University of Zawia Journal of Engineering Sciences and Technology (UZJEST)
Volume 4, Issue 2, (2026), pp 172-190, ISSN 3006-2764

Techno-Economic Assessment of a Solar-Powered Iron Production Plant Based on Wadi Al-Shati Iron Ore in Libya

Yuosef Adraider*[1], Ibrahim Imbayah [2], El Mahboub Edreder [3], Zohra Gebrel [4], Yasser Nassar [5], Ali Elhatmi [1]

[1] Department of Energy Engineering, College of Renewable Energy, Tajoura, Libya
[2] Mechanical Power Engineering Department, Technical College of Civil Aviation & Meteorology, Esbeai, Libya
[3] National Oil Corporation (NOC), Libya
[4] Department of Physics, Faculty of Science, Sabratha University, Libya
[5] Mechanical and Renewable Energy Eng. Dept., Faculty of Eng., Wadi Alshatti University, Libya
*Corresponding author email: yadraider@yahoo.com

Received: 20-08-2026 | Accepted: 20-10-2026 | Available online: 24-10-2026 | DOI:10.26629/uzjest.2026.14

ABSTRACT

The iron industry is among the most energy-intensive and carbon-emitting industrial sectors, motivating renewable-energy-based solutions. Libya possesses iron ore deposits in the Wadi Al-Shati region together with exceptional solar resources. This study evaluates the feasibility of solar photovoltaic (PV) energy for powering iron ore mining and processing in Wadi Al-Shati at an annual capacity of 100,000 tons The methodology combines iron ore characterization, solar resource assessment, and a techno-economic model that quantifies the contribution of solar energy to ore-processing stages and compares energy use and emissions with a conventional system. With a specific energy consumption of 25 kWh per ton, the annual demand is 2.5 GWh, and the proposed system provides about 2.2 GWh of usable solar energy annually, meeting roughly 88% of demand. The economic assessment covers capital expenditure (CAPEX), operation and maintenance (O&M) costs, energy cost savings, net present value (NPV), internal rate of return (IRR), levelized cost of electricity (LCOE), and emission factor (EF). The solar system costs approximately 1.40 million USD, with a first-year net cash flow of 449,000 USD. At an 8% discount rate and a 20-year lifespan, the NPV is approximately 2.85 million USD and the IRR is 31.4%. The LCOE is 0.084 USD/kWh, about 62% below the assumed conventional electricity cost of 0.22 USD/kWh, and the avoided emissions are 1,540 tons of CO_2 per year. These pre-feasibility results suggest solar integration is a promising economic and environmental option for the Wadi Al-Shati region.

Keywords: iron ore, solar photovoltaic, iron industry, carbon dioxide emissions, sustainability.

التقييم الفني والاقتصادي لإنتاج الحديد بالطاقة الشمسية في مصنع يعتمد على خام الحديد من وادي الشاطئ في ليبيا

يوسف إدريدر[1]، إبراهيم إمبية [2]، المحبوب إدريدر[3]، زهراء جبريل[4]، ياسر نصار[5]، على الحاتمي [1]

[1] قسم هندسة الطاقة، كلية الطاقات المتجددة، تاجوراء، ليبيا
[2] قسم هندسة الطاقة الميكانيكية، الكلية التقنية للطيران المدني والأرصاد الجوية، اسبيعة، ليبيا
[3] المؤسسة الوطنية للنفط، ليبيا
[4] قسم الفيزياء، كلية العلوم، جامعة صبراتة، ليبيا
[5] قسم الهندسة الميكانيكية والطاقات المتجددة، كلية الهندسة، جامعة وادي الشاطئ، ليبيا

"Articles published in *Univ Zawia J Eng Sci Technol* are licensed under a Creative Commons Attribution-NonCommercial 4.0 International License."

