluation of energy consumption patterns, and the analysis of the existing gas turbine system that currently supplies the plant's electrical demand.

The second chapter focuses on the assessment of renewable energy resources available in the Adrar region. Particular attention is given to solar energy potential through the analysis of solar irradiation data and climatic conditions, in order to evaluate the suitability of photovoltaic technology for industrial applications.

The third chapter is devoted to the simulation and optimization of the proposed hybrid energy system using HOMER Pro software. Different configurations integrating photovoltaic generation, battery storage, and the existing gas turbine are modeled and compared from technical, economic, and environmental perspectives to determine the most suitable solution for the energy transition of the cement plant.

Finally, the thesis concludes with a summary of the main findings, the limitations encountered during the study, and recommendations for future research and development in the field of renewable energy integration within industrial systems.

CHAPTER 1 ENERGY ANALYSIS OF THE CEMENT
PLANT

1.1 Introduction

The cement industry is one of the most energy intensive industrial sectors, requiring large amounts of electrical and thermal energy throughout the production process. Improving energy efficiency and reducing dependence on fossil fuels have become essential challenges for ensuring sustainable industrial development. Before implementing renewable energy solutions, a detailed understanding of the plant's energy consumption and existing power generation system is necessary. Therefore, this chapter presents an analysis of the GICA Timokten cement plant, focusing on its production process, energy consumption profile, major electrical loads, and the performance of the existing gas turbine. The results obtained provide the foundation for evaluating the integration of renewable energy technologies in the following chapters.

1.2 Description of the Cement Manufacturing Process

The cement production process consists of several key stages, each requiring significant energy input [1]



Figure 1-1 Ultra wide picture for the field of GICA cimentrie industry Timokten, Adrar

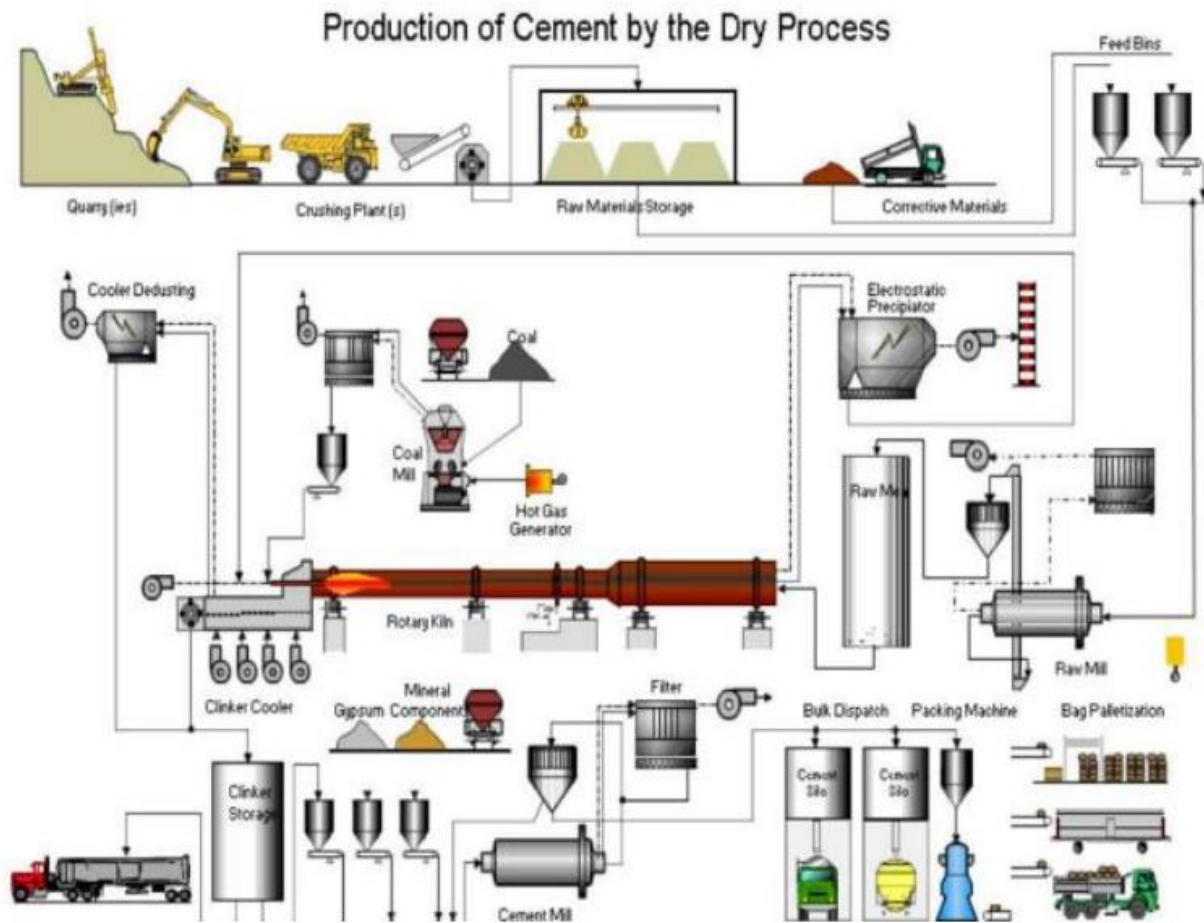


Figure 1-2 The making of cement the process [1]

1.2.1 Quarrying and Raw Material Preparation:

In the quarrying process, raw materials such as limestone, clay, or shale are extracted from quarries using blasting or drilling techniques. The extracted materials are then transported to the cement plant, where they undergo crushing, grinding, and blending to create a uniform raw mix. This process ensures that the raw materials are properly proportioned and homogenized, allowing for the consistent quality and chemical composition of the raw mix. [1]



Figure 1-3 clay deposit [2]



Figure 1-4 storage of gypsum [2]



Figure 1-5 Iron storage [2]

1.2.2 Raw Mix Grinding:

The raw mix, consisting of crushed and blended raw materials, is further ground into a fine powder in a grinding mill. The most used mills for this purpose are ball mills or vertical roller mills . These mills utilize mechanical forces to reduce the particle size of the raw mix, increasing its surface area and enhancing the chemical reactions during the subsequent processes. [1]



Figure 1-6 Pre-homogenization piling yard at the cement plant [2]



Figure 1-7 Storage of mixed materials in storage warehouses before entering the reaction stage at GICA cement plant

➤ **Crusher after clinker firing**

It is a cylinder crusher, it finds their application when crushing an ore friable, clogging and non-abrasive, like limestone. The principle of operation of the cylinder crusher is extremely simple the latter consists of two cylinders arranged horizontally and rotating in the opposite direction relative to each other [1]

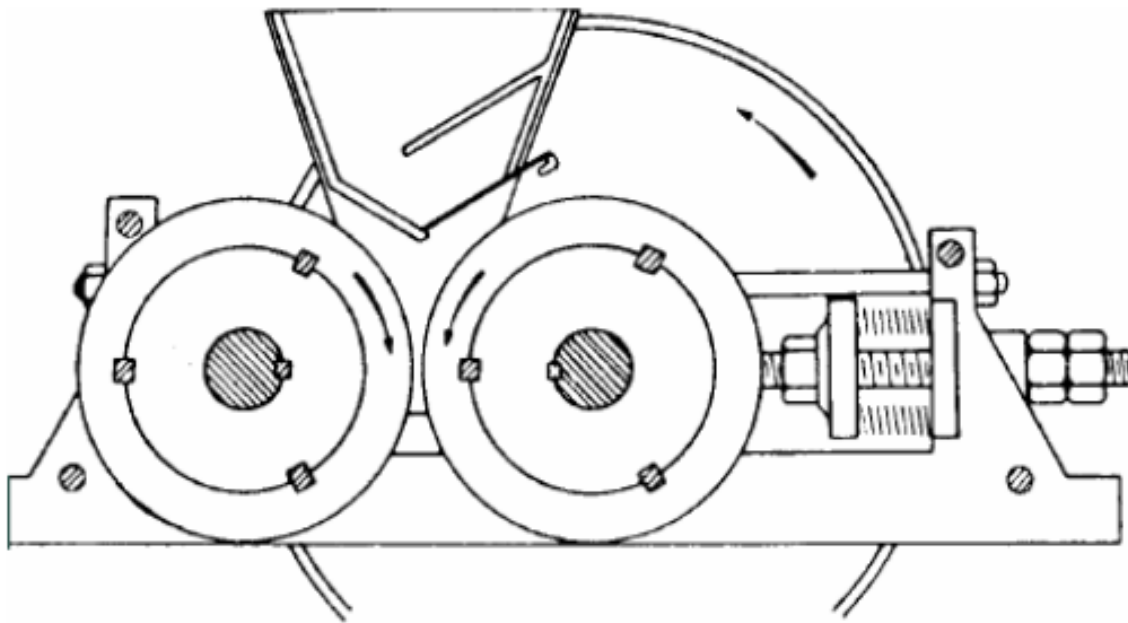


Figure 1-8 Cylindrical crusher after [2]

1.2.3 Preheating and Pre-calcining:

To improve energy efficiency and reduce fuel consumption, the powdered raw mix undergoes preheating and precalcination. The raw mix enters a preheater, where it comes into contact with hot gases from the kiln. This preheating step helps to remove moisture and preheat the raw mix before it enters the kiln. The preheated raw mix then moves to the pre-calciner, where partial decomposition of carbonates occurs, further reducing the energy requirement during clinker formation.[1]



Figure 1-9 Raw material dosing station [2]

1.2.4 Clinker Production:

The preheated and precalcined raw mix is fed into a rotary kiln, a large cylindrical furnace. Inside the kiln, the raw mix is subjected to high temperatures (around $1,450^{\circ}\text{C}$ or $2,642^{\circ}\text{F}$) and a long residence time. This thermal treatment causes chemical reactions, including the formation of clinker. A clinker is a nodular material with hydraulic properties that serve as the main ingredient for cement. The composition and quality of clinker have a significant impact on the properties of the final cement product. [1]



Figure 1-10 ball mill [2]

1.2.5 Cement Grinding:

The clinker, along with a small amount of gypsum, is finely ground in a cement mill to produce cement. The grinding process is typically carried out using ball mills, which are horizontal rotating cylinders containing steel or ceramic balls. The clinker and gypsum are fed into the mill, where they are ground to a fine powder. The addition of gypsum regulates the setting time of cement and enhances its workability.

1.2.6 Cement Storage and Packaging:

After grinding, the cement is stored in silos before being dispatched to customers. Proper storage conditions are crucial to maintaining the quality and stability of the cement. Depending on the mode of transportation and customer requirements, cement can be shipped in bulk or packed into bags for distribution.[1]



Figure 1-11 Cement factory shipping area

1.3 Global Energy Balance of the Cement Plant

The cement industry is an energy intensive industry. In India the industry accounts for 10.3% of total fuel consumption in the manufacturing sector. The energy costs account for about 26% of the manufacturing cost of cement. In terms of the primary energy usage about 25% of the input energy is electricity while 75% is thermal energy. The specific energy consumption varies from about 3.40 GJ/t for the dry process to about 5.29 GJ/t for the wet process. The best practice specific energy consumption in India is 3.06 GJ/t while in some countries of the world it is lower than 2.95 GJ/t. The higher specific energy consumption in India is partly due to the harder raw material and the poor quality of the fuel. Waste heat recovery from the hot gases in the system has been recognized as a potential option to improve energy efficiency. However there are few detailed

thermodynamic analyses of operating cement plants that evaluate the option of waste heat recovery. This paper builds up an energy balance for an operating plant and estimates the power that can be generated from the waste heat streams. The process of manufacture of cement can be divided into three basic steps, preparation of raw materials, pyroprocessing to produce clinker, and grinding and blending clinker with other products to make cement. The raw materials obtained from the quarry are crushed, ground and mixed as a slurry in the wet process and a powder in the dry process. This mixture is then fed into a calciner and preheater before being fed into the kiln, for pyroprocessing (clinker formation). The kiln reaches temperatures greater than 1450 °C. The clinker nodules produced and any additives are then ground to the desired fineness in the cement grinder. Pyroprocessing consumes 99% of the fuel energy while electricity is mainly used to operate both raw material (33%) and clinker (38%) crushing and grinding equipment. Pyroprocessing requires another 22% of the electricity hence it is the most energy intensive step of the production process.

1.3.1 System definition and data source

The cement plant considered is Maihar Cement—Unit 2, Madhya Pradesh, India. A schematic of the plant **Figure 1 12** shows the flow of various streams and the components of the plant. The plant runs on dry process with a five stage suspension preheater and an inline calciner. The production capacity is 3800 tonne per day. The specific energy consumption for the plant is 3.7 GJ per ton.

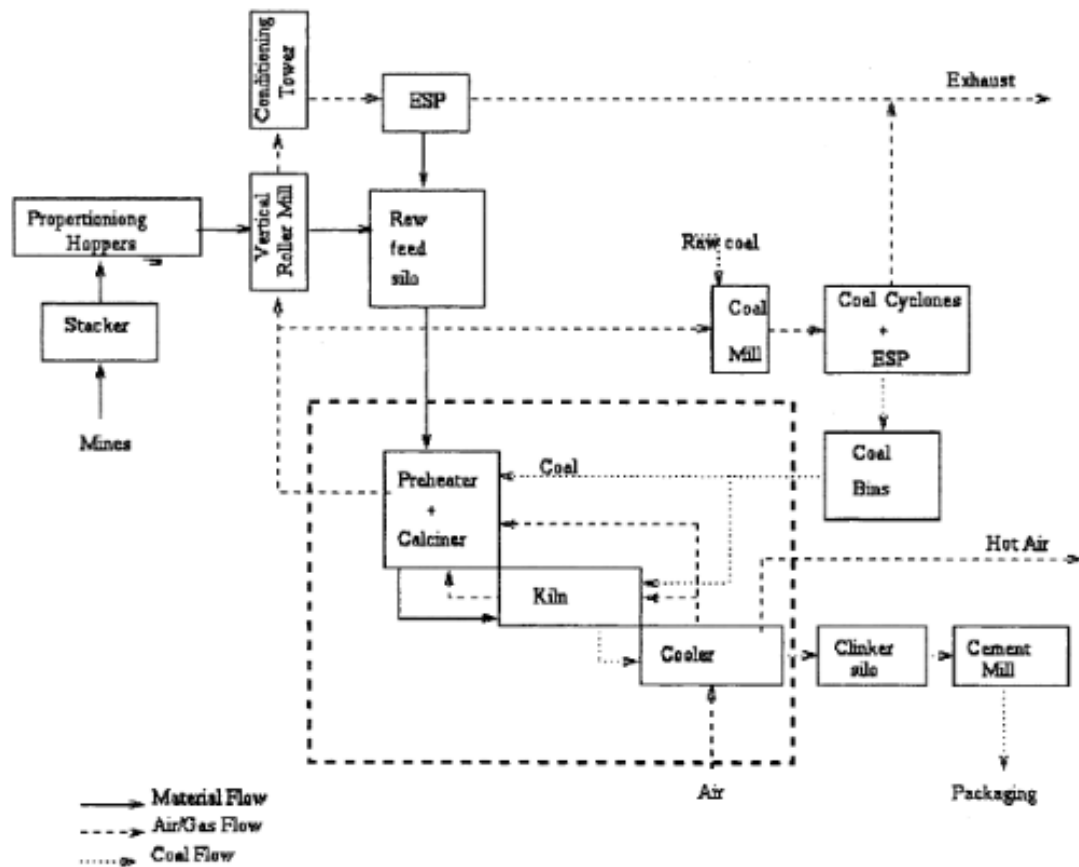


Figure 1-12 chematic of the Maihar cement plant [3]

of clinker and 87 kWh (0.31 GJ) of electricity per tonne of cement. Since it is one of the more efficient plants in the country it is suitable as a reference case for study. The system under consideration for the energy balance is enclosed in the rectangular box in **Figure 1 12**. It is the pyroprocessing unit that includes the preheater, the calciner, the kiln and the clinker cooler. The streams into the system are the raw material, the air into the cooler and the coal fired into the kiln and the calciner. The streams leaving the system are clinker out from the cooler, the exhaust gases from the preheater and the hot air out from the cooler. The system along with all the data available is summarized in **Figure 1 13**.

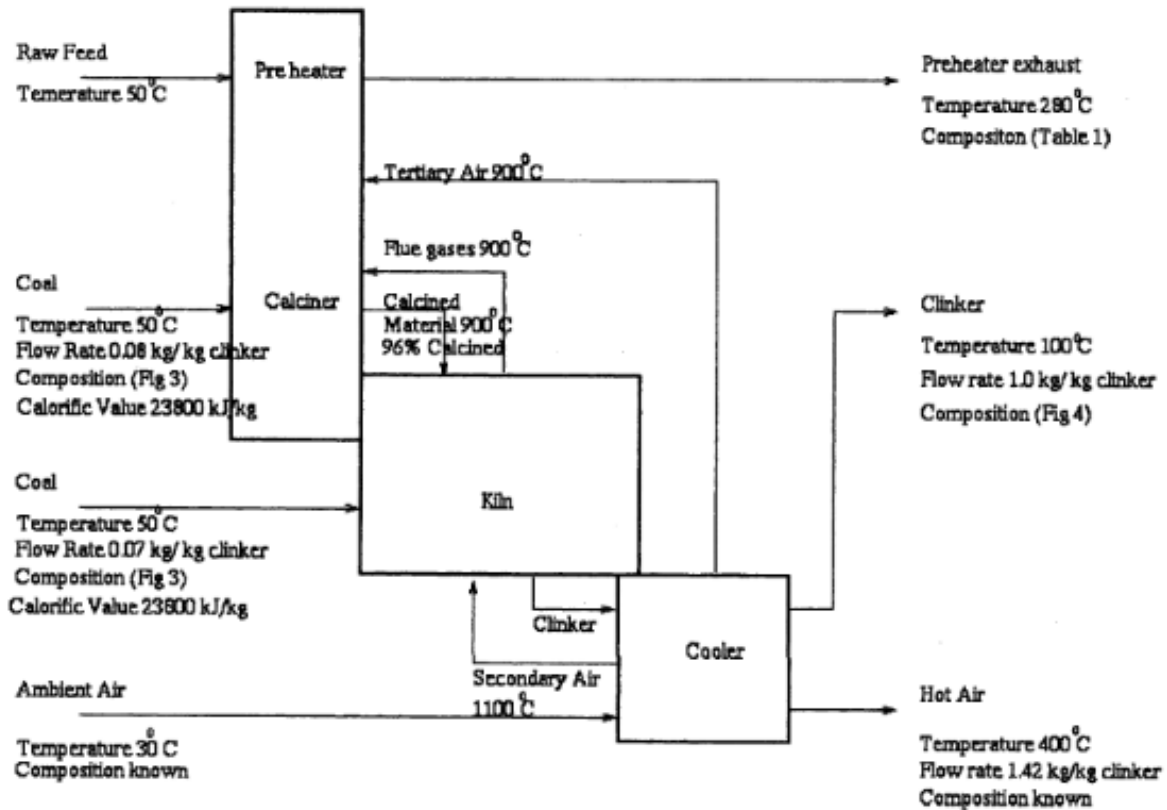


Figure 1-13 Data available for the streams entering the system[3]

1.3.2 Power generation

The two waste heat streams are available for power generation and it is proposed that a waste heat recovery steam generator (WHRSG) be used to generate steam that is passed through a steam turbine to generate power. A schematic is shown in **Figure 1 14**. The nature of the two streams is different, the preheater exhaust is heavily dust laden (70 g/Nm³) hence separate exchangers should be designed for the two streams.