ملخـــــص البحـــــث

تُعد صناعة الحديد من أكثر القطاعات الصناعية استهلاكًا للطاقة وانبعاثًا لثاني أكسيد الكربون، مما يدفع إلى البحث عن حلول قائمة على الطاقة المتجددة. تمتلك ليبيا رواسب خام الحديد في منطقة وادي الشاطئ، إلى جانب إمكانات شمسية هائلة. تهدف هذه الدراسة إلى تقييم جدوى استخدام الطاقة الشمسية الكهروضوئية لتلبية احتياجات الكهرباء لعمليات استخراج خام الحديد ومعالجته في وادي الشاطئ بطاقة إنتاجية سنوية تبلغ 100,000 طن. تعتمد المنهجية على تحليل خصائص الخام، وتقييم الإمكانات الشمسية للمنطقة، وتطوير نموذج فني اقتصادي يحدد مساهمة الطاقة الشمسية في مراحل المعالجة، مع مقارنة استهلاك الطاقة والانبعاثات بين النظام التقليدي والنظام الشمسي. وباستهلاك نوعي للطاقة قدره 25 كيلوواط/ساعة لكل طن، يبلغ الطلب السنوي 2.5 جيجاواط/ساعة، ويوفر النظام المقترح نحو 2.2 جيجاواط/ساعة من الطاقة الشمسية القابلة للاستخدام سنويًا، أي نحو 88% من الطلب. شمل التقييم الاقتصادي النفقات الرأسمالية (CAPEX)، وتكاليف التشغيل والصيانة (O&M)، ووفورات تكاليف الطاقة، والقيمة الحالية الصافية (NPV)، ومعدل العائد الداخلي (IRR)، والتكلفة المُعَدَّلة للكهرباء (LCOE)، وعامل الانبعاثات (EF). تبلغ تكلفة النظام نحو 1.40 مليون دولار أمريكي، وصافي التدفق النقدي للسنة الأولى 449,000 دولار أمريكي. وعند معدل خصم 8% وعمر مشروع 20 عامًا، تبلغ القيمة الحالية الصافية نحو 2.85 مليون دولار أمريكي ومعدل العائد الداخلي 31.4%. وتبلغ التكلفة المُعَدَّلة للكهرباء 0.084 دولار أمريكي/كيلوواط ساعة، أي أقل بنحو 62% من التكلفة المفترضة للكهرباء التقليدية البالغة 0.22 دولار أمريكي/كيلوواط ساعة، وتبلغ الانبعاثات المتجنبة 1,540 طن من ثاني أكسيد الكربون سنويًا. وتشير هذه النتائج الأولية إلى أن دمج الطاقة الشمسية يمثل خيارًا اقتصاديًا وبيئيًا واعدًا لمنطقة وادي الشاطئ.

الكلمات الدالة: خام الحديد، الطاقة الشمسية، صناعة الحديد، انبعاثات ثاني أكسيد الكربون، الاستدامة.

1. Introduction

Iron is considered one of the most essential materials in modern industrial development, playing a key role in the construction, transportation, and engineering sectors. However, traditional iron production relies heavily on fossil fuel energy sources, resulting in high energy consumption and the emission of greenhouse gases. Libya possesses natural assets that could facilitate the development of a low-emission iron industry; the Wadi Al-Shati region in southwestern Libya contains significant iron ore deposits and benefits from high levels of annual solar radiation.

Despite the availability of these resources, the exploitation of domestic iron ore remains limited, and the Libyan iron industry relies heavily on imported ores. Therefore, this study examines the feasibility of integrating solar energy into the iron production process using Wadi Al-Shati ore.

The global iron and steel industry remains one of the most energy- and carbon-intensive branches of heavy manufacturing, responsible for roughly seven percent of global anthropogenic CO_2 emissions, the large majority of it tied to coal-fired blast furnace (BF) operation, which still produces about 90% of the world's hot metal [1]. Smelting reduction, a third route that combines ore melting and reduction in a single vessel, offers a lower-capital alternative to the coke-oven/sinter/BF chain but remains less commercially mature at scale [2]. Though the electricity demand of the H_2-DRI-EAF pathway, on the order of 3.7 MWh per ton of liquid steel, is somewhat higher than the roughly 3.5 MWh per ton required by conventional BF-BOF production, making the carbon intensity of that electricity, not just its cost, decisive for the technology's climate benefit [3]. Hydrogen-based direct reduction of iron (H_2-DRI) coupled with an electric arc furnace (EAF) offers one of the most credible low-carbon alternatives: reducing iron oxide with hydrogen rather than carbon monoxide can cut process CO_2 emissions by

roughly 90% relative to the BF route [4]. Because H_2-DRI depends on electrolytic hydrogen and grid or renewable electricity, it is generally regarded as the most tractable near-term route for coupling ironmaking to variable solar or wind generation [5-8].