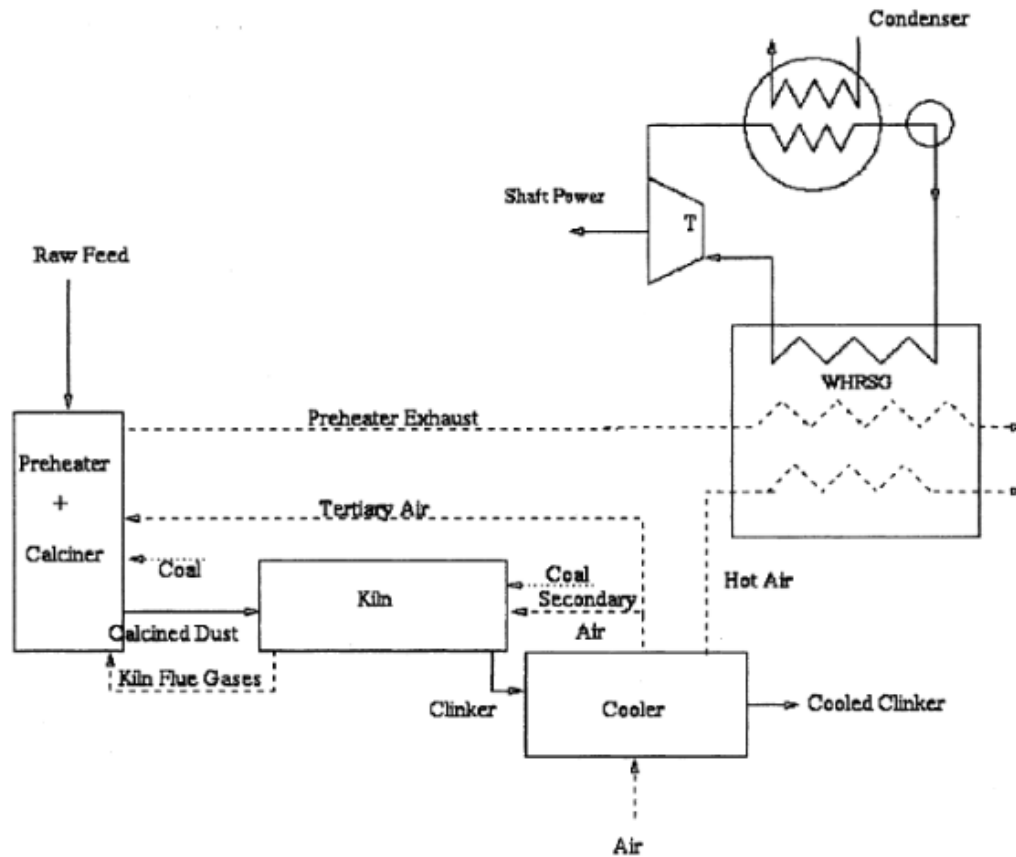


Figure 1-14 Schematic for the power generation system[3]

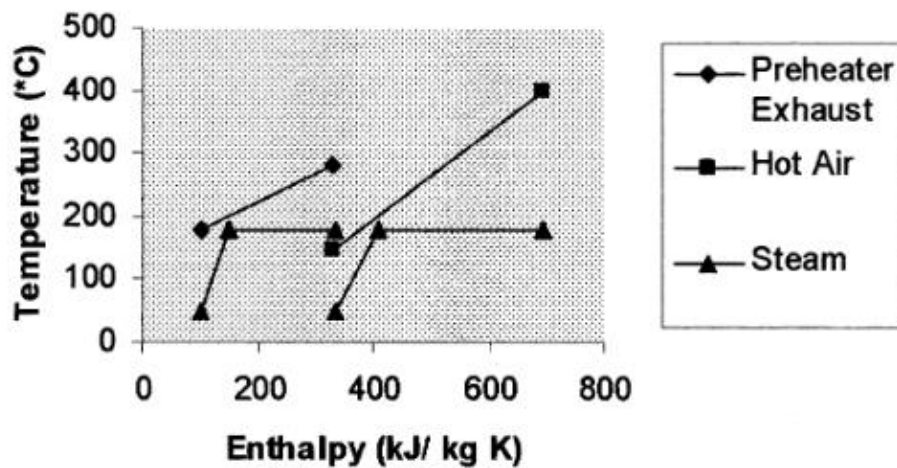


Figure 1-15 Temperature–enthalpy diagram for the HRSG [3]

Based on the temperature of the streams a steam cycle is selected. A pinch point (minimum approach temperature) of 20 °C is taken. The steam parameters are taken as 10 bar saturated at the

steam turbine inlet. The condenser temperature is selected at 50 °C as the ambient temperature reaches higher than 40 °C in the summer months. The streams in the WHRSG are represented on a temperature enthalpy diagram in **Figure 1 15**. From the stream temperature it is seen that exchangers in parallel should be used for higher recovery as compared to a series configuration for the two streams. The preheater exhaust stream gets cooled to 178 °C while the hot air stream gets cooled to 140 °C. Both these stream temperatures are above the acid dew point of the streams. The power generated for the system is about 100 kJ/kg clinker which amounts to 4.4 MW with a production rate of 3800 tonne per day. This amounts to about 30% of the total power requirement of the plant. The design of a WHRSG for the gas streams needs to consider that the flue gases are heavily dust laden. Prediction of the performance of the heat exchanger would require an estimation of the fouling characteristics of the streams. The dust is also likely to cause abrasion particularly at the bends and needs to be considered while design. Prediction of the fouling characteristics of the dust laden gases requires experimentation. Since the power recoverable is significant, a project to predict the fouling behavior is suggested. Theoretical models for prediction of deposition of dust from streams can be used for a first estimate of the fouling characteristics. The implementation of the system would require special consideration of the layout of the system, and might pose a problem in some of the older plants that have undergone a number of structural changes. The primary energy efficiency of the cement plant with the cogeneration system is 60% which indicates an improvement of 10%. The cost of electricity supplied by the electricity board is about Rs. 4.5 (US\$ 0.096) per kWh hence for the plant the savings from the recovered energy amount to around Rs. 16 crores (US\$ 3.4 million) per annum for a working of 330 days in an year, assuming a shutdown of about 5 days for system maintenance due to excessive fouling caused by the dust, every three months. The first cost estimate for the system is about Rs. 5 crores per MW and taking into account the operating costs, the payback period for the system is estimated within 2 years. The production of cement in India is about 110 Mt per annum, extrapolating the results about 450 MW of power can be generated from the various plants in India. A large number of plants in the country are relatively inefficient when compared with the plant considered with a higher temperature of the exhaust gases, hence it is expected that the power generated will be higher than estimated. One of the prime considerations in the design of the system has been to make it a retrofit and using the gas streams only down stream of the process and the operation of the kiln, calciner and preheater stays unaffected. This will ensure easier acceptability of the option

and if required a shut down of the cogeneration system can be taken without affecting the cement plant output. [3]

1.4 Energy Consumption Profile

Time-of-use (ToU) pricing structures were implemented by South African electricity utility Eskom as one of the important approaches of demand-side management (DSM). Their purpose was to persuade, especially large industrial consumers, such as cement manufacturing plants, to shift their electrical loads by means of a ToU tariff which is sectioned into time of day (viz. peak, standard, and off-peak periods) and season (viz. summer, winter). The ToU tariffs (1 April 2010–31 March 2011) during the summer are in c/kWh; 38.73 peak, 23.74 – standard, 16.61 – off-peak, and during the winter are; 138.56 – peak, 36.05 standard, 19.29 – off-peak as can be seen in **Figure 1 16**.

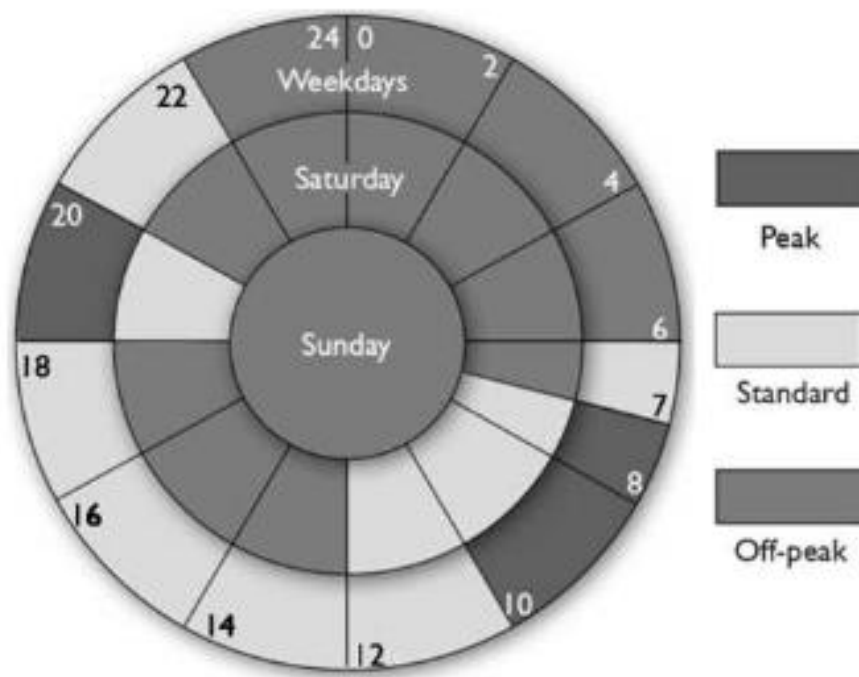


Figure 1-16 Time-of-use tariff structure implemented by electrical utility Eskom (2010) [4]

Table 1-1 Equipment Cementrie at GICA plant Adrar timokten and rated power of each equipment with the type of start

Equipment	Voltage KV	Rated Power KW	Start Mode	Power plant unit
Hammer Crusher A	10	800	Liquid rheostat	2
Hammer Crusher B	10	800	Liquid rheostat	2
High pressure belt	10	220		1
Raw Mill Motor	10	2500	Liquid rheostat	3
Raw Mill Fan Motor	10	2500	VDS	1
HT Fan Motor	10	1600	VDS	1
Exhaust Motor	0.69	710	VDS	1
Exhaust Motor	0.69	630	VDS	1
Roller Press A Motor	10	710	Liquid rheostat	
Roller Press A Motor	10	710	Liquid rheostat	
CeentMill A Motor	10	1600	Liquid rheostat	
CeentMill A Fan Motor	0.69	630	VDS	1
Roller Press B Motor	10	710	Liquid rheostat	
Roller Press B Motor	10	710	Liquid rheostat	
CeentMill B Motor	10	1600	Liquid rheostat	
CeentMill B Fan Motor	0.69	630	VDS	1
Kiln Soil Machine		450	VDS	1

Table 1-1 presents the main electrical equipment installed at the GICA Timokten cement plant, together with their rated power, operating voltage, and starting methods. The inventory highlights the high electrical power requirements of the cement manufacturing process and confirms that cement production is an energy-intensive industrial activity.

The data show that the largest electrical loads are associated with the grinding and material-processing stages. In particular, the raw mill motor and raw mill fan motor each have a rated power of 2500 kW, making them among the most energy-demanding components in the plant. Other major consumers include the cement mill motors, rated at 1600 kW, and the high-temperature fan motor rated at 1600 kW. These units are essential for maintaining continuous production and therefore contribute significantly to the overall electricity demand of the facility.

The table also indicates that several high-power motors operate at a voltage level of 10 kV and use liquid rheostat starting systems. This starting method is commonly employed for large motors because it limits the inrush current during startup and reduces mechanical stress on the equipment. Variable Speed Drives (VSDs) are used for other motors, providing greater operational flexibility and allowing speed control according to process requirements, which can improve energy efficiency.

Furthermore, the presence of multiple crushing, grinding, ventilation, and conveying units demonstrates the complexity of the cement production process and explains the continuous and substantial electrical demand observed in the plant. The concentration of high-power equipment in the grinding and airflow systems suggests that these areas offer significant opportunities for energy optimization and efficiency improvements.

Overall, **Table 1-1** provides a detailed overview of the plant's electrical infrastructure and serves as a basis for understanding the energy consumption profile of the facility. The high installed power of the equipment justifies the investigation of alternative energy solutions, such as the integration of photovoltaic generation and energy storage systems, to reduce operating costs, fuel consumption, and environmental impacts while maintaining reliable plant operation.

1.4.1 Electrical consumption profile

With the available load-shifting hours having been established, it is necessary to determine whether the mill motor would be able to achieve the load-shift and how it would affect the electrical consumption profile. These available hours may be restricted by DSM load-shifting regulations. The original profile of the mills may not increase during Eskom's standard time. Therefore, the load-shifting hours have to be taken up entirely during off-peak periods. This is limited by the operating capacity of the mill motor, as it is sometimes not possible to maintain production solely during the off-peak periods. The degree to which the available hours are limited can be determined by optimizing usage profiles to remain below operating capacity. Another spreadsheet-simulation is used to determine the best possible load-shifting strategy without exceeding motor installed capacity or raising the standard time usage. The simulation calculates an updated profile for the preceding 31-day range. This will determine how present performance compares to the original baseline. If the standard time values of the updated profile are not above the original values, load may be shifted from peak periods. If not, an amount of Load-shifting would also have to occur during standard time for the following days to lower the profile.

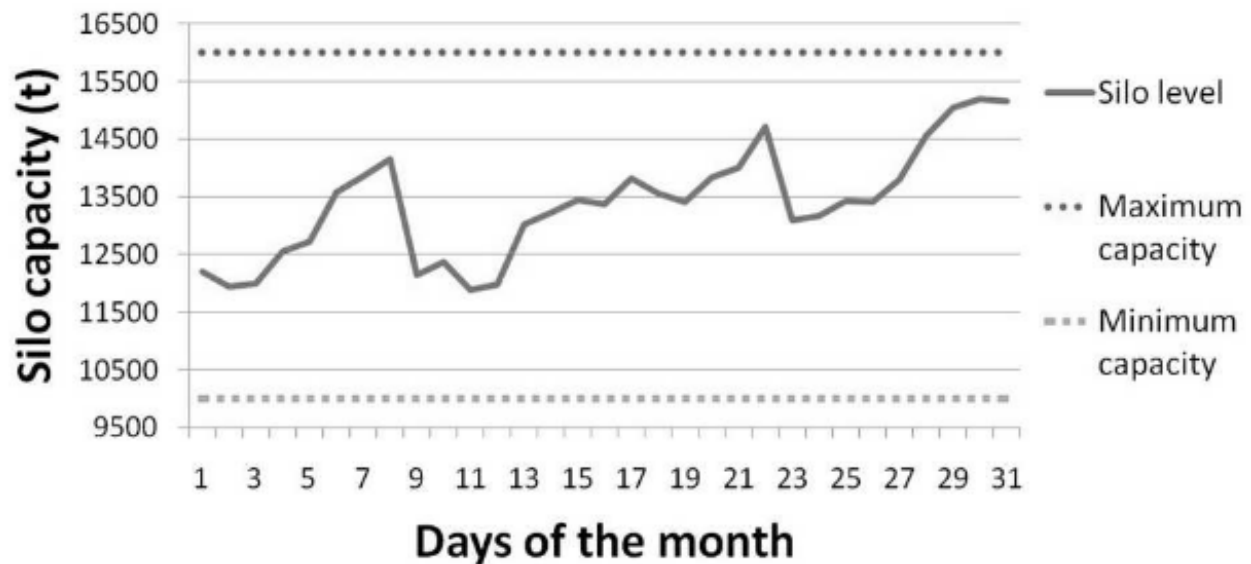


Figure 1-17 Change in raw meal silo level with six hours of load-shifting per day, calculated by spreadsheet-simulation [4]

The new profile must have the same total area under the curve (AUC). The AUC indicates how often the mill motors are run and therefore, indicative of the mill's production. If the AUC is lowered, the production will be adversely affected. The new profile consists of the original baseline with two changes:

1. A number of peak period hours are equated to zero. These are the load-shifted hours. The maximum number of hours is calculated by the previous silo simulations;
2. The off-peak usage is increased to ensure the AUC is not reduced during the load-shifting scheme.

If the off-peak values are higher than the operating capacity of the mill motors, then the consumption profile is not achievable and less load-shifting hours need to be implemented. The new off-peak power consumption should be marginally, say 2%, lower than the operating capacity of the motor to allow for unplanned breakages. With a 2% margin, an extra 14.4 hours per month of unplanned breakages can occur during off-peak periods without affecting production. With this logic an optimized profile was developed. **Figure 1 17** presents the achievable load-shifting scheme for the mills calculated from the usage simulation. The profiles of Raw Mill #3 illustrate how only two hours of load-shifting are possible without changing standard time usage or exceeding the operating capacity of 4 MW. The areas under the curve for both profiles are equal, indicating that production is not affected. The extra hours available for load-shifting will likely be taken up by unplanned stoppages due to over-full silo levels during standard and off-peak periods. This can also be implemented during morning peak periods but have to be planned on a daily basis with respect to actual baseline, occurring incidents and silo levels of that day.