Renewable-energy-based steel production is most competitive where high-quality iron ore coincides with strong solar or wind resources, a combination identified globally as concentrated in belts near the tropics of Cancer and Capricorn [9]. Three solar technologies are candidates for supplying that energy locally. Photovoltaic (PV) generation converts sunlight directly into electricity and can power electrolysis, EAF, and ore-beneficiation loads. Concentrated solar power (CSP) instead focuses direct solar radiation onto a receiver, delivering dispatchable electricity via thermal storage or process heat up to several hundred degrees Celsius, relevant to ore preheating and drying [10]. Non-concentrating solar thermal collectors sit between the two, simpler and cheaper than CSP but limited to lower-temperature duties. Of the three, PV is currently the most cost-competitive and the best match to a plant of the scale considered here, though CSP's dispatchability remains relevant to later-stage plant design [11,12]. Beyond stand-alone PV, hybrid configurations that combine PV with storage or complementary sources are increasingly applied to industrial, remote-community and grid-connected loads [14, 37–45]; Section 2.4 reviews these applications and positions the present PV–battery study within them.

Libya sits squarely within this favorable combination. The Wadi Al-Shati region in the country's southwest hosts extensive sedimentary iron ore deposits, characterized by Oolitic hematite and goethite mineralization; grades are lower than premium seaborne ores but amenable to beneficiation and direct reduction [13]. The same region lies within one of the highest-irradiance desert belts in the country, with annual solar yields confirmed across independent Libyan resource assessments, including large-scale PV installations elsewhere in Libya [14-17]. Despite this pairing of resources, Wadi Al-Shati ore remains largely unexploited, and Libya's broader energy system remains almost entirely fossil-fuel dependent, a condition recent assessments attribute to institutional fragmentation, chronic underinvestment, and policy gaps rather than any shortage of physical renewable resource [18,19].

Previous studies have established several important foundations for the integration of renewable energy into the iron and steel sector. Research on low-carbon ironmaking has primarily focused on hydrogen-based direct reduction (H2-DRI), electric arc furnaces (EAF), and the role of renewable electricity in reducing the carbon intensity of steel production. Other studies have examined the potential of solar technologies, including photovoltaic (PV) and concentrated solar power (CSP), for supplying electricity or process heat to energy-intensive industrial operations. In parallel, techno-economic studies of renewable energy in mining have investigated the feasibility of PV, hybrid renewable systems, and energy storage for reducing the dependence of mining operations on grid or diesel-generated electricity [20–32]. Studies specific to Libya have also characterized the country's solar-resource potential and examined the mineralogical and geological characteristics of the Wadi Al-Shati iron ore deposits [11–19, 34–36].

However, these previous studies generally address these aspects separately. Studies on Wadi Al-Shati have mainly focused on the geological, mineralogical, and resource characteristics of the iron ore, while studies of Libya's solar potential have primarily assessed renewable-energy resources and their applications in electricity generation. International studies on renewable-powered mining and low-carbon ironmaking have provided useful technical and economic methodologies, but their results cannot be directly transferred to Wadi Al-Shati without considering the specific ore characteristics, solar resource, operating conditions, electricity costs, and economic assumptions applicable to Libya. Furthermore, most studies on renewable steelmaking focus on downstream processes such as hydrogen production, direct reduction, and electric-arc-furnace operation, whereas the integration of solar PV and

battery energy storage specifically into the upstream Wadi Al-Shati ore-mining and processing system has received limited attention.

The present study therefore addresses a more specific and localized research question: to what extent can a solar-PV and battery energy-storage system reduce conventional electricity requirements for processing Wadi Al-Shati iron ore, and is such integration technically and economically feasible under defined Libyan conditions? Unlike previous studies that investigate the individual components of the problem, this work combines the local iron-ore resource, the regional solar-energy potential, the electricity demand of ore-processing operations, and a techno-economic assessment within a single pre-feasibility framework.

Accordingly, the specific contribution of this study is not to propose a completely solar-powered steelmaking route or to replace hydrogen-based ironmaking studies. Instead, it quantifies the potential contribution of solar PV and battery storage to the electricity demand of a 100,000-ton-per-year Wadi Al-Shati iron-ore processing operation. The study develops an energy balance, estimates the solar contribution and remaining conventional-energy requirement, and evaluates CAPEX, O&M costs, LCOE, NPV, IRR, avoided electricity costs, and associated CO_2-emission reductions. Sensitivity to key economic and technical parameters is also considered. This approach provides a Libya-specific pre-feasibility assessment that links the country's domestic iron-ore resource with its high solar-energy potential and establishes a quantitative basis for subsequent, more detailed studies involving hourly energy dispatch, process-specific load data, battery degradation, and downstream DRI/EAF or hydrogen-based ironmaking.

2. Previous Studies

2.1 Iron Ore in Libya

Geological studies indicate the presence of significant iron ore deposits in Wadi Al-Shati, characterized by iron minerals such as hematite and magnetite [13]. Several studies have investigated the mineralogical and geophysical properties of these deposits [34-36].