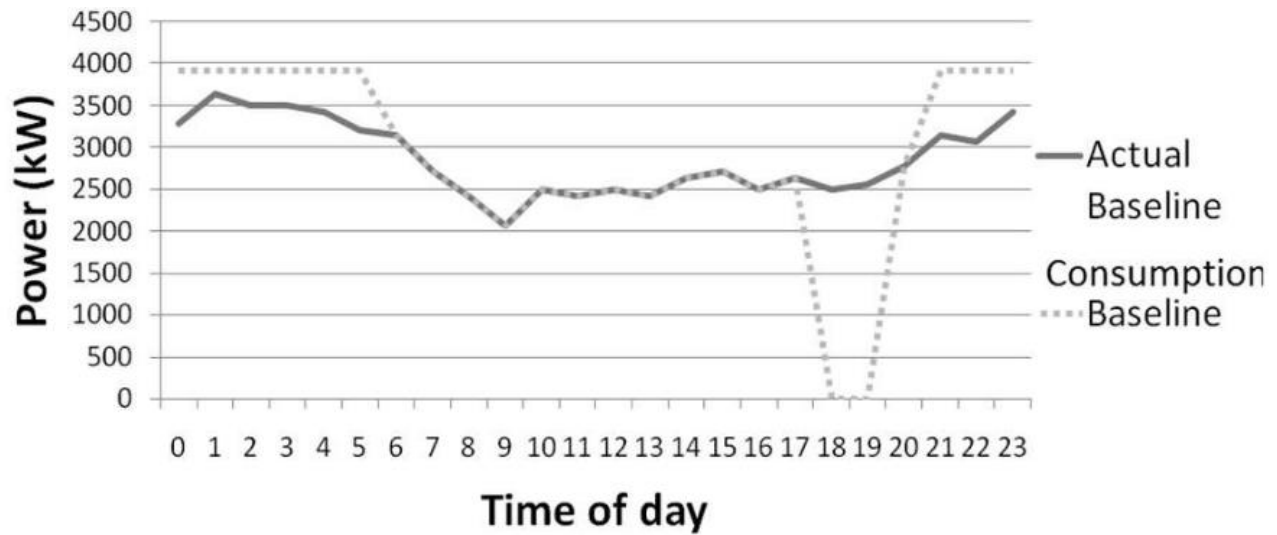


Figure 1-18 Raw Mill #3 optimized profile, calculated with spreadsheet-simulation [4]

Table 1-2 Consumption Profile at GICA cement plant

	Period	Consumption (kW/h)		
		Gaz Turbine	Local Electric group	TOTAL (Gaz Turbine + Local Electric group)
2025	APRIL	800 594	380 560	1 181 154
	MAY	2 499 663	93 688	2 593 351
	JUNE	2 371 439	0	2 371 439
	JULY	2 471 824	199 896	2 671 720
	AUGUST	3 221 588	31 712	3 253 300
	SEPTEMBER	2 893 469	86 656	2 980 125
	OCTOBER	3 660 420	44 472	3 704 892
	NOVEMBER	3 408 356	145 256	3 553 612
	DECEMBER	2539 387	0	3539387

Table 1-2 presents the monthly electrical energy consumption of the GICA Timokten cement plant during the period from April to December 2025. The results indicate significant variations in energy demand throughout the year, reflecting changes in production activity and operational requirements.

The highest total electricity consumption is recorded in October, reaching approximately 3.70 GWh, followed by November and December. In contrast, the lowest consumption occurs in April, with approximately 1.18 GWh. This variation suggests that the plant operates under different production levels depending on seasonal and operational conditions.

The data also show that the gas turbine represents the principal source of electricity supply for the plant, providing the majority of the consumed energy. Electricity imported from external sources or local generation contributes a smaller share of the total demand. This confirms the strong dependence of the cement plant on natural-gas-based power generation, which increases fuel consumption and greenhouse gas emissions.

The observed energy demand profile highlights the importance of implementing energy optimization measures and integrating renewable energy sources. Since the plant exhibits substantial and continuous electricity consumption, photovoltaic generation can effectively offset part of the daytime demand, thereby reducing the operating load of the gas turbine and improving the overall energy efficiency of the system. The consumption profile presented in this table therefore serves as a fundamental basis for sizing and evaluating the hybrid PV–Gas Turbine–Battery system proposed in this study.

1.4.2 Performance of the silo simulation

Figure 1 22 provides a comparison of the actual silo level during the pilot study against the level generated by the silo simulation. The operating hours obtained from **Figure 1 23** were used in the simulation to create the change in level for every hour. The simulation has an average error of 3.5%. This deviation may be due to the changing flow rates of the equipment. The simulation uses the average flow rate values obtained from the three months of his torical SCADA data. Raw Mill #3 has a flow rate standard deviation of 15%. The actual fluctuation of flow rates experienced would most likely bring about the differences that are seen in **Figure 1 21**. With a 3.5% error, the simulation would be able to provide acceptable information regarding the changing levels of the silos over a monthly period.

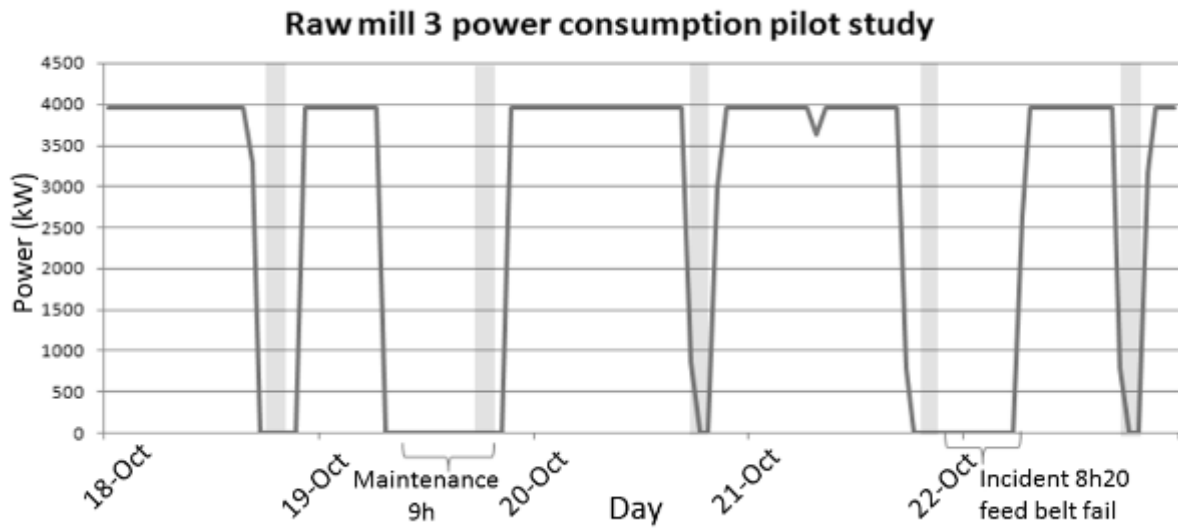


Figure 1-19 RM3 power consumption pilot study [4]

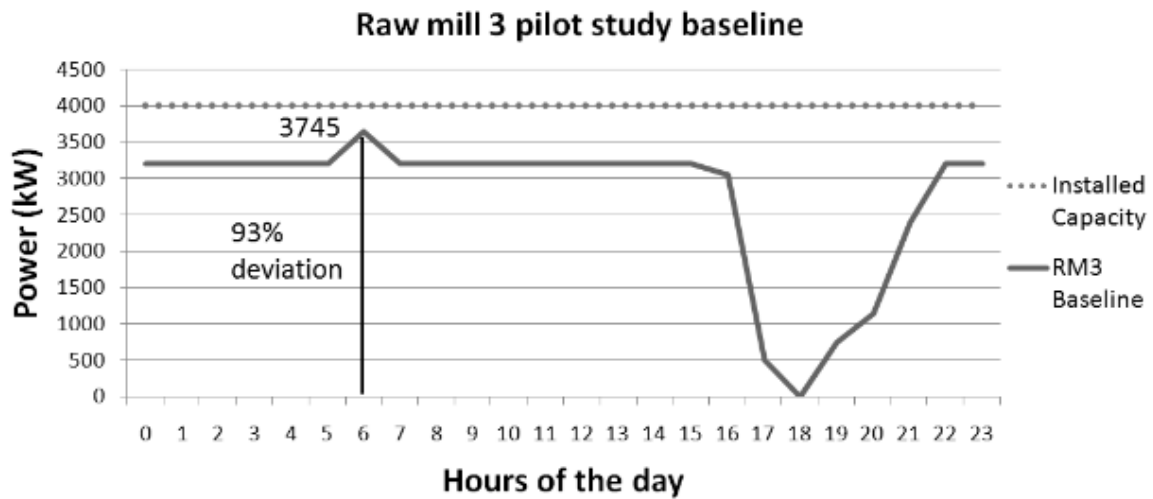


Figure 1-20 RM3 pilot study baseline [4]

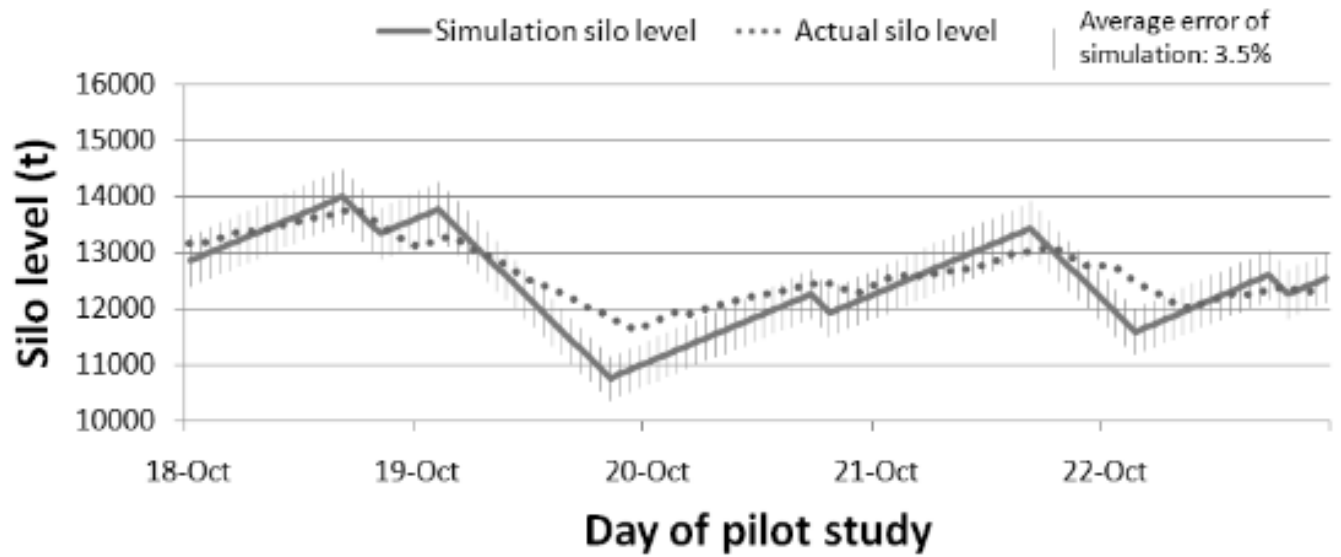


Figure 1-21 Simulation comparison [4]

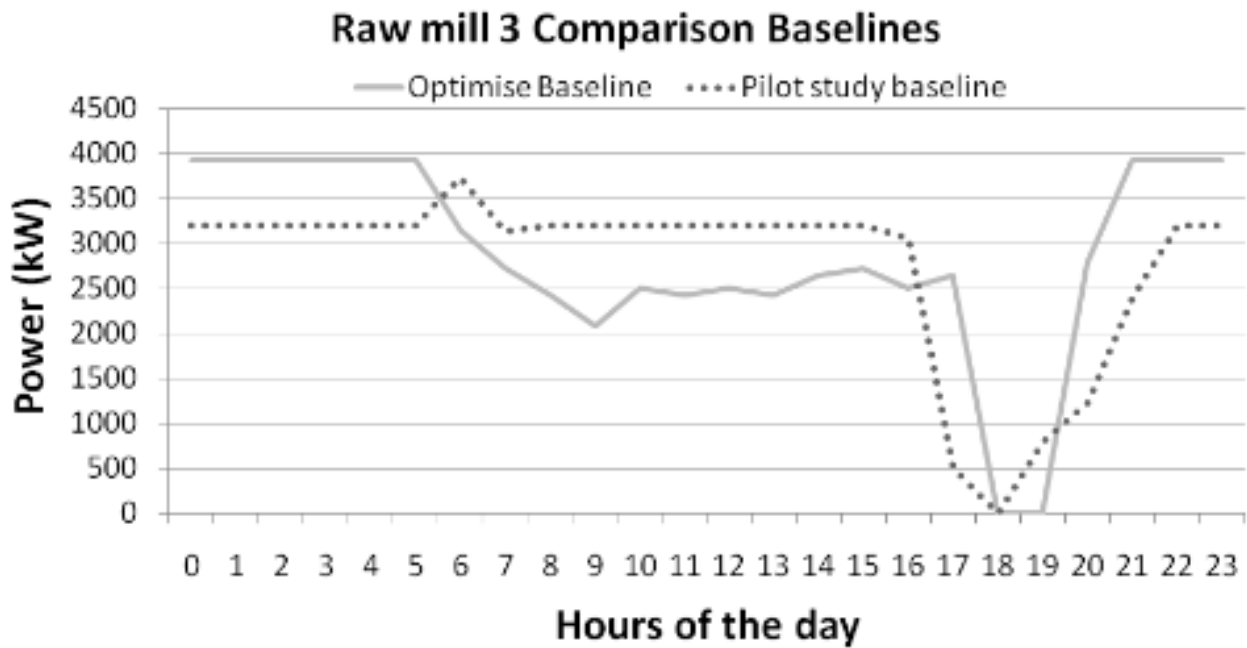


Figure 1-22 Comparative profiles [4]

1.5 Analysis of the Existing Gas Turbine

The increasing global demand for electricity, driven by economic growth, population expansion, and industrial development, has intensified the need for more efficient power generation systems. One approach to addressing this challenge is improving the performance of existing power plants. Gas turbine power plants, such as the 20 MW facility in Pekanbaru, Indonesia, can benefit from efficiency enhancement through exergy analysis. Unlike conventional energy analysis based solely on the first law of thermodynamics, exergy analysis incorporates the second law of thermodynamics, allowing the evaluation of energy quality and the identification of irreversibilities within system components. This method is widely used for the design, optimization, and performance assessment of power plants. Previous studies have demonstrated that exergy analysis is an effective tool for locating major sources of exergy destruction and evaluating component efficiencies in gas turbine and combined-cycle power plants. Results from various investigations indicate that factors such as turbine inlet temperature, pressure ratio, and combustion processes significantly influence exergetic performance. Therefore, the main objective of this study is to assess the performance of a gas turbine power plant and identify the components responsible for the highest exergy destruction, providing insights for efficiency improvement and optimization.

1.5.1 Methodology

➤ Data Collection

Data such as average daily power generated, pressure, and temperature of different points, mass flow rate (air, fuel and gas of combustion) used for this study were collected from the gas turbine power plant's record log books. Parameters that could not be directly measured were derived using appropriate existing equations such as combustion temperature, outlet temperature from combustion chamber, and inlet turbine. From the record of log books, the ambient temperature is 300.03 K and the ambient pressure was assumed to be 1.01325 Bar.

➤ System Description

The gas turbine power plant of 20 MW used in this study is an open cycle single shaft system and is located at Pekanbaru, Riau. The schematic of the 20 MW gas turbine power plant is shown in **Figure 1 23** The system consists of an Air-Compressor (AC), Combustion Chamber (CC), and Gas Turbine (GT). Isentropic efficiency of the compressor and gas turbine are assumed to be 86%, and the pressure drop through the combustion chamber is assumed to be 3% .

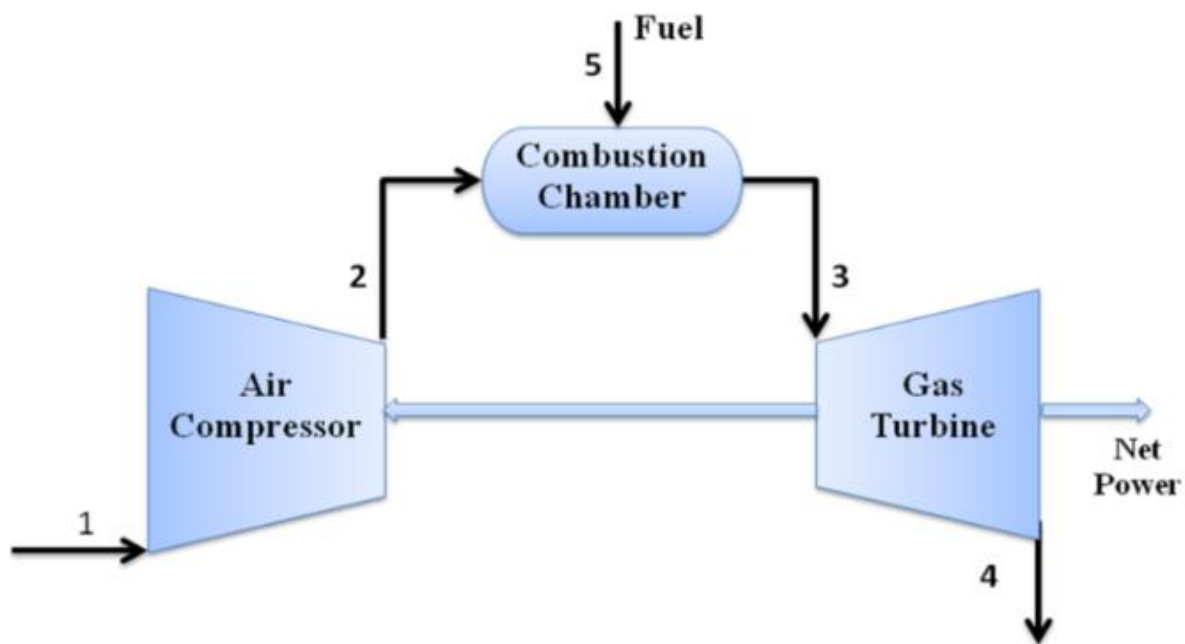


Figure 1-23 Schematic of methodology [5]

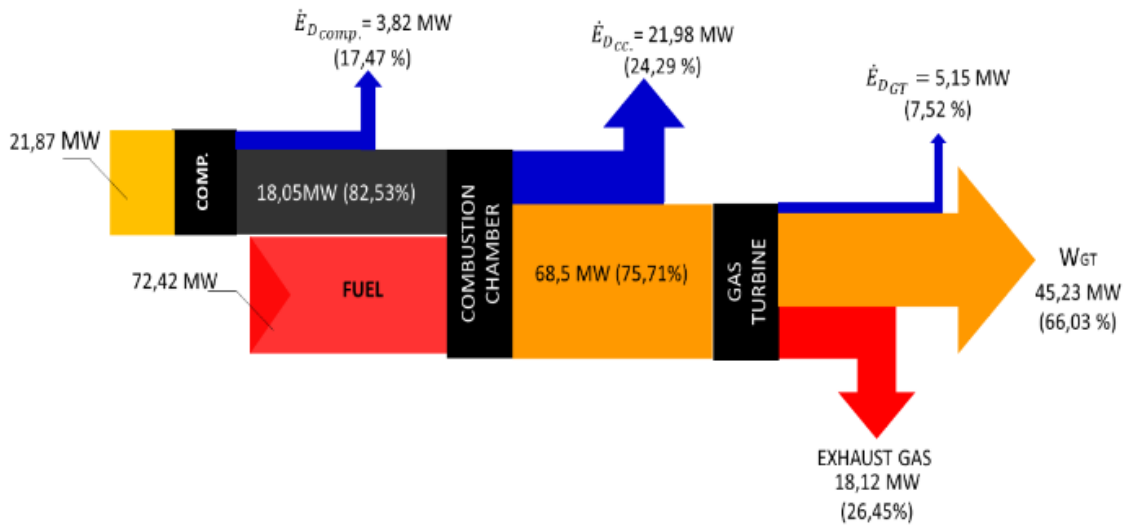


Figure 1-24 Grassmann diagram of gas turbine power plant [5]

1.5.2 Gas Turbine Operation in the Cement Plant

The gas turbine serves as the primary source of electrical energy for the cement plant, ensuring a continuous and reliable power supply required for industrial production processes. It converts the chemical energy contained in natural gas into mechanical energy and subsequently into electrical energy through an electric generator.

The operating principle of the gas turbine is based on three main stages: air compression, combustion, and expansion. Ambient air is first drawn into the compressor, where its pressure is increased. The compressed air is then mixed with natural gas in the combustion chamber and ignited. The combustion process produces high-temperature and high-pressure gases that expand through the turbine blades, causing the turbine shaft to rotate. This rotational mechanical energy is transmitted to the generator, which produces electricity for the plant.

In the GICA Timokten cement plant, the gas turbine plays a crucial role in meeting the continuous electrical demand of various production units, including crushers, mills, conveyors, fans, and auxiliary equipment. Because cement manufacturing requires uninterrupted operation, the gas turbine provides stable and dispatchable power independent of weather conditions or solar resource availability.

Within the proposed hybrid energy system, the gas turbine operates in coordination with the photovoltaic system and battery storage. During periods of high solar irradiation, part of the electrical demand is supplied by the PV array, reducing the turbine's fuel consumption. When solar generation is insufficient or unavailable, particularly during nighttime hours, the gas turbine compensates for the power deficit and maintains the reliability of the electricity supply. This complementary operation improves the overall efficiency of the hybrid system while reducing fuel consumption and greenhouse gas emissions.

Therefore, the gas turbine remains an essential component of the energy system, providing operational flexibility, reliability, and continuous power generation required for cement production [5]

1.6 Conclusion

This chapter provided a comprehensive analysis of the energy characteristics of the GICA Timokten cement plant. The results revealed that cement production is a highly energy-intensive process characterized by substantial and continuous electricity demand throughout the year. The analysis of the consumption profile showed significant variations in energy use, with the highest demand reaching approximately 3.7 GWh in October 2025. Furthermore, the study demonstrated that the gas turbine remains the principal source of electricity generation, ensuring reliable operation of the plant while contributing significantly to fuel consumption and greenhouse gas emissions. The identification of major electrical loads and the evaluation of the plant's energy requirements highlighted the potential benefits of integrating renewable energy sources. These findings confirm that the implementation of a hybrid energy system based on photovoltaic generation and energy storage could reduce dependence on natural gas and improve the overall energy performance of the cement plant.

CHAPTER 2 ASSESSMENT OF RENEWABLE
ENERGY

1.1 Introduction

This chapter evaluates the renewable energy potential of the Adrar region in southern Algeria, with a focus on solar resources. Given the high solar irradiation levels in Saharan areas, solar energy represents a key opportunity for reducing fossil fuel consumption in energy-intensive industries such as cement production. The assessment includes photovoltaic (PV).

2.2 Photovoltaic Solar Energy (PV)

2.2.1 Solar Irradiation in Adrar

The performance of photovoltaic systems strongly depends on solar irradiation, which represents the amount of solar energy received per unit area. The Adrar region benefits from one of the highest solar irradiation levels in the world, typically exceeding **2000 kWh/m²/year**, making it highly suitable for PV installations.

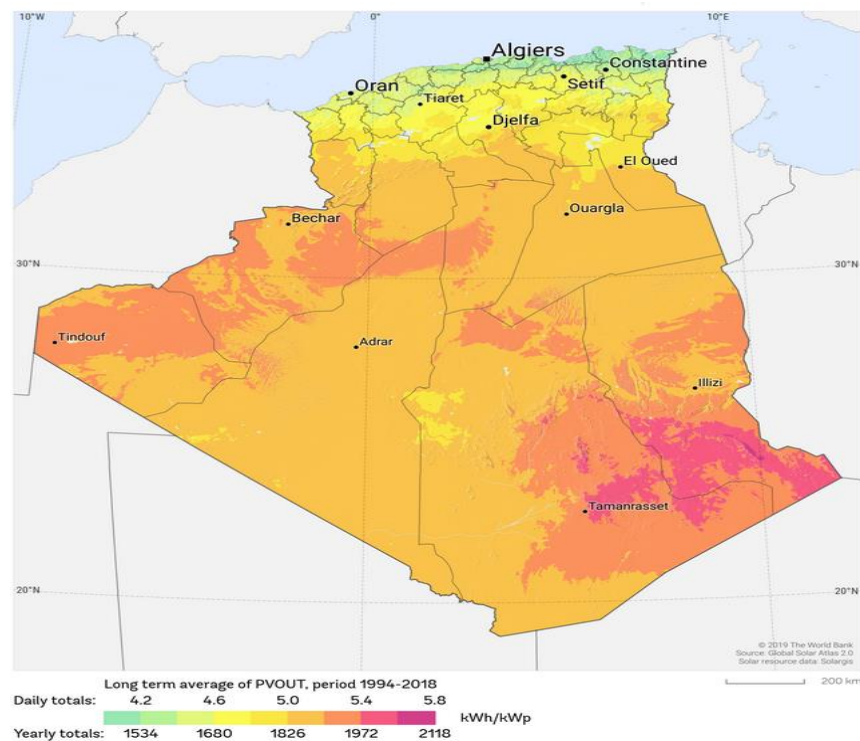


Figure 2-1 Photovoltaic power potential in Algeria [6]

The use of renewable energy is essential for reducing the impacts of climate change and supporting the global transition toward cleaner energy systems. Renewable energy production has increased significantly in recent years, with solar energy becoming one of the most

important and widely adopted solutions due to its abundance, availability, and environmental benefits. In Algeria, the development of solar photovoltaic (PV) farms has expanded rapidly because of the country's high solar potential, especially in desert regions.

The efficiency and economic viability of solar PV installations depend mainly on the amount of solar radiation received at a specific location. However, solar radiation varies across time and space, making its analysis complex. Advanced analytical approaches such as time-series analysis, regression models, machine learning, and spatial analysis are commonly used to study this variability and improve the management of solar energy resources.

Several studies have focused on analyzing long-term solar radiation trends and their relationship with climatic and meteorological factors such as temperature, humidity, precipitation, cloud cover, and wind speed. These studies are important for understanding the effects of climate change on solar irradiance and for improving renewable energy planning and management.

The present study investigates the temporal variability and climatological trends of surface solar irradiation in southern Algeria using ten years of ground-measured data collected between 2011 and 2020 at the Renewable Energy Research Unit in the Saharan Environment (URER/MS). The study also uses long-term satellite and reanalysis data covering the period from 1991 to 2020 to complement the analysis. Due to the limited availability of high-quality radiometric stations in desert regions, such detailed ground-based studies remain relatively rare.

The research aims to characterize solar radiation variability in the Algerian desert climate and provide reliable scientific data for renewable energy applications. The study includes statistical analyses of solar radiation at different temporal scales, from hourly variations to long-term climatic trends, and contributes to improving knowledge about solar energy potential in Saharan environments. [7]

2.2.2 Study area

This study was carried out in the southwestern region of Algeria **Figure 2 2**, exactly in the province of Adrar. This

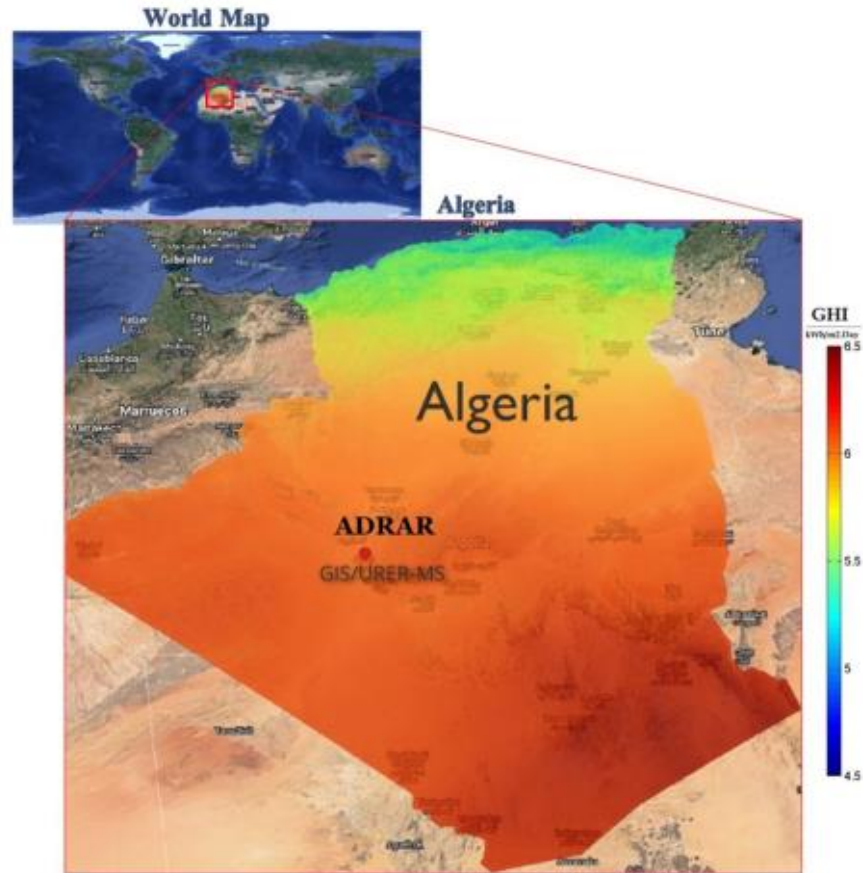


Figure 2-2 Photovoltaic power potential in Algeria [7]

The region is rich in solar potential, as illustrated by the spatial distribution of the annual average daily global solar irradiation at the surface. The region has a hot desert climate and is characterized by very high summer temperatures, moderate winter temperatures, and generally low relative humidity. The mean annual temperature is approximately 27 °C, with an average daily maximum of 34 °C and an average daily minimum of 20 °C. July is the hottest month, with average maximum temperatures reaching 46.8 °C, while January is the coldest month, with average minimum temperatures of 6.4 °C. The average relative humidity is around 24%, and rainfall is scarce throughout the year. The region receives approximately 9.7 hours of sunshine per day on average. Seasonal variations are limited, except for a period of dust-laden winds that typically occurs

between March and May and occasionally during winter. Meteorological parameters such as sunshine duration and solar radiation are generally expressed in solar time, which corresponds to Greenwich Mean Time.

2.2.3 Hourly irradiation

The hourly change of the global solar radiation on the horizontal plane **Figure 2 3** shows that the hourly change per day of radiation on a horizontal plane varies during the day from sunrise to sunset, it exceeds 500 Wh/m² between 9 a.m. and 3 p.m. the maximum is recorded around solar noon with over 800 Wh/m². For the hourly change per month in the year **Figure 0-3**, when we take the average of the hourly energy for the peak hour at solar noon over all the years studied, we notice that the month of June records an average of about 1000 Wh/m² at this time, for the other month the average of the hourly energy at noon is above 600 Wh/m² at this time. A heatmap illustrating the intensity of hourly global solar irradiance across the months is presented in **Figure 0-4**. The horizontal columns represent the hours of the day, while the vertical rows represent the months of the year. The hours with the highest values are evident by the presence of warmer red colors. The figure illustrates that the site experiences consistently high solar radiation intensity throughout the year. On a monthly basis, the intensity reaches its peak between 11:00 a.m. and 2:00 p.m. local time. In June, the hourly peak of solar irradiance reaches 1007.2 Wh/m². To analyze the distribution of hourly solar irradiation over the entire time series, we utilize a frequency distribution graph presented in **Figure 2 6**; we select specific data within the time range of 09:00 to 16:00 local time (GMT + 1). This corresponds to a time range that excludes sunrise and sunset time throughout the year and to avoid the measurement affected by natural masks, especially at the beginning and end of the day. From the frequency histogram shown in **Figure 2 6**, it was observed that the highest peak frequencies correspond to the range of global solar radiation between 600 and 700 Wh/m² with a value equal to 15.08%. On the other hand, the lowest peak frequencies in the histogram correspond to the range of solar radiation below 100 W/m² with a value equal to 3.39%. We can observe that all other ranges of solar radiation, especially the ranges within 300 to 1000 Wh/m² have near values of frequency distribution, and the hourly solar irradiance of more than 300 Wh/m² occurs about 84.5%.

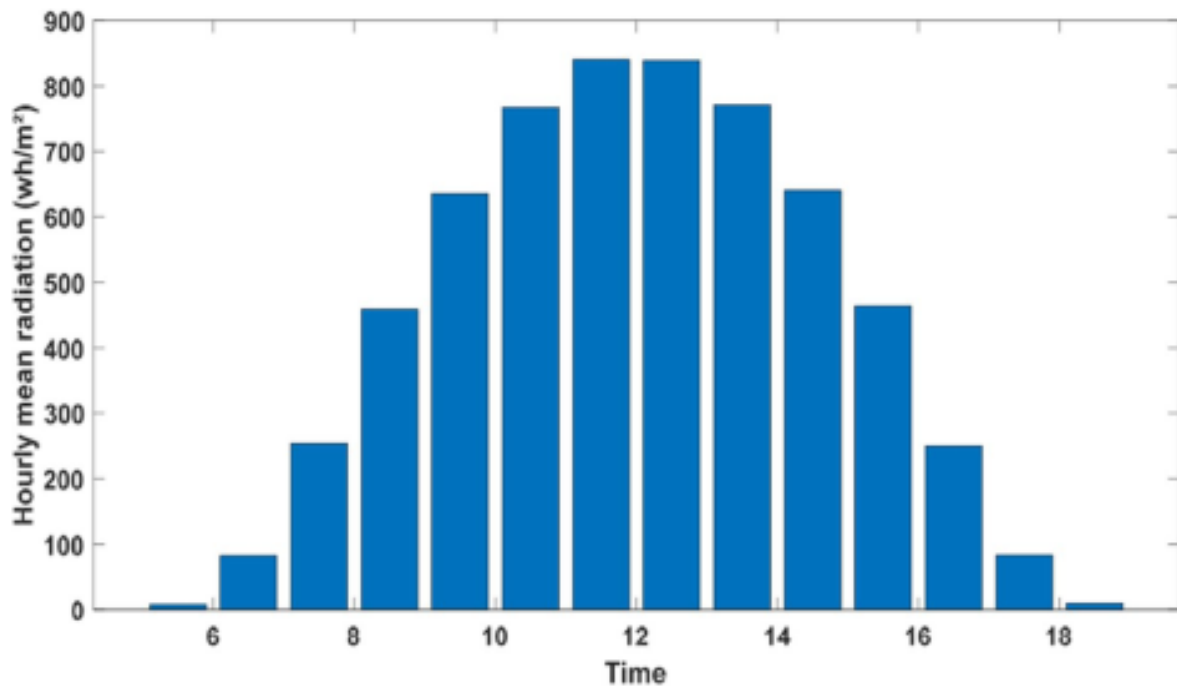


Figure 2-5 Hourly global irradiation distribution measurements at Adrar station (2011–2020) [7]

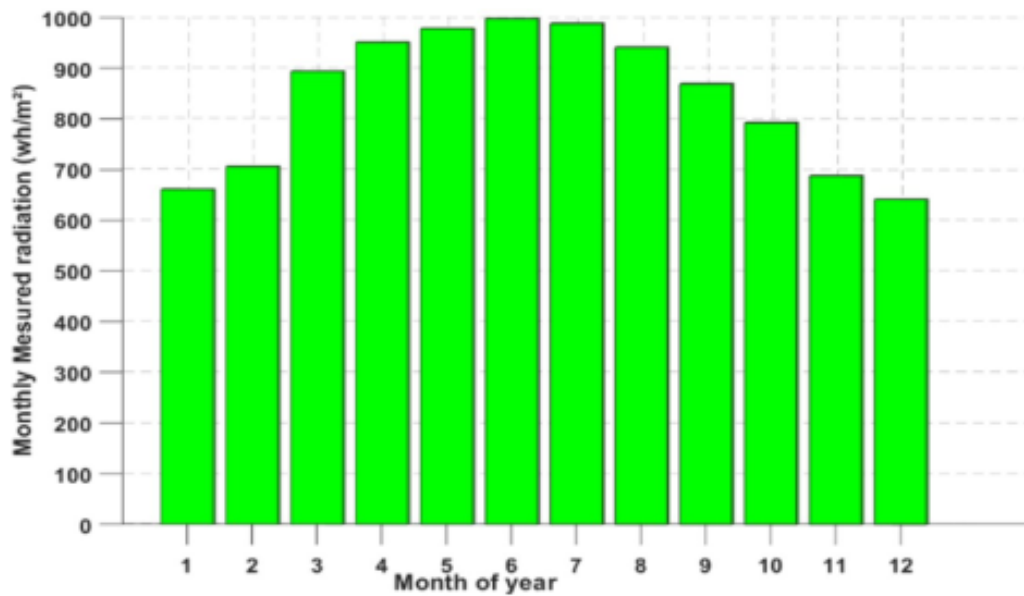


Figure 2-6 Monthly average hourly global irradiation distribution on a horizontal plane—Adrar (2011–2020) [7]

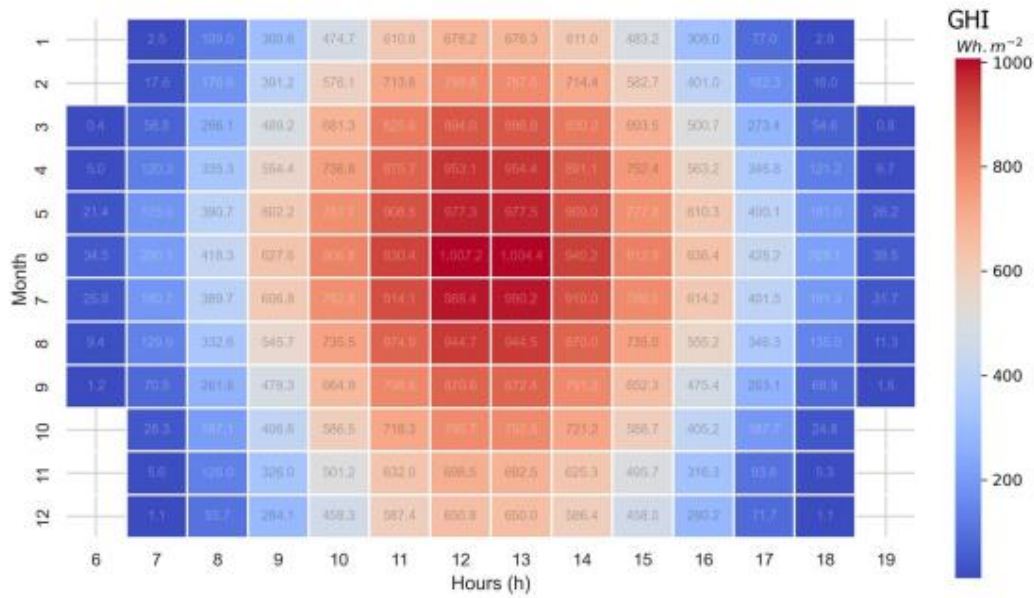


Figure 2-7 Monthly average hourly global irradiation distribution on a horizontal plane Adrar(2011–2020) [7]