2.2 Solar Energy in Libya

Libya is characterized by high levels of solar radiation, particularly in the southern desert regions, making the use of solar photovoltaic systems a suitable option for supplying electricity to industrial projects [11].

2.3 Renewable Energy and the Iron Industry

Most recent studies focus on reducing emissions in the iron industry through renewable electricity and green hydrogen [7-9].

2.4 Hybrid Renewable Energy Systems and Storage in Different Applications

Hybrid renewable energy systems, which combine complementary generation technologies and/or energy storage, are widely used to improve supply continuity, cost and emissions performance across a range of applications. For the Libyan grid, an optimal PV/wind/pumped-hydro-storage configuration comprising a 1000 MW PV field, a 200 MW wind farm and an 854 MWh storage system was reported to supply the modelled load entirely from sustainable sources at a levelized power cost of about 49.9 USD/MWh [40]. Solar electricity generation combined with green-hydrogen production has likewise been assessed as a pathway to low-carbon transportation in Gaza [37], and a 600 MW floating PV system at Al-Khums, Libya, has been modelled with PVsyst [14]. Because storage is the enabling element of most such hybrids, a review of electrical energy storage technologies and their application potential in

power-system operation [45] provides the technical background for the battery component adopted in the present study.

At the national and system-integration level, a systematic review of renewable-energy resources, costs and implement ability in Libya traces the evidence from resource characterisation, through techno-economic performance, to deployment value [38]. Renewable transition and net-zero pathways have also been framed as the co-optimisation of variable solar and wind generation with grid upgrades, inverter-based stability services, storage and demand-side flexibility [41]. Application-specific PV studies further illustrate the use of PV-based supply in Libya and the wider region, including solar street lighting for a remote road in southern Libya [42] and for a main street in Gaza [44], and AI-based monitoring of dust accumulation and fault detection on PV modules in desert environments [39], which is pertinent to PV plant performance in settings such as Wadi Al-Shati.

Heavy industry is a further application area. A life-cycle assessment of the Libyan cement industry estimated the CO_2 emission factor of cement consumed in Libya at about 1,083.6 kg CO_2 per tonne of cement and indicated that switching from heavy fuel oil to natural gas could reduce CO_2 emissions from energy use in cement plants by more than 11% [43]. This confirms that the energy supply is a first-order determinant of emissions in Libyan materials-processing industries and motivates the substitution of fossil-based electricity by PV–battery hybrid supply in the ore-processing chain considered here. In contrast to the studies above, which address grid-scale, community, transport or lighting loads, the present work evaluates a PV–battery arrangement with grid or diesel backup for an ore-processing load in Wadi Al-Shati.

3. Study Area: Wadi Al-Shati

Located in southwestern Libya, the Wadi Al-Shati region is considered one of the country's most important iron ore areas.

The Wadi Al-Shati region is characterized by:

1. Significant iron ore reserves.
2. Vast areas suitable for the construction of solar power plants.
3. Low population density.
4. Climatic conditions favorable for solar energy.
5. Research gap and study contribution

Despite extensive work on Wadi Al-Shati mineralogy [13], Libyan solar resources [11,12,14–19], and renewable-powered mining [20–32], a focused techno-economic assessment that combines Wadi Al-Shati iron ore processing with a PV–BESS system remains limited. The present study addresses this gap at the pre-feasibility level. Its novelty lies not in proposing a fully solar-powered steel plant, but in quantifying the extent to which solar PV and storage can displace conventional electricity in the upstream mining and ore-processing segment under explicit Libyan assumptions. In this respect, the PV–BESS configuration with grid or diesel backup considered here extends the hybrid-system applications reviewed in Section 2.4 [37]–[45] to an ore-processing load.

4. Wadi-Ashatti iron ore Location

4.1 Location coordinates:

- **Latitude: 27.55° N**

- **Longitude: 14.27° E**

The iron ore in Wadi Al-Shatti extends for a distance of approximately 200 km and a width of approximately 20 km, and includes several sites and ores distributed along the length of the Wadi Al-Shatti. A shown in figure 1. Location of Wadi Al-Shati on Libyan map