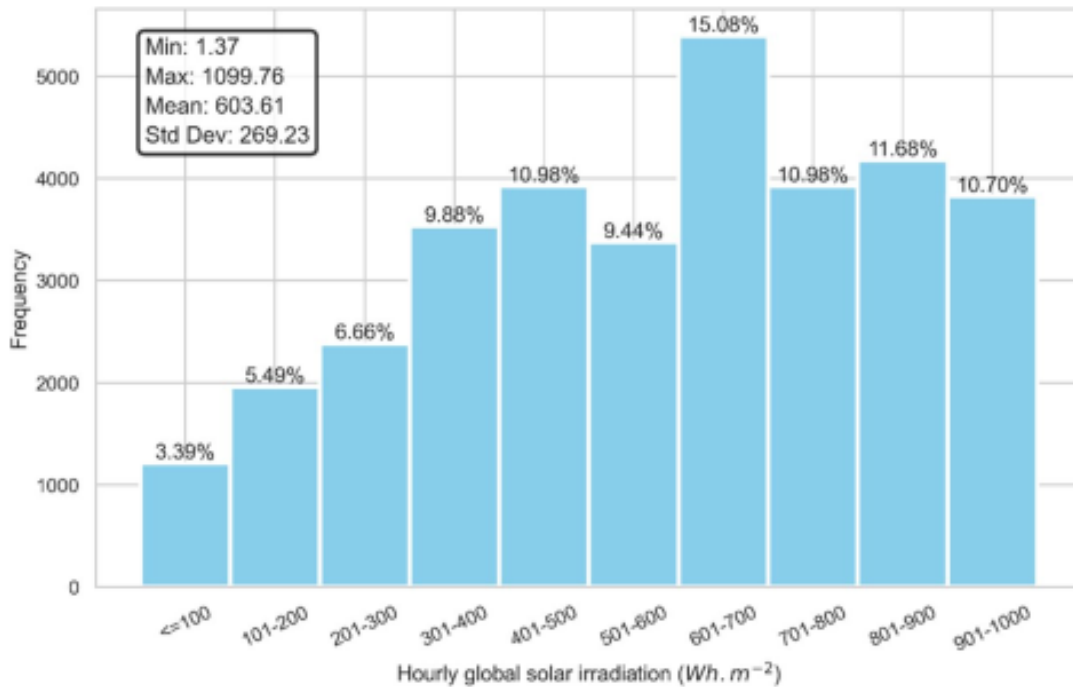


Figure 2-8 Frequency distribution of hourly solar irradiation [7]

2.2.3.2 Daily irradiation

The daily change of the global solar radiation on the horizontal plane **Figure 2 6** shows that it changes per day of radiation during the year from January to December. The daily energy is calculated from sunrise to sunset for each day of the year; it exceeds 3.5 kWh/m² for most days of the year. The maximum is recorded between June 5th and 15th with more than 8.4 kWh/m² per day; in this decade (2011–2020), the average of the day which recorded the maximum energy is June 10 with over 8.5 kWh/m². Understanding how daily global irradiation varies by month or season is crucial for solar energy applications, especially in system design and maintenance. In this context the monthly average and total of daily global solar radiation on horizontal surfaces using the daily data are calculated for each month over a period of 10 years from 2011 to 2020. **Figure 2 7** represents the monthly distribution of daily global horizontal irradiation.

In **Figure 2 8**, we can find a representation of the monthly average and total of daily global solar radiation on horizontal surfaces. It can be observed that the monthly mean and total variations of radiation during the year from January to December, the monthly mean energy is calculated from all days of each month in this studied decade (2011–2020); it has a minimum in December with over 4000 Wh/m²/day and a maximum of 8000 Wh/m²/day in June. The monthly total radiation is calculated by summing of energy of all days of the month in the year; it has also a minimum in December of 126 kWh/m²/month and a maximum of 242 kWh/m²/month in July.

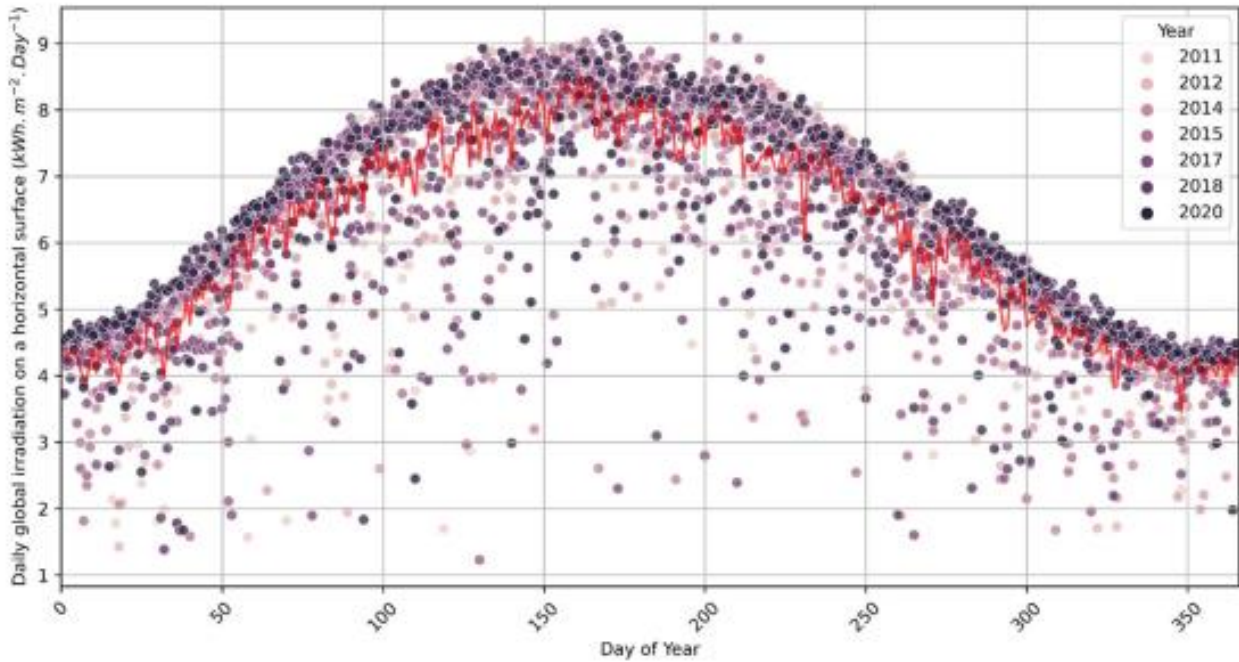


Figure 2-9 Daily global irradiation on a horizontal surface at Adrar (2011–2020). The red line shows the 10 years daily average [7]

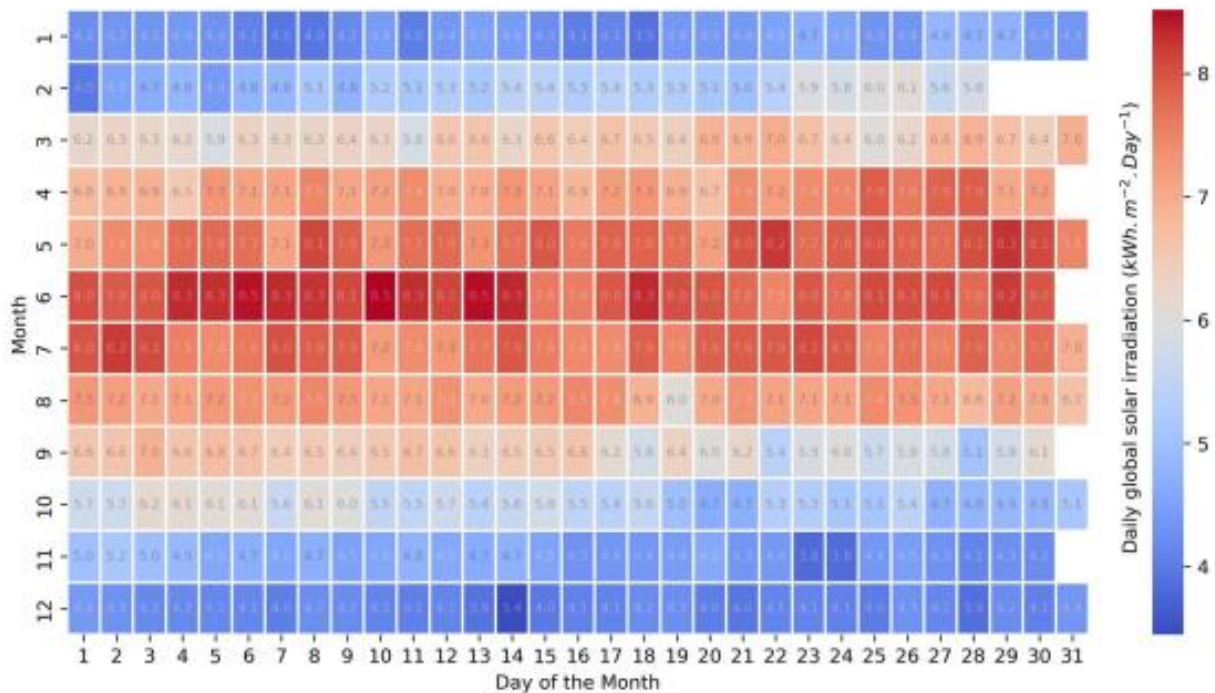


Figure 2-10 Monthly average of daily global horizontal irradiation distribution—Adrar (2011 2020) [7]

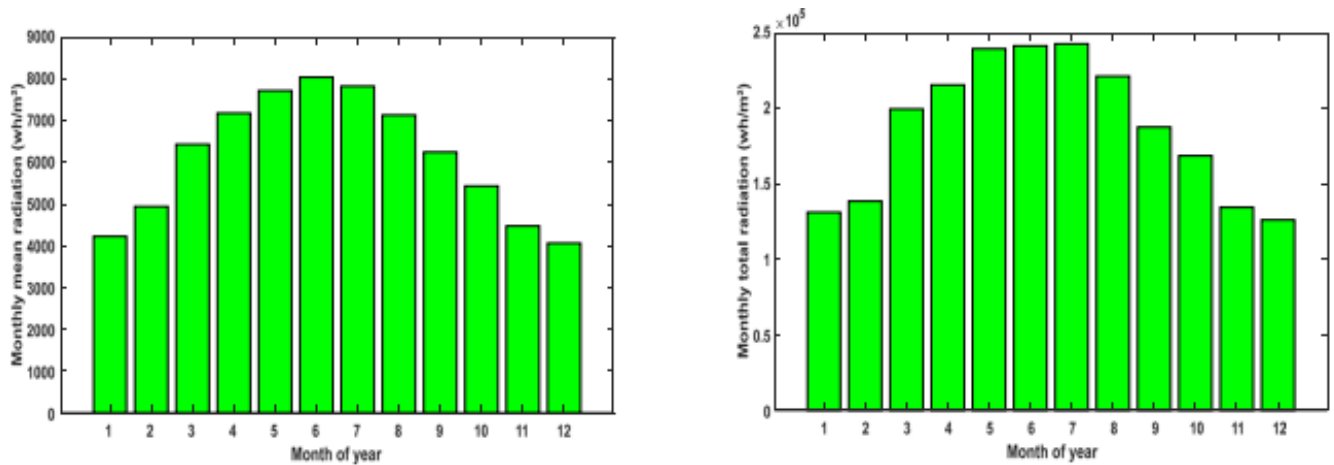


Figure 2-11 Monthly average daily and total global irradiation—Adrar site (2011–2020) [7]

The box plots of seasonal and annual variability of global solar irradiation at the surface are presented in **Figure 2 9 a** and **b**, respectively. The line within each box corresponds to the median values, while the boxes and vertical bars visually represent the extent of annual average variation, taking into account one-standard deviation and two-standard deviation intervals.

Figure 2 9 a shows that during the summer months, the median of the global solar irradiation is higher with less variability compared to the other seasons, while the winter season exhibits the lowest intensity. The amplitude of the daily variability of solar radiation is wider in spring and autumn. This observed behavior aligns with the prevailing climatic conditions experienced during these specific seasons, which can be attributed to the influence of cloud cover and the presence of dust particles in the atmosphere. The box plots in **Figure 2 9 b** highlight the diverse annual variations in daily global solar irradiation over the decade from 2011 to 2020. The datasets exhibit significant differences in median and standard deviation over the years, with noticeable positive and negative trends. The annual average value is about 6.18 kWh/m²/day, the maximum, of about 6.34 kWh/m²/day, is reached in 2019, and the minimum, of around 5.98 kWh/m²/Day, is reached in 2017. In terms of annual total energy, the value ranges from 2.1 to 2.3 MWh/ m² per year. Daily global solar irradiation frequency histogram was conducted using 10 years of data **Figure 0-12** The figure shows that daily solar irradiance of more than 4 kWh/m²/day occurs about 92.1%. The highest frequency occurs at solar irradiance of 4–5 kWh/m²/day, with a value equal to 22.66%. Another important aspect to consider regarding daily solar irradiation is identifying interannual variability using the standardized variable index. As shown in **Figure 2 10**, a statistically

significant positive trend was observed on an annual basis during two periods: from 2011 to 2013 and from 2017 to 2019, with significance in the latter period. In contrast, a negative trend was observed from 2013 to 2017.[7]

1.2 Conclusion

The assessment of renewable energy resources demonstrated that the Adrar region possesses exceptional solar potential, making it one of the most favorable locations in Algeria for photovoltaic energy production. The analysis of solar irradiation data revealed high and stable solar energy availability throughout the year, with average daily irradiation values exceeding 6 kWh/m²/day and reaching more than 7 kWh/m²/day during the summer season. These results confirm the suitability of the site for large-scale photovoltaic installations and highlight the significant contribution that solar energy can provide to industrial applications. Consequently, the renewable energy potential identified in this chapter establishes a strong basis for the integration of photovoltaic generation into the energy supply system of the Timokten cement plant.

*CHAPTER 3 SIMULATION AND OPTIMIZATION OF
THE HYBRID ENERGY SYSTEM*

3.1 Introduction

The increasing energy demand in industrial sectors and the environmental impact associated with fossil fuel consumption have encouraged the development of hybrid energy systems integrating renewable energy sources. In energy-intensive industries such as cement manufacturing, the use of renewable energy technologies can significantly improve energy efficiency, reduce greenhouse gas emissions, and decrease operating costs. Following the assessment of the renewable energy potential in the Adrar region presented in the previous chapter, this chapter focuses on the simulation and optimization of a hybrid energy system for the cement plant using HOMER Pro. The objective is to evaluate the technical, economic, and environmental performance of different system configurations combining photovoltaic energy with the existing gas turbine system. The simulation process allows the analysis of system behavior under various operating conditions by considering solar resource availability, industrial load demand, component specifications, and operational constraints. Particular attention is given to the interaction between the photovoltaic system and the gas turbine, especially regarding turbine minimum operating limits and system stability. Different hybrid scenarios are proposed and compared in order to identify the most suitable configuration capable of ensuring reliable energy supply while minimizing fuel consumption and carbon dioxide emissions. The obtained results provide valuable insights into the feasibility and effectiveness of integrating renewable energy technologies into industrial applications.

3.2 Simulation using HOMER PRO

The proposed hybrid system is designed to supply the electrical demand of the cement plant through the integration of renewable and conventional energy sources. The system configuration modeled in HOMER Pro consists mainly of a photovoltaic generator coupled with the existing gas turbine system. In an additional configuration, a battery storage system is incorporated to improve operational flexibility and energy management.

The photovoltaic system converts solar irradiation into electrical energy during daytime operation periods. The generated electricity contributes directly to supplying the industrial load, thereby reducing the energy produced by the gas turbine and decreasing fuel consumption.

The gas turbine remains the primary dispatchable source responsible for ensuring continuous operation of the cement plant and compensating for fluctuations in photovoltaic generation. The operational characteristics of the turbine, including installed power, efficiency, and minimum technical load, are considered in the simulation process to maintain realistic operating conditions.

In the second hybrid configuration, battery storage is integrated to store excess photovoltaic energy produced during periods of high solar irradiation. The stored energy can later be supplied to the load during low solar production periods, contributing to enhanced renewable energy utilization and improved system stability.

The main system components considered in this study are:

- Photovoltaic array
- Gas turbine
- Battery storage system
- Power converter
- Industrial electrical load

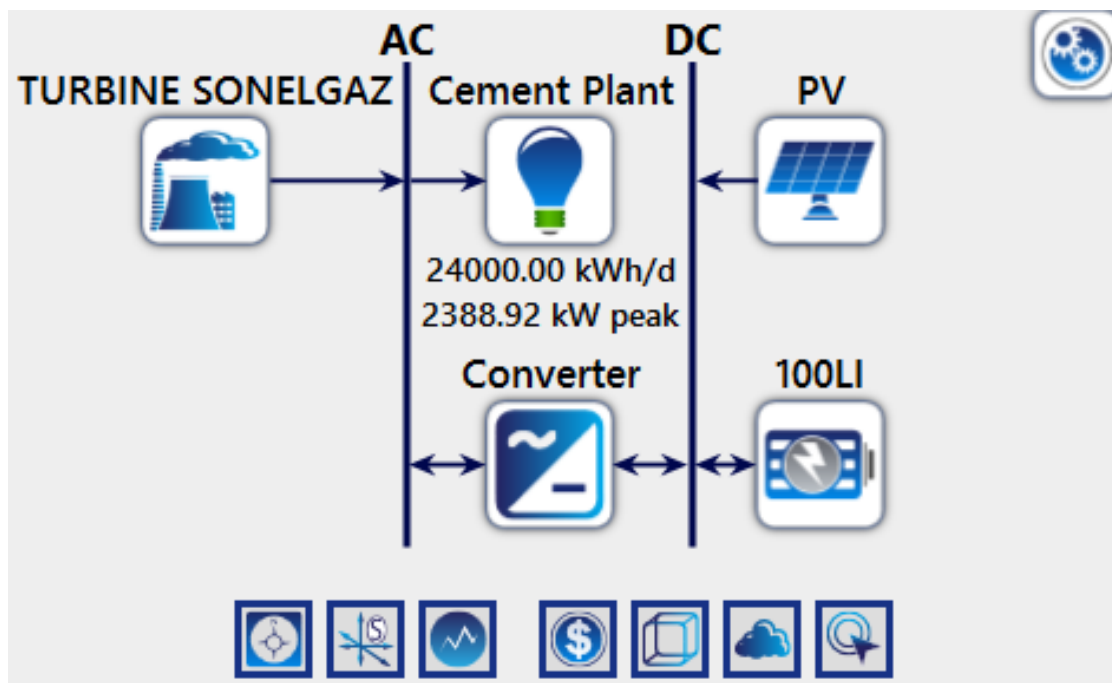


Figure 3-1 HOMER Pro hybrid system architecture

3.2.1 Input Data and Simulation Parameters

The simulation and optimization process requires accurate technical, climatic, and economic input data to ensure reliable results. In this study, the simulation parameters are based on the renewable energy potential of the Adrar region and the operational characteristics of the cement plant.

The solar resource data used in HOMER Pro include monthly average solar irradiation values representative of the climatic conditions in Adrar. These data are essential for estimating the electrical production of the photovoltaic system throughout the year.

The electrical load profile of the cement plant is introduced into the simulation to represent the variation of energy demand during daily and seasonal operating conditions. The load profile constitutes a fundamental parameter in determining the required system capacity and operational strategy.

The gas turbine technical specifications integrated into the model include installed power capacity, efficiency, fuel consumption characteristics, and minimum operating load constraints. These parameters play a significant role in evaluating the interaction between the conventional and renewable energy sources.

Economic parameters such as fuel cost, component lifetime, operation and maintenance costs, and project duration are also included to enable the economic comparison of the proposed scenarios.

Table 3-1 Solar Resource Data

Months	Clearness Index	Daily Radiation (kwh/m²/day)
Jan	0.611	3.91
Feb	0.654	4.95
Mar	0.66	5.97
Apr	0.63	6.52
May	0.643	7.12
Jun	0.641	7.25
Jul	0.662	7.39
Aug	0.637	6.73
Sep	0.607	5.74
Oct	0.61	4.87
Nov	0.593	3.94

The solar resource data indicate that the Adrar region benefits from excellent solar energy potential throughout the year. The average daily solar irradiation varies from approximately 3.91 kWh/m²/day in January to 7.39 kWh/m²/day in July, while the clearness index remains relatively high, ranging between 0.593 and 0.662. These values demonstrate the high availability of solar energy and the favorable climatic conditions of the region for photovoltaic applications. The highest irradiation levels occur during the summer months, which enables maximum PV electricity generation during this period. Therefore, the solar resource characteristics confirm the suitability of Adrar for integrating photovoltaic systems into the cement plant energy supply.

Table 3-2 Gas Turbine Characteristics

Quantity	Value	Units
Hours of Operation	8,760	hrs/yr
Number of Starts	1	starts/yr
Operational Life	20	yr
Capacity Factor	5.18	%
Fixed Generation Cost	150	\$/hr
Marginal Generation Cost	0.00119	\$/kWh
Electrical Production	9,079,807	kWh/yr
Mean Electrical Output	1,037	kW
Minimum Electrical Output	700	kW
Maximum Electrical Output	20,000	kW
Fuel Consumption	2,938,303	m ³
Specific Fuel Consumption	0.324	m ³ /kWh
Fuel Energy Input	29,015,742	kWh/yr
Mean Electrical Efficiency	31.3	%

The gas turbine represents the main dispatchable source in the proposed hybrid system. The results show an annual electricity production of approximately 9.08 GWh with a mean electrical efficiency of 31.3%. The turbine consumes about 2.94 million m³ of natural gas annually and operates continuously throughout the year. The minimum operating power of 700 kW imposes an important technical constraint on the integration of photovoltaic energy because the turbine cannot be operated below this limit without affecting system stability. Consequently, any renewable energy integration strategy must account for this operational restriction to ensure reliable plant

Table 3-3 PV System Parameters

Category	Parameter	Value
General	Name	Generic flat plate PV
General	Abbreviation	PV
Properties	Panel Type	Flat plate
Properties	Rated Capacity (kW)	15000
Properties	Temperature Coefficient	-0.5
Properties	Operating Temperature (°C)	47
Properties	Efficiency (%)	13
Properties	Manufacturer	Generic
Cost	Capacity (kW)	1
Cost	Capital (\$)	850
Cost	Replacement (\$)	700
Cost	O&M (\$/year)	15
Lifetime	Time (years)	25
Site Specific Input	Derating Factor (%)	85
Electrical Bus	Type	DC
Sizing	Method	HOMER Optimizer™

The photovoltaic system is designed with a rated capacity of 15 MW, which is significantly larger than the average electrical demand of the plant. The module efficiency of 13% and the derating factor of 85% reflect realistic operating conditions considering temperature effects, dust accumulation, and system losses. The selected PV configuration aims to maximize solar energy utilization and reduce dependence on fossil fuels. The long project lifetime of 25 years also contributes to the economic attractiveness of the proposed renewable energy solution.

Table 3-4 Battery Specifications

Quantity	Value	Units
Batteries	1,092	qty.
String Size	1	batteries
Strings in Parallel	1,092	strings
Bus Voltage	600	V
Autonomy	87.4	hr
Storage Wear Cost	0.0675	\$/kWh
Nominal Capacity	109,200	kWh
Usable Nominal Capacity	87,360	kWh
Lifetime Throughput	5,460,000	kWh
Expected Life	1.02	yr
Average Energy Cost	0	\$/kWh
Energy In	5,646,589	kWh/yr
Energy Out	5,088,129	kWh/yr
Storage Depletion	6,534	kWh/yr
Losses	564,994	kWh/yr
Annual Throughput	5,363,359	kWh/yr
Annual EFCs	49.1	1/yr
Average Daily EFCs	0.135	1/day

The battery storage system provides a nominal capacity of 109.2 MWh and an autonomy of approximately 87.4 hours. The storage system allows excess photovoltaic energy generated during periods of high irradiation to be stored and reused during periods of low solar production. Annual energy throughput exceeds 5.36 GWh, demonstrating intensive battery utilization. The battery therefore improves renewable energy penetration, enhances operational flexibility, and reduces fluctuations associated with solar generation. However, its relatively short expected life increases replacement costs and impacts the overall economic performance of the system.

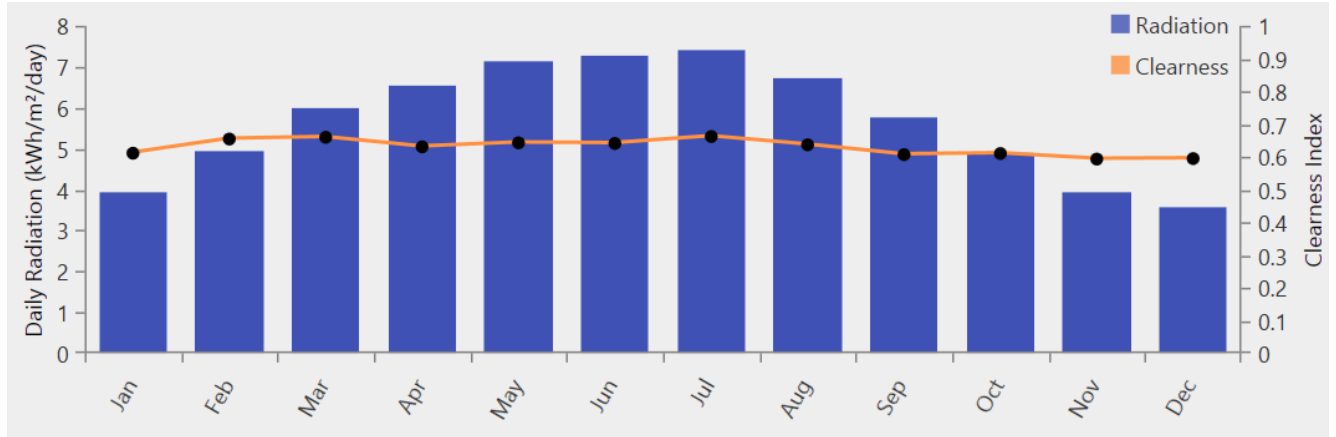


Figure 3-2 Solar irradiation profil

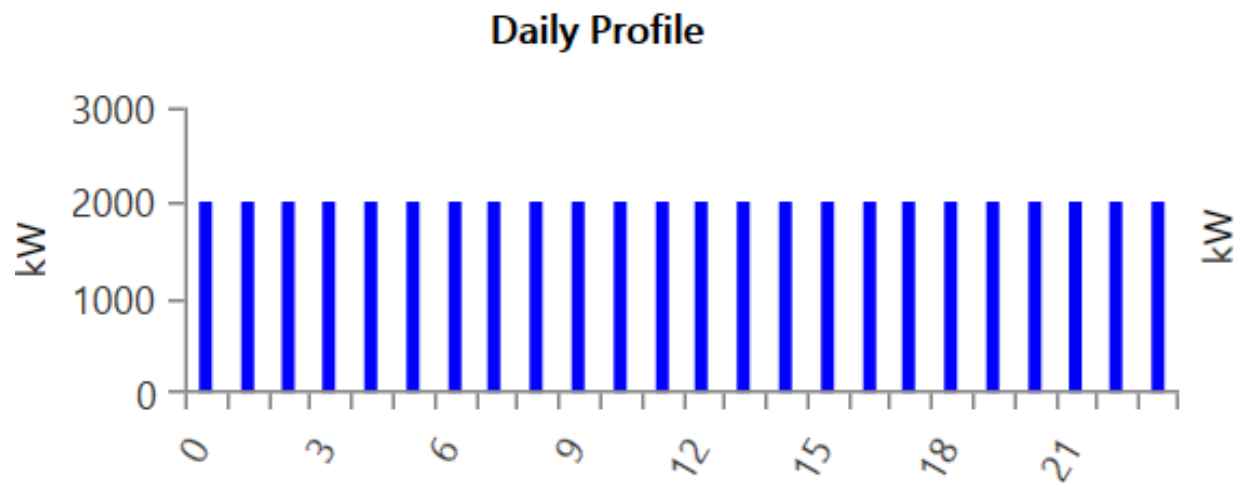


Figure 3-3 Daily load curve

Figure 3-3 presents the daily electrical load profile of the cement plant. The load demand remains relatively high throughout the day due to the continuous operation of industrial processes. Variations in demand are associated with changes in equipment utilization and production activities. Understanding the daily load pattern is essential for the proper sizing and operation of the hybrid energy system.

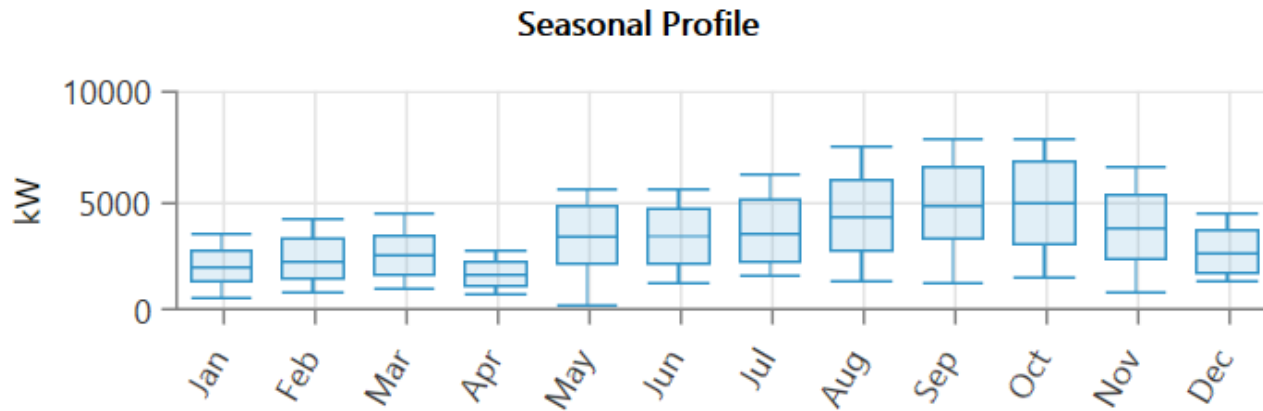


Figure 3-4 Seasonal load profile

Figure 3-4 shows the seasonal variation of electrical demand throughout the year. Although the cement plant maintains a relatively stable operation, slight fluctuations are observed due to production requirements and environmental conditions. These variations must be considered when designing the hybrid energy system to ensure reliable power supply under all operating conditions.

3.2.2 Simulation Scenarios

To determine the optimal hybrid energy configuration for the cement plant, different simulation scenarios are developed and evaluated using HOMER Pro.

3.2.2.1 Scenario 1: PV and Gas Turbine Hybrid System

This scenario consists of integrating a photovoltaic system with the existing gas turbine without energy storage. During periods of high solar irradiation, the photovoltaic system supplies part of the plant electrical demand, reducing the operating load of the gas turbine and consequently lowering fuel consumption and carbon dioxide emissions.

Special attention is given to the operational constraints of the gas turbine to ensure that the photovoltaic contribution does not reduce turbine operation below the minimum technical load limit required for stable operation.

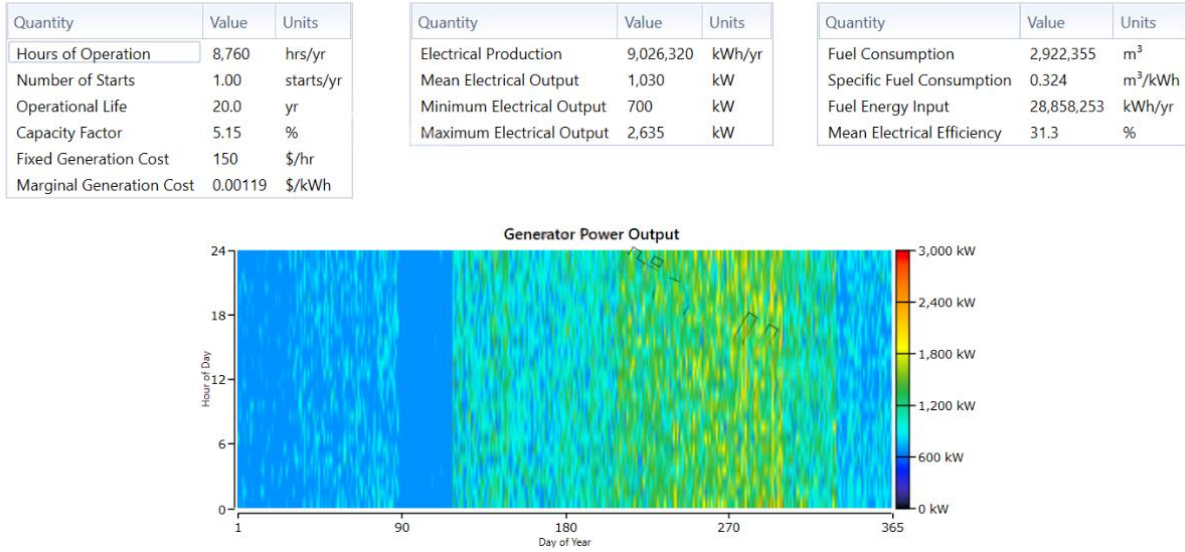


Figure 3-5 Scenario 1 HOMER configuration of Gas Turbine

Figure 3-5 presents the configuration of the gas turbine component used in Scenario 1. The gas turbine serves as the primary dispatchable energy source, ensuring continuous electricity supply to the cement plant. Its operational characteristics, including rated capacity and fuel consumption, significantly influence the technical and economic performance of the hybrid system.

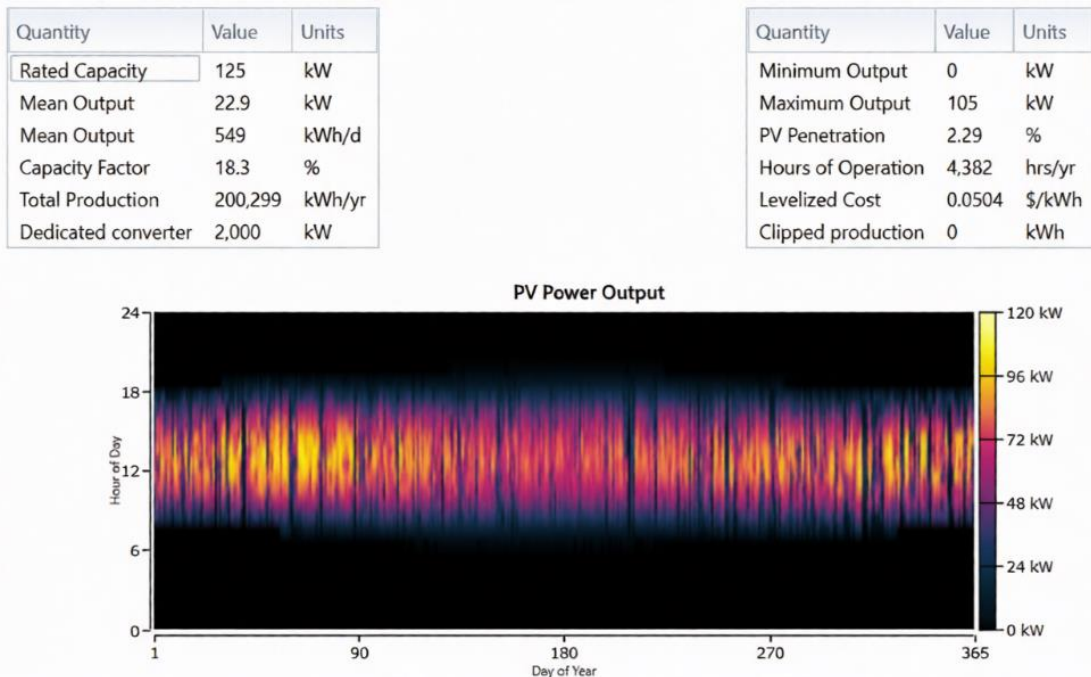


Figure 3-6 Scenario 1 HOMER configuration of PV

Figure 3-6 illustrates the photovoltaic system configuration implemented in Scenario 1. The PV array converts solar irradiation into electrical energy and directly contributes to the plant load demand. The integration of photovoltaic generation reduces the energy required from the gas turbine and enhances the renewable energy share within the system.

Table 3-5 Energy dispatch results

Production	KWh/yr	%
Generic flat plate PV	200,299	2.17
Generic Large Genset (size-your-own)	9,026,320	97.8
Total	9,226,619	100
Consumption	KWh/yr	%
AC Primary Load	8,760,000	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	8,760,000	100
Quantity	KWh/yr	%
Excess Electricity	463,804	5.03
Unmet Electric Load	0	0
Capacity Shortage	0	0
Quantity	Value	Units
Renewable Fraction	0	%
Max. Renew. Penetration	45.8	%

The energy dispatch results show that the gas turbine remains the dominant electricity source, contributing approximately 97.8% of annual electricity production, while the photovoltaic system contributes 2.17%. Total annual generation reaches 9.23 GWh, which fully satisfies the plant demand of 8.76 GWh. The system also produces approximately 463.8 MWh of excess electricity, representing 5.03% of total production. The absence of unmet load and capacity shortage confirms that the hybrid configuration ensures a reliable power supply for the cement plant under all operating conditions.

3.2.2.2 Scenario 2: PV, Battery, and Gas Turbine Hybrid System

In this scenario, battery storage is integrated into the hybrid system to improve renewable energy utilization and operational flexibility. Excess photovoltaic electricity generated during daytime periods is stored in the batteries and later used during low irradiation periods or peak demand conditions. The inclusion of battery storage contributes to reducing energy fluctuations and enhancing system reliability. However, this configuration also increases the total investment and maintenance costs of the project.