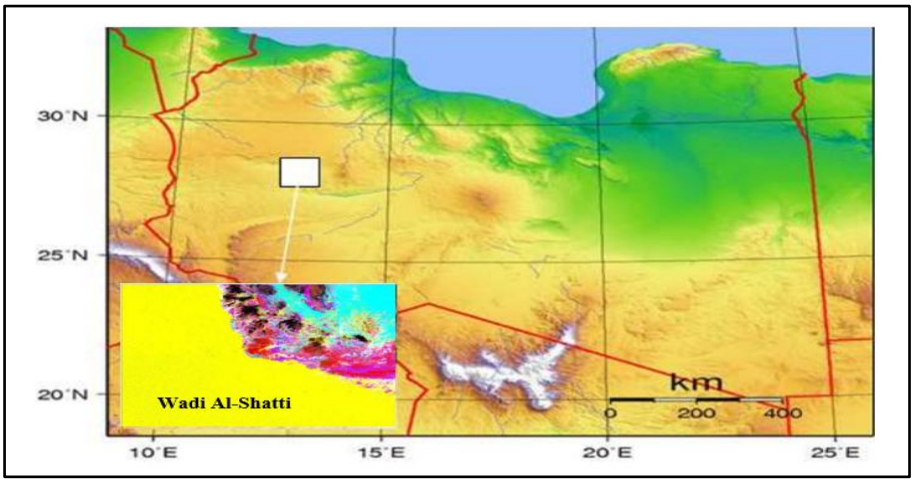

Figure 1. Location of Wadi Al-Shati on Libyan map

4.2 Geological map:

Based on published geological studies regarding the sedimentary iron ores in Wadi Shati. The table 1shows the most significant ore concentration sites.

Table 1: Principal iron-ore locations considered in the Wadi Al-Shati context

Location	Geological description
Tarut	The areas most extensively explored by drilling, where the principal sedimentary iron ore-bearing strata are located.
Brak Al-Shati	Situated in the middle of the belt, it serves as the primary geographical reference for iron ores, with ore-bearing formations distributed around it.
Wadi Shati Sedimentary Belt	It extends east-northeast for a distance of approximately 160 to 200 km, with a width of about 20 km, and contains iron-bearing sedimentary strata within upper Devonian and lower Carboniferous formations.

4.3 Solar radiation data

The Wadi Al-Shati region is among the areas in Libya with the highest solar energy potential; the average Global Horizontal Irradiance (GHI) ranges from approximately 6.0 to 6.8 kWh/m²/day, with peak values occurring in summer and the lowest in winter. These data are based on the NASA POWER database, which is widely used in solar energy studies in Libya. Figure 2. Shown the monthly solar radiation profile for Wadi Al-Shati.

Table 2 indicates the approximate monthly averages of solar radiation in the Wadi Al-Shati region. The annual average is approximately 6.1 kWh/m²/day (equivalent to about 2,225 kWh/m²/year).

Table 2: Solar radiation in the Wadi Al-Shati region

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
GHI (kWh/m²/day)	3.9	4.8	6.0	7.1	7.8	8.2	8.0	7.4	6.6	5.5	4.5	3.8

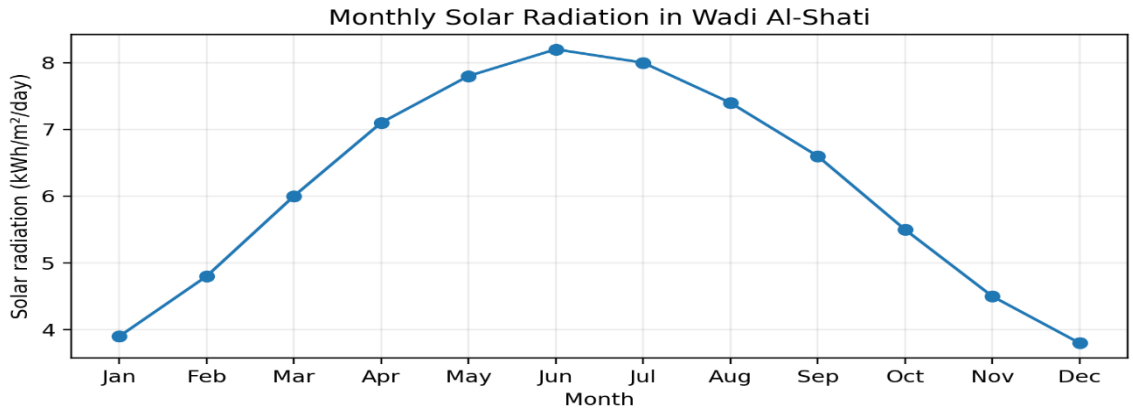

Figure 2. Monthly solar radiation profile for Wadi Al-Shati.

4.4 Iron Ore Production Processes

The proposed flowchart for the iron production processes is shown in Figure 3, incorporating a solar photovoltaic (PV) system as a primary source of the electrical energy required to operate the various industrial units. This proposal aims to reduce reliance on conventional energy sources, lower greenhouse gas emissions, and improve energy efficiency within the iron industry.