Quantity	Value	Units
Hours of Operation	1,852	hrs/yr
Number of Starts	652	starts/yr
Operational Life	94.5	yr
Capacity Factor	3.77	%
Fixed Generation Cost	150	\$/hr
Marginal Generation Cost	0.00119	\$/kWh

Quantity	Value	Units
Electrical Production	6,608,084	kWh/yr
Mean Electrical Output	3,568	kW
Minimum Electrical Output	742	kW
Maximum Electrical Output	5,078	kW

Quantity	Value	Units
Fuel Consumption	2,019,180	m ³
Specific Fuel Consumption	0.306	m ³ /kWh
Fuel Energy Input	19,939,407	kWh/yr
Mean Electrical Efficiency	33.1	%

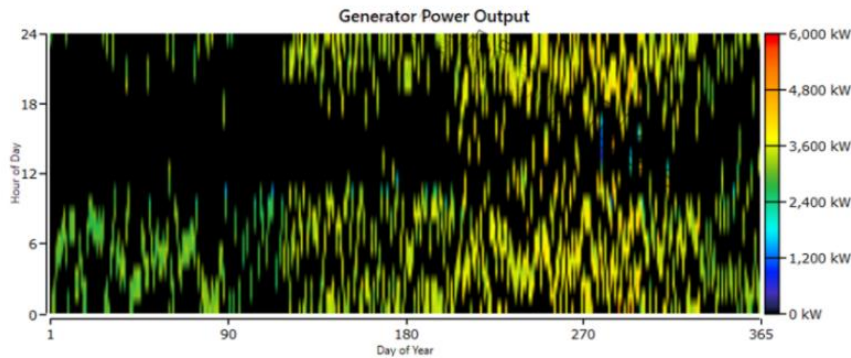


Figure 3-7 Scenario 2 HOMER configuration for the gas turbine

Figure 3-7 shows the gas turbine configuration adopted in Scenario 2. Similar to Scenario 1, the gas turbine ensures system reliability and compensates for fluctuations in photovoltaic production. The operational behavior of the turbine is evaluated under different renewable penetration levels to determine its impact on fuel consumption and system performance.

Quantity	Value	Units
Rated Capacity	2,115	kW
Mean Output	387	kW
Mean Output	9,283	kWh/d
Capacity Factor	18.3	%
Total Production	3,388,404	kWh/yr
Dedicated converter	2,000	kW

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	1,773	kW
PV Penetration	38.7	%
Hours of Operation	4,382	hrs/yr
Levelized Cost	0.0504	\$/kWh
Clipped production	0	kWh

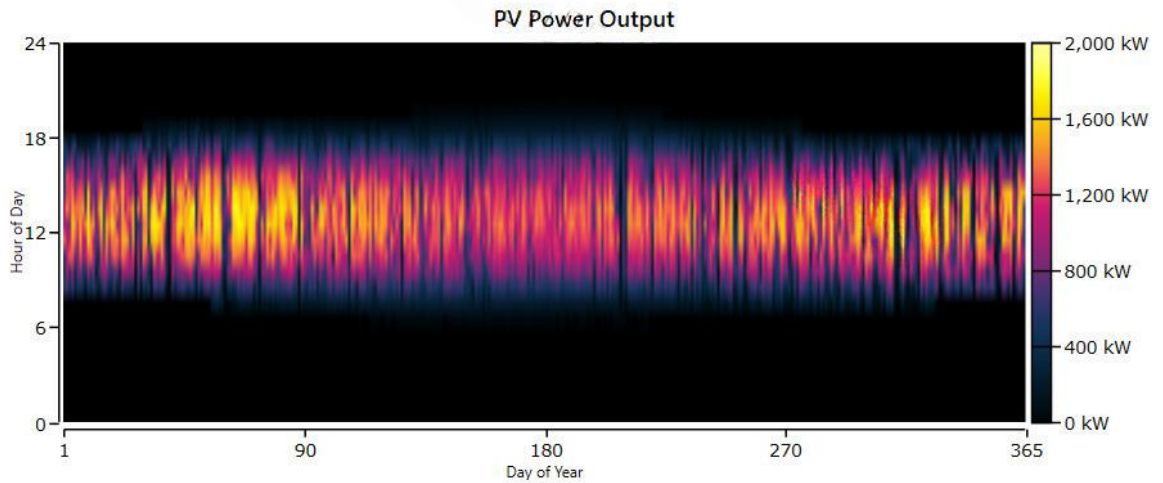


Figure 3-8 Scenario 2 HOMER configuration for the PV

Figure 3-8 presents the photovoltaic subsystem used in Scenario 2. The increased integration of solar energy aims to maximize renewable electricity production and reduce reliance on natural gas. The simulation evaluates the effectiveness of this configuration under the climatic conditions of Adrar.



Figure 3-9 Scenario 2 HOMER configuration for the Storage system

Figure 3-9 illustrates the battery storage system integrated into Scenario 2. The storage unit is designed to store excess photovoltaic energy generated during periods of high solar irradiation and deliver it during periods of low solar production. This improves energy management, increases renewable energy utilization, and enhances overall system stability.

3.3 Simulation Results and Discussion

The simulation results obtained from HOMER Pro provide a comprehensive evaluation of the proposed hybrid system configurations from technical, economic, and environmental perspectives.

The analysis includes the annual electrical production of each energy source, renewable energy contribution, fuel consumption, excess electricity generation, and operational costs. In addition, the environmental performance of each scenario is evaluated through the estimation of carbon dioxide emissions.

The results demonstrate that the integration of photovoltaic energy significantly reduces the dependence on fossil fuels by decreasing the operational load of the gas turbine during daytime periods. Furthermore, the incorporation of battery storage improves renewable energy penetration

and operational flexibility by allowing excess photovoltaic energy to be stored and reused when needed.

However, the economic analysis indicates that the inclusion of batteries increases the initial investment cost of the system. Therefore, a balance between technical performance and economic feasibility must be considered when selecting the optimal configuration.

3.3.1 Results

Table 3-6 Technical Comparison of Scenarios

Parameter	Scenario 1	Scenario 2
Renewable Fraction (%)	0	24.6
Total fuel consumed (m ³)	2,922,355	2,019,180
CO ₂ Emissions (kg/year)	5,604,141	3,872,142
Excess Electricity (%)	5.03	1.77

The comparison between the two scenarios clearly demonstrates the advantages of integrating battery storage. Scenario 2 achieves a renewable fraction of 24.6%, whereas Scenario 1 exhibits almost no significant renewable contribution. Fuel consumption decreases from 2.92 million m³ to 2.02 million m³, corresponding to a reduction of approximately 31%. Similarly, annual CO₂ emissions decrease from 5.60 million kg to 3.87 million kg, representing a reduction of about 30.9%. Furthermore, excess electricity decreases from 5.03% to 1.77%, indicating a more efficient utilization of the generated solar energy. These results confirm that battery storage significantly enhances the technical performance of the hybrid system.

Table 3-7 Nominal Cash flows a of next 10 years

Year	Scenario 1	Scenario 2	Difference
0	(\$111,874.43)	(\$2,536,047.73)	\$2,424,173.30
1	(\$1,327,751.84)	(\$612,904.58)	(\$714,847.26)
2	(\$1,327,751.84)	(\$646,824.58)	(\$680,927.26)
3	(\$1,327,751.84)	(\$646,824.58)	(\$680,927.26)
4	(\$1,327,751.84)	(\$646,824.58)	(\$680,927.26)
5	(\$1,327,751.84)	(\$646,824.58)	(\$680,927.26)
6	(\$1,327,751.84)	(\$612,904.58)	(\$714,847.26)
7	(\$1,327,751.84)	(\$646,824.58)	(\$680,927.26)
8	(\$1,327,751.84)	(\$646,824.58)	(\$680,927.26)
9	(\$1,327,751.84)	(\$646,824.58)	(\$680,927.26)

The economic analysis reveals that Scenario 2 requires a substantially higher initial investment due to the installation of battery storage and additional equipment. Although annual operating costs remain significant in both configurations, the battery-supported system provides long-term savings through reduced fuel consumption. The negative cash flows observed during the operational years are mainly associated with fuel costs, maintenance expenses, and component replacement. Therefore, the economic viability of Scenario 2 depends on balancing the higher capital investment against the fuel savings and environmental benefits achieved over the project lifetime.

**Figure 3-10 Monthly electrical production Scenario 1**

Figure 3-10 shows the monthly electrical energy production obtained under Scenario 1. The results indicate that photovoltaic generation contributes significantly during periods of high solar irradiation, while the gas turbine provides the remaining energy required to satisfy the plant

demand. The hybrid configuration allows a reduction in fossil fuel consumption while maintaining reliable operation.



Figure 3-11 Monthly electrical production Scenario 2

Figure 3-11 presents the monthly electrical production for Scenario 2. Compared with Scenario 1, the integration of battery storage improves the utilization of photovoltaic energy and increases the renewable contribution to the total energy supply. This leads to better energy management and reduced dependence on the gas turbine.

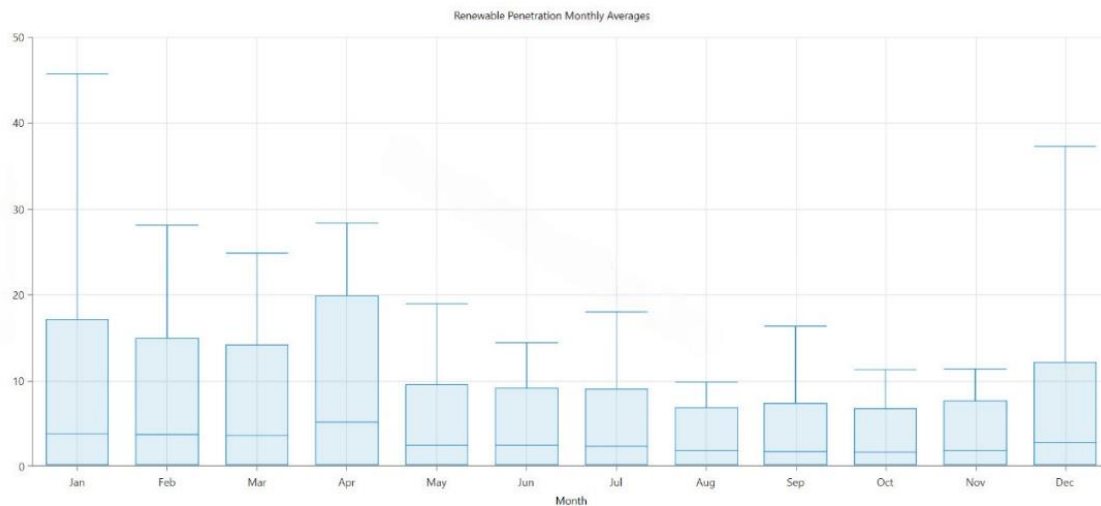


Figure 3-12 Renewable Penetration results Scenario 1

Figure 3-12 illustrates the renewable energy penetration achieved in Scenario 1. The results demonstrate that the photovoltaic system provides a substantial share of the total electricity production. The integration of renewable energy contributes to reducing greenhouse gas emissions and improving the sustainability of the cement plant energy system.

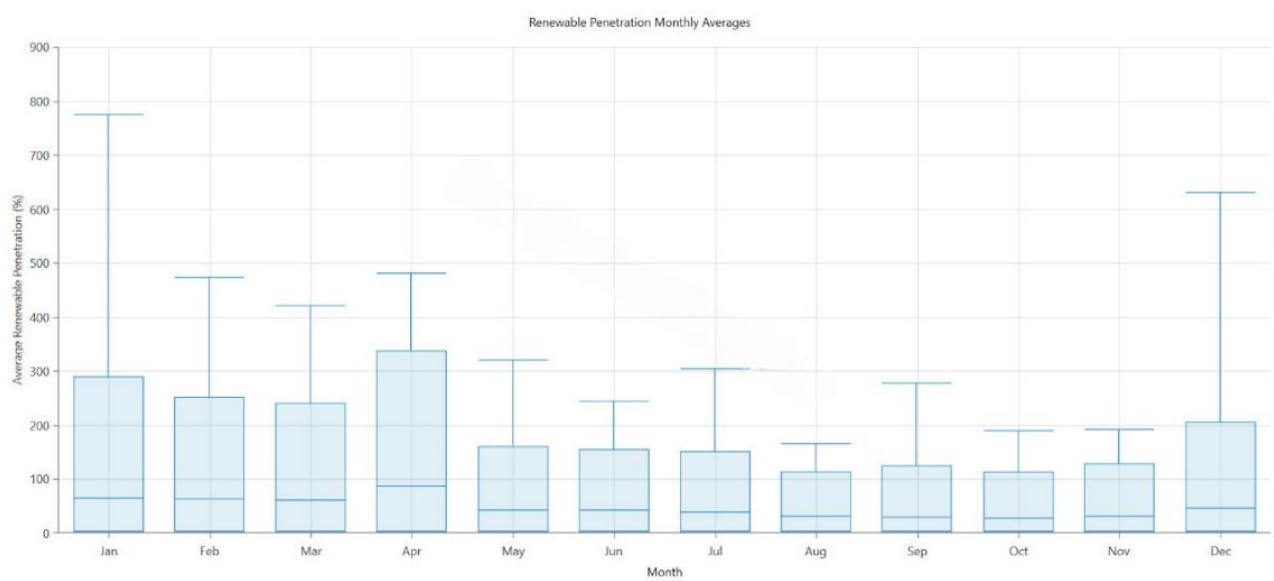


Figure 3-13 Renewable Penetration results Scenario 2

Figure 3-13 shows the renewable penetration level obtained in Scenario 2. The presence of battery storage allows a greater utilization of photovoltaic energy, resulting in higher renewable penetration compared with Scenario 1. This confirms the positive impact of energy storage on renewable energy integration.

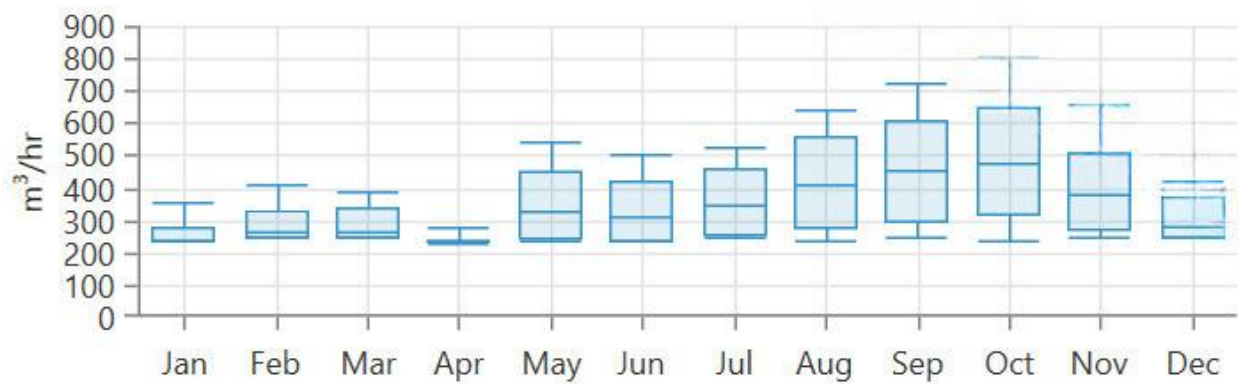


Figure 3-14 Fuel consumption for the Scenario 1

Figure 3-14 presents the fuel consumption of the gas turbine in Scenario 1. The contribution of photovoltaic energy reduces the operating requirements of the turbine, leading to a noticeable

decrease in natural gas consumption. This reduction directly contributes to lower operating costs and environmental impacts.

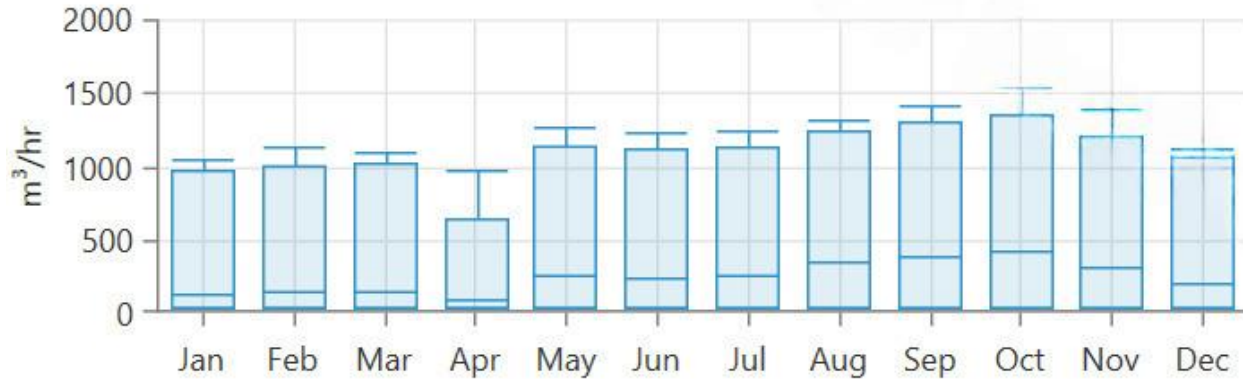


Figure 3-15 Fuel consumption for the Scenario 2

Figure 3-15 illustrates the fuel consumption results for Scenario 2. The incorporation of battery storage further decreases the dependence on the gas turbine by allowing stored solar energy to be used when photovoltaic production is insufficient. Consequently, fuel consumption is lower than in Scenario 1.

Table 3-8 Emissions results of the both scenario

	Scenario 1	Scenario 2
Carbon Dioxide (kg/yr)	5,604,141	3,872,142
Carbon Monoxide (kg/yr)	39,645	27,392
Unburned Hydrocarbons (kg/yr)	2,104	1,454
Particulate Matter (kg/yr)	339	234
Sulfur Dioxide (kg/yr)	0	0
Nitrogen Oxides (kg/yr)	7,598	5,250

The environmental comparison highlights the positive impact of renewable energy integration. Scenario 2 reduces carbon dioxide emissions from 5.60 million kg/year to 3.87 million kg/year, corresponding to a reduction of approximately 1.73 million kg/year. Similar reductions are observed for carbon monoxide, unburned hydrocarbons, particulate matter, and nitrogen oxides.

These improvements result directly from the reduced operating hours and fuel consumption of the gas turbine. Consequently, Scenario 2 offers superior environmental performance and contributes significantly to the decarbonization objectives of the cement industry.