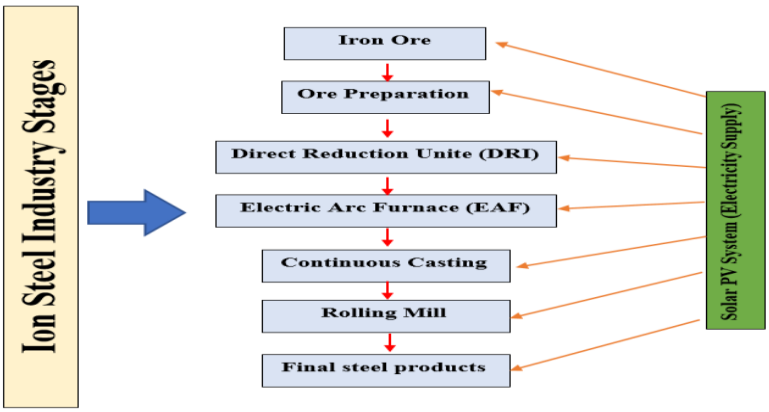

Figure 3. Stages of Iron Ore Production plant

The process begins with the iron ore preparation stage, which involves crushing, screening, and conditioning the ore to achieve the appropriate size and properties for the direct reduction process. Electricity generated by the solar photovoltaic system powers mechanical equipment such as crushers, conveyor belts, and screens, thereby reducing the consumption of electricity derived from fossil fuels. Subsequently, the ore is transferred to the Direct Reduction Unit, where iron ore is reduced to produce Direct Reduced Iron (DRI). In this proposal, electricity generated by the solar energy system powers the auxiliary equipment, control systems, compressors, and fans associated with the reduction unit, while the chemical reduction process utilizes a suitable reducing agent such as natural gas or hydrogen in accordance with the operational scenario adopted in the study. The iron is subsequently transferred to an Electric Arc Furnace (EAF), where it is melted to produce liquid steel. As this furnace is a major consumer of electricity, powering it with energy generated from a solar power system while retaining

the option to draw from the electrical grid or energy storage systems when necessary helps reduce conventional energy consumption and lower carbon emissions.

The molten steel is subsequently directed to the continuous casting unit to produce billets or slabs, and then to the rolling mill to shape final products such as rebar, sheets, and steel sections. Additionally, electricity generated by the solar energy system powers rolling mill motors, conveyor systems, cooling units, and control systems, thereby enhancing energy efficiency and reducing operating costs. In Table 3: The role of solar energy in each iron industry stage.

Table 3: The role of solar energy in each iron industry stage

Industry stage	Solar PV role
Ore Preparation	Operating crushers, conveyor belts, screens, and pumps using electricity generated by solar panels.
Direct Reduction Unit (DRI)	Supplying electricity to direct reduction units and auxiliary equipment, thereby reducing the consumption of electricity generated from fossil fuels
Electric Arc Furnace (EAF)	Supplying the electric arc furnace with electrical energy generated from the solar system, with the option of supplementing it via the grid or batteries when needed
Continuous Casting	Operating continuous casting equipment, as well as control and cooling systems, using solar electricity
Rolling Mill	Powering rolling mill motors, handling systems, and auxiliary equipment with solar energy.

5. Governing equations

The governing relations below are standard formulations from the ironmaking, PV-engineering and engineering-economics literature. The source(s) supporting each relation are cited beside its title, and the symbol definitions follow those sources.

❖ **Production Rate:** [46]

$$p = \frac{m}{t} \tag{1}$$

Where:

P is production rate (**ton/h**), ***m*** is produced iron mass (**ton**), ***t*** is production time (**h**)

❖ **Iron Recovery Efficiency: [46]**

$$\eta = \frac{m_{actual}}{m_{theoretical}} \text{ x } 100\% \tag{2}$$

Where:

m_{actual} is the actual iron produced, $\boldsymbol{m}_{theoretical}$ is the theoretical iron yield

❖ **Reduction Degree: [4, 47]**

$$R = \frac{O_i - O_f}{O_i} \times 100\% \tag{3}$$

Where:

$\boldsymbol{O_i}$ is the initial oxygen content; $\boldsymbol{O_f}$ is the final oxygen content after reduction