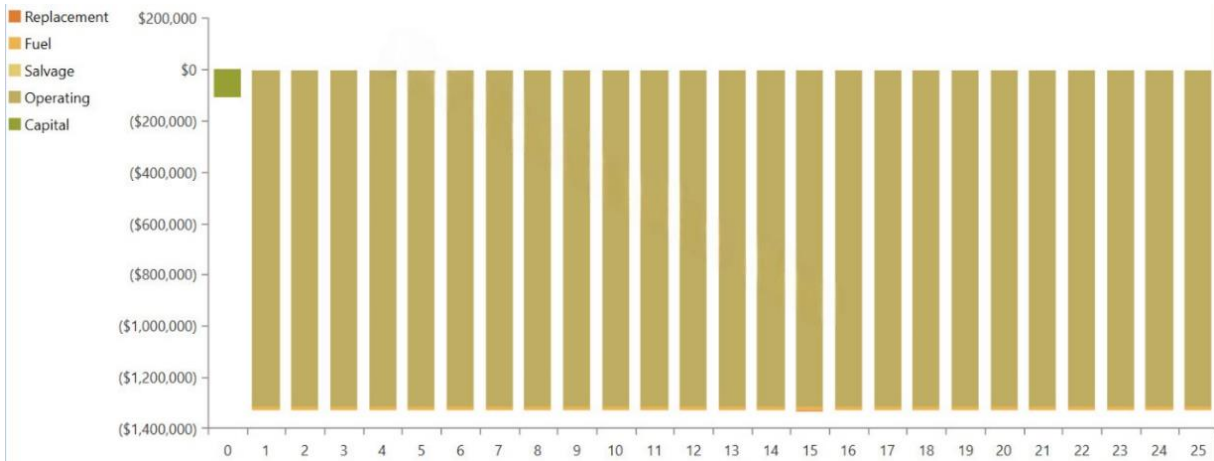


Figure 3-16 Cash flow graph for the first Scenario

Figure 3-16 shows the projected cash flow associated with Scenario 1 over the project lifetime. The initial investment is mainly related to the installation of the photovoltaic system, while operational savings are achieved through reduced fuel consumption. The results demonstrate the economic viability of integrating renewable energy into the cement plant.

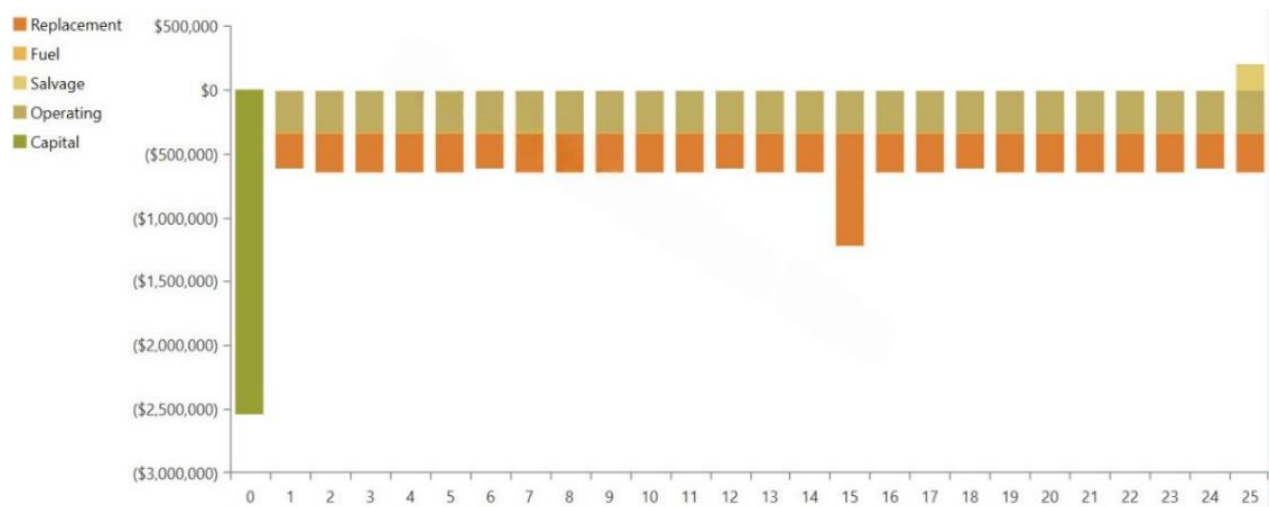


Figure 3-17 Cash flow graph for the Second Scenario

Figure 3-17 presents the cash flow analysis for Scenario 2. Although the addition of battery storage increases the initial investment cost, the improved utilization of renewable energy generates additional savings during operation. The economic performance of the system is evaluated over the project lifetime to determine its feasibility.

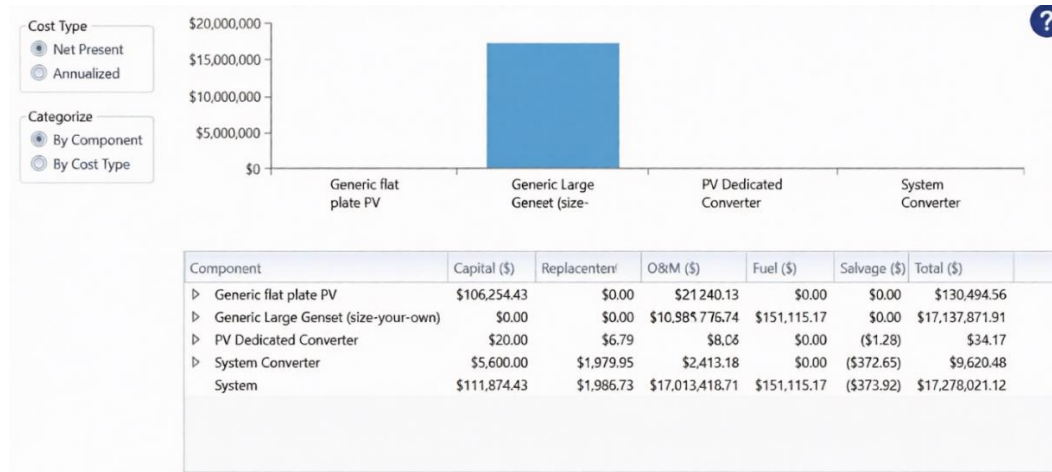


Figure 3-18 Cost Summary of the first Scenario

Figure 3-18 summarizes the distribution of costs associated with Scenario 1. Fuel costs, operation and maintenance expenses, and capital investment represent the main economic components of the project. The results highlight the economic benefits obtained from reducing fossil fuel consumption through photovoltaic integration.



Figure 3-19 Cost Summary of the Second Scenario

Figure 3-19 presents the overall cost distribution for Scenario 2. While battery storage increases the capital cost, the enhanced renewable energy utilization reduces fuel expenditure and improves long-term economic performance. The results demonstrate the trade-off between initial investment and operational savings in hybrid energy systems.

3.3.2 Discussion

The simulation results obtained using HOMER Pro demonstrate the feasibility of integrating renewable energy sources into the electrical supply system of the cement plant located in Adrar. Two configurations were evaluated and compared in terms of technical performance, economic viability, and environmental impact.

From a technical perspective, both configurations were capable of satisfying the electrical demand of the plant without any unmet load or capacity shortage, confirming the reliability of the proposed systems. However, the addition of battery storage in Scenario 2 significantly improved the utilization of photovoltaic energy. The battery allowed excess solar energy produced during periods of high irradiation to be stored and later supplied to the load when solar generation decreased. As a result, the renewable fraction increased considerably compared to Scenario 1, while excess electricity was reduced, indicating a more efficient management of the available energy resources.

The reduction in natural gas consumption achieved in Scenario 2 represents one of the most important findings of this study. By increasing the contribution of photovoltaic generation and improving energy management through storage, the hybrid PV–Battery–Gas Turbine system reduced fuel consumption by approximately 31% compared with the conventional configuration. This reduction directly decreases the dependency on fossil fuels and enhances the sustainability of the energy supply system.

From an environmental standpoint, the integration of renewable energy produced significant benefits. Carbon dioxide emissions were reduced by approximately 1.73 million kilograms per year, corresponding to a decrease of nearly 31%. Similar reductions were observed for other pollutants such as carbon monoxide, nitrogen oxides, particulate matter, and unburned hydrocarbons. These results demonstrate that renewable energy integration can play an important

role in mitigating the environmental impact of energy-intensive industries such as cement manufacturing.

Economically, the incorporation of battery storage increases the initial investment cost due to the high capital cost of batteries and their periodic replacement. Nevertheless, this additional investment is partially compensated by the reduction in fuel consumption throughout the project lifetime. Therefore, the selection of the optimal configuration should not be based solely on the initial investment but rather on a comprehensive evaluation of long-term operational savings, environmental benefits, and energy security.

Overall, the results indicate that Scenario 2, which combines photovoltaic panels, battery storage, and a gas turbine, offers the most balanced solution. Although it requires a higher capital investment, it achieves better energy efficiency, lower fuel consumption, reduced emissions, and greater utilization of renewable energy. Consequently, this configuration can be considered the most suitable option for improving the sustainability and environmental performance of the cement plant while maintaining a reliable electricity supply.

Finally, it should be noted that the results depend on the assumptions used in the HOMER Pro simulations, including solar resource availability, fuel prices, battery characteristics, and load demand profiles. Future work may investigate advanced energy management strategies, larger renewable energy penetration levels, and alternative storage technologies to further enhance system performance.

3.4 Optimal System Selection

The selection of the optimal system was based on a comprehensive evaluation of the technical, economic, and environmental performance of the investigated configurations. Among the analyzed scenarios, the hybrid PV–Battery–Gas Turbine system (Scenario 2) demonstrated the most favorable balance between energy reliability, renewable energy utilization, fuel savings, and environmental impact.

From a technical perspective, both scenarios were able to satisfy the electrical demand of the cement plant without any unmet load. However, Scenario 2 achieved a significantly higher

renewable energy contribution due to the integration of battery storage, which enabled the storage of surplus photovoltaic energy and its use during periods of low solar production. This resulted in a renewable fraction of 24.6% and a substantial reduction in excess electricity generation.

In terms of fuel consumption, Scenario 2 reduced natural gas usage from approximately 2.92 million m³/year to 2.02 million m³/year, representing a reduction of about 31%. This decrease improves energy efficiency and reduces dependence on fossil fuels, contributing to the long-term sustainability of the system.

Environmental performance also strongly favored Scenario 2. The annual carbon dioxide emissions were reduced by approximately 1.73 million kilograms, corresponding to a reduction of nearly 31% compared with Scenario 1. Similar decreases were observed for other atmospheric pollutants, confirming the environmental advantages of increasing renewable energy penetration within the hybrid system.

Although Scenario 2 requires a higher initial capital investment due to the inclusion of battery storage, the additional cost is compensated by lower fuel consumption, reduced emissions, and improved utilization of renewable energy resources. Therefore, considering the combined technical, economic, and environmental criteria, Scenario 2 was identified as the optimal configuration for supplying the electrical demand of the cement plant.

The selected optimal system consists of:

- A photovoltaic array rated at 15 MW;
- A battery energy storage system with a nominal capacity of 109.2 MWh;
- A natural gas turbine operating as a dispatchable backup source.

This configuration ensures reliable operation, maximizes renewable energy utilization, minimizes fuel consumption, and significantly reduces greenhouse gas emissions, making it the most suitable solution for the studied application.

3.5 Conclusion

The simulation and optimization results confirmed the technical feasibility of integrating photovoltaic generation and battery storage into the existing energy system of the Timokten cement plant. The HOMER Pro analysis demonstrated that the proposed hybrid configuration can significantly reduce the reliance on natural gas while maintaining a reliable electricity supply for industrial operations. The incorporation of renewable energy improved the overall system performance by increasing the renewable energy contribution, reducing fuel consumption, and lowering carbon dioxide emissions. Furthermore, the economic evaluation identified the most suitable configuration in terms of operational efficiency and long-term sustainability. These results demonstrate that the adoption of a hybrid PV–Gas Turbine–Battery system represents an effective solution for supporting the energy transition of the cement plant and enhancing its environmental performance.



GENERAL CONCLUSION

GENERAL CONCLUSION

This thesis investigated the feasibility and performance of a hybrid energy system combining photovoltaic (PV) generation, battery energy storage, and a natural gas turbine to supply the electrical demand of a cement plant located in Adrar, Algeria. The primary objective was to design a reliable, economically feasible, and environmentally sustainable energy system capable of reducing dependence on fossil fuels while ensuring continuous industrial operation.

The study first evaluated the solar energy potential of the Adrar region, which confirmed the excellent availability of solar resources and highlighted the suitability of large-scale photovoltaic deployment. Based on these conditions, two hybrid system configurations were modeled and optimized using the HOMER Pro software and subsequently compared according to technical, economic, and environmental criteria.

The simulation results demonstrated that both configurations were capable of satisfying the electrical demand of the cement plant without any unmet load, thereby ensuring reliable system operation. However, the integration of battery energy storage significantly improved the overall performance of the hybrid system by increasing the utilization of photovoltaic energy and reducing excess electricity production. The optimal configuration, consisting of a **15 MW photovoltaic array**, a **109.2 MWh battery energy storage system**, and a **natural gas turbine**, achieved a renewable energy fraction of **24.6%**, providing a balanced compromise between reliability and renewable energy penetration.

One of the most significant outcomes of this research is the reduction in natural gas consumption achieved through the integration of renewable energy and battery storage. Compared with the conventional configuration, the optimized system reduced annual natural gas consumption from approximately **2.92 million m³** to **2.02 million m³**, corresponding to a reduction of about **31%**. This reduction not only improves energy efficiency but also decreases dependence on fossil fuels and enhances the sustainability of the electricity supply system.

The environmental benefits of the proposed hybrid system are equally remarkable. Annual carbon dioxide emissions were reduced by approximately **1.73 million kilograms**, representing a decrease

of nearly **31%**. Significant reductions were also achieved for other atmospheric pollutants, including carbon monoxide, nitrogen oxides, particulate matter, and unburned hydrocarbons. These results demonstrate the considerable potential of hybrid renewable energy systems to reduce the environmental footprint of energy-intensive industries such as cement manufacturing.

From an economic perspective, although the integration of battery storage increases the initial capital investment, the associated reduction in fuel consumption and the improved utilization of renewable energy contribute to lower operating costs over the project lifetime. Therefore, the economic evaluation indicates that long-term operational savings and environmental benefits can justify the additional investment required for battery storage.

Overall, this study demonstrates that the **PV–Battery–Gas Turbine** hybrid system represents the most suitable solution for the investigated cement plant. It successfully combines high supply reliability, improved renewable energy utilization, significant fuel savings, and substantial emission reductions while maintaining continuous industrial operation. The proposed configuration therefore provides an effective pathway toward cleaner and more sustainable electricity generation for industrial facilities in Algeria.

This work also contributes to the broader objective of promoting renewable energy integration in the Algerian industrial sector. It provides a practical framework for evaluating hybrid energy systems under local climatic and operational conditions and demonstrates the potential of such systems to support the country's energy transition and decarbonization strategy.

Future research may investigate higher photovoltaic penetration levels, advanced energy management and control strategies, alternative energy storage technologies, demand-side management techniques, and techno-economic analyses under different fuel price scenarios. Such developments could further enhance the efficiency, flexibility, and sustainability of hybrid energy systems for industrial applications.

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Abstract

This thesis investigates the integration of a hybrid photovoltaic (PV)–Battery–Gas Turbine system to supply the electrical demand of the GICA Timokten cement plant in Adrar, Algeria. The objective is to evaluate the technical, economic, and environmental benefits of increasing renewable energy penetration while ensuring a reliable electricity supply. Two hybrid system configurations were modeled and optimized using HOMER Pro based on the plant's energy demand and the region's solar potential. The results indicate that the optimal configuration, consisting of a **15 MW PV array**, a **109.2 MWh battery energy storage system**, and a **natural gas turbine**, provides the best overall performance. The proposed system achieves a renewable energy fraction of **24.6%**, reduces annual natural gas consumption by approximately **31%**, and decreases CO₂ emissions by about **1.73 million kg/year** (around **31%**). Battery storage improves the utilization of photovoltaic energy by storing excess generation and supplying electricity during periods of low solar irradiance. The study demonstrates that the proposed hybrid system is a reliable and sustainable solution for improving energy efficiency and reducing the environmental impact of cement plants and other energy-intensive industries.

Keywords: Photovoltaic energy, Hybrid energy system, Battery energy storage, Gas turbine, Cement plant, HOMER Pro.

المخلص

تهدف هذه الدراسة إلى تقييم دمج نظام هجين يتكون من الطاقة الكهروضوئية والبطاريات وتوربين الغاز لتزويد مصنع جيكا تيموكتين للإسمنت بأدرار بالطاقة الكهربائية. ويهدف هذا النظام إلى تحسين الكفاءة الطاقوية، وتقليل استهلاك الغاز الطبيعي، والحد من التأثيرات البيئية مع ضمان استمرارية التغذية الكهربائية. وقد تم نمذجة ومحاكاة تكوينين مختلفين للنظام باستخدام برنامج **HOMER Pro** اعتماداً على الطلب الكهربائي للمصنع والإمكانات الشمسية للمنطقة. أظهرت النتائج أن التكوين الأمثل، المكوّن من **حقل كهروضوئي باستطاعة 15 ميغاواط**، و**نظام تخزين بالبطاريات بسعة 109.2 ميغاواط ساعي**، و**توربين غازي**، حقق أفضل أداء، حيث بلغت نسبة مساهمة الطاقة المتجددة **24.6%**، وانخفض استهلاك الغاز الطبيعي بحوالي **31%**، كما انخفضت انبعاثات ثاني أكسيد الكربون بحوالي **1.73 مليون كغ سنوياً** (حوالي **31%**). كما ساهم نظام التخزين في تحسين استغلال الطاقة الشمسية وزيادة كفاءة النظام. تؤكد هذه النتائج أن النظام الهجين المقترح يمثل حلاً موثوقاً ومستداماً لتحسين الكفاءة الطاقوية وتقليل الأثر البيئي في صناعة الإسمنت.

الكلمات المفتاحية: الطاقة الكهروضوئية، النظام الهجين، تخزين الطاقة بالبطاريات، توربين الغاز، مصنع الإسمنت، HOMER Pro.

Résumé

Ce mémoire étudie l'intégration d'un système hybride **photovoltaïque–batterie–turbine à gaz** pour assurer l'alimentation électrique de la cimenterie **GICA Timokten** à Adrar (Algérie). L'objectif est d'évaluer les performances techniques, économiques et environnementales d'un tel système afin de réduire la consommation de gaz naturel tout en garantissant une alimentation électrique fiable. Deux configurations hybrides ont été modélisées et optimisées à l'aide du logiciel **HOMER Pro**. Les résultats montrent que la configuration optimale, composée d'un **champ photovoltaïque de 15 MW**, d'un **système de stockage par batteries de 109,2 MWh** et d'une **turbine à gaz**, offre les meilleures performances. Elle atteint une **fraction d'énergie renouvelable de 24,6 %**, réduit la consommation annuelle de gaz naturel d'environ **31 %** et diminue les émissions de CO₂ d'environ **1,73 million de kilogrammes par an**, soit près de **31 %**. Le stockage par batteries améliore également l'exploitation de l'énergie photovoltaïque en valorisant l'énergie solaire excédentaire. Les résultats confirment que ce système hybride constitue une solution fiable, performante et durable pour améliorer l'efficacité énergétique et réduire l'impact environnemental des cimenteries.

Mots-clés : Énergie photovoltaïque, Système hybride, Stockage par batteries, Turbine à gaz, Cimenterie, HOMER Pro.