❖ **Hematite Reduction Reaction: [4, 47]**

Using carbon monoxide:

$$Fe_2O_3+3CO \rightarrow 2Fe+3CO_2$$

Using hydrogen:

$$Fe_2O_3+3H_2 \rightarrow 2Fe+3H_2O$$

❖ **Specific Energy Consumption (SEC): [1], [2]**

$$SEC = \frac{E}{m} \quad (4)$$

Where:

SEC is specific energy consumption (**kWh/ton**); ***E*** is total energy consumed (**kWh**); ***m*** is steel or iron produced (**ton**)

❖ **Furnace Thermal Efficiency: [48], [55]**

$$\eta = \frac{Q_{useful}}{Q_{input}} \times 100\% \quad (5)$$

Where:

Q_{useful} is useful heat, Q_{input} is total heat supplied

❖ **Heat Balance: [47], [55]**

$$Q_{input} = Q_{product} + Q_{loss} \quad (6)$$

Where:

Q_{input} is total input heat, $Q_{product}$ is heat utilized in production, Q_{loss} is heat losses.

❖ **Blast Furnace Productivity: [47], [48]**

$$BP = \frac{M}{V \times t} \quad (7)$$

Where:

BP is blast furnace productivity (**t/m³/day**), ***M*** is hot metal production (**ton**)

V is effective furnace volume (**m³**), ***t*** is operating time (**day**)

❖ **Coke Rate: [47], [48]**

$$CR = \frac{m_{coke}}{m_{hot\ metal}} \quad (8)$$

Where:

CR is coke consumption (**kg/t of hot metal**)

m_{coke} is the mass of coke consumed (**kg**), $m_{hot\ metal}$ is the mass of hot metal produced (**ton**)

❖ **CO_2 Emission Factor: [1], [54]**

$$EF = \frac{m_{CO2}}{m_{steel}} \quad (9)$$

Where:

EF is the CO_2 emissions factor, m_{CO2} is the total mass of carbon dioxide emitted (**kg**), m_{steel} is the total mass of steel produced (**kg**)

❖ **Solar PV Energy Output: [49], [50]**

$$E_{PV} = A \times G \times \eta PV \quad (10)$$

Where:

E_{PV} is electrical energy generated by the PV system (**kWh**), A is PV array area (**m²**), G is solar irradiance (**kWh/m²**), η_{PV} is PV efficiency

❖ **Overall Solar System Efficiency: [45], [50], [51]**

$$\eta_{system} = \eta_{PV} \times \eta_{inverter} \times \eta_{battery} \quad (11)$$

Where:

η_{system} is overall system efficiency, η_{PV} is photovoltaic panel efficiency

$\eta_{inverter}$ is inverter efficiency, $\eta_{battery}$ is battery round-trip efficiency

❖ **Net Present Value (NPV): [52], [53]**

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} \quad (12)$$

Where:

CF_t is the cash flow in year (t), r is the discount rate, and n is the project lifetime

❖ **Internal Rate of Return (IRR): [52], [53]**

$$0 = \sum_{t=0}^{n} \frac{CF_t}{(1+IRR)^t} \quad (13)$$

Where:

IRR is the internal Rate of Return (%), CF_t is the net cash flow in year (t), t is the year number

n is project lifetime (years)

❖ **Levelized Cost of Energy (LCOE): [28], [52]**

$$LCOE = \frac{PV\ (CAPEX) + PV\ (O\&M)}{PV\ (E_{useful})} \quad (14)$$

6. Techno-Economic model

A mathematical model is developed to design and evaluate the solar-powered iron and steel plant considered in this study. The mathematical model needs to be economically stronger while remaining technically defensible. Below, a base-case mathematical model is developed for the production capacity of the 100,000 t/year Wadi Al-Shati iron-ore project. In Table 4: Techno-Economic Model Parameters.

Table 4: Techno-Economic Model Parameters

Parameter	Value	Unite
Iron ore production	100,000	t/year
Specific electricity consumption	25	kWh/t
Annual electricity demand	2.50	GWh/year
PV capacity	1.8	MWp
Battery	1	1 MWh
Useful solar electricity	2.20	GWh/year
Solar contribution	88%	annual electricity demand
Remaining electricity	0.30	GWh/year
Avoided electricity/diesel cost	0.22	USD/kWh
Project life	20	year
Discount rate	8%	-
O&M	35,000	USD/year

6.1 Production model

Annual production:

$$Q = 100{,}000 \text{ t/year}$$

Operating schedule:

330 days/year

16 h/day

Annual operating hours:

$$H = 330 \text{ days/year} \times 16 \text{ h/day} = 5{,}280 \text{ h/year}$$

Production rate:

$$Q_h = 100{,}000 \text{ t/year} / 5{,}280 \text{ h/year}$$

$$Q_h = 18.94 \text{ t/h}$$

6.2 Electricity requirement

The Specific Energy Consumption is:

$$SEC = 25 \text{ kWh/t}$$

$$E_{load} = 100{,}000 \text{ t/year} \times 25 \text{ kWh/t}$$

$$E_{load} = 2.50 \text{ GWh/year}$$

6.3 PV and battery sizing methodology

The PV and battery capacities were selected using a conceptual pre-feasibility sizing approach rather than a formal mathematical optimization algorithm. The sizing objective was to identify a practical PV–BESS configuration capable of supplying a high fraction of the annual electricity demand of the 100,000 t/year ore-processing facility while retaining a conventional electricity source for periods of insufficient solar generation. The annual electricity demand was estimated as 2.50 GWh/year based on a specific electricity consumption of 25 kWh/t. The PV capacity was then selected using the assumed Wadi Al-Shati solar resource and a conceptual annual PV yield of 1,869 kWh/kWp/year. A nominal PV capacity of 1.8 MWp gives an estimated annual gross generation of:

EPV = 1.8 MWp × 1,869 kWh/kWp/year = 3.364 GWh/year.

This capacity was selected to provide sufficient annual solar generation to cover most of the plant's electricity demand after accounting conceptually for timing mismatch, conversion losses, battery losses, curtailment, and operational constraints. Based on these assumptions, approximately 2.20 GWh/year of solar electricity is considered useful to the plant, corresponding to approximately 88% of the estimated annual electricity demand. The battery capacity was selected as 1 MWh to provide short-duration energy shifting between periods of solar generation and evening or low-solar plant operation. Assuming an 80% depth of discharge, the usable battery energy is approximately 0.80 MWh. The battery is therefore intended primarily for short-term load shifting and solar-energy utilization rather than for providing long-duration independent operation of the plant. Accordingly, the 1.8 MWp PV and 1 MWh BESS configuration should be interpreted as a base-case conceptual design for pre-feasibility analysis, rather than as the unique globally optimal configuration. A formal optimization would require hourly plant-load data, hourly solar-resource data, battery charging/discharging constraints, battery degradation,

minimum state-of-charge requirements, and a defined objective function such as minimizing the net present cost or LCOE while satisfying a specified solar fraction. Such an optimization is beyond the scope of the present annualized pre-feasibility model and is identified as an area for future work.

6.4 Battery system

It's Assuming that 80% usable depth of discharge:

$$E_{usable} = 1 \text{ MWh} \times 0.8$$

$$E_{usable} = 0.8 \text{ MWh}$$

The battery is mostly used at evening plant loads.

6.5 Solar contribution

We assume that after accounting for timing, battery losses, curtailment, and operational constraints, approximately **2.20GWh/year** of solar electricity is actually useful to the mine.

The solar fraction is:

$$SF = 2.20 / 2.5$$

$$SF = 88\%$$

Therefore:

$$E_{backup} = 2.50 - 2.20$$

$$E_{backup} = 0.30 \text{ GWh/year} \quad \textbf{or} \quad 300{,}000 \text{kWh/year}$$

This remaining 12% can be supplied by a grid connection or diesel generator.

This hybrid arrangement is much more realistic than claiming the mine will operate entirely from solar PV. Comparable PV-based hybrid arrangements with storage or backup supply have been reported for other applications [37], [40], [45].

6.6 PV configuration

We assume 550 Wp modules:

$$N = 1{,}800{,}000 / 550$$

$$N \approx 3{,}273 \text{ modules}$$

So the total required solar panels are approximately 3300 Panels.

6.7 Capital expenditure

We need to design a more efficient system.

The cost of the solar PV station:

If the cost of 1 kWp is 550 USD, then:

$$CAPEX_{PV} = 1{,}800 \text{ MWp} \times 550 \text{ USD}$$

$$CAPEX_{PV} = 990{,}000 \text{ USD}$$

The cost of **the battery:**

If the cost of 1 kWp is 300 USD, then:

$$CAPEX_{BESS} = 1{,}000\ MWp \times 300\ USD$$

$$CAPEX_{BESS} = 300{,}000\ USD$$

So the cost of PV + battery = 990,000 USD + 300,000 USD = 1,290,000 USD

Add approximately 8.5% for engineering, controls, installation, contingency, and electrical integration:

$CAPEX_{total} \approx 1{,}400{,}000$ USD **or** CAPEX = 1.40 million USD

6.8 Annual energy savings

If the mine uses 2.20 GWh/year of useful solar electricity, we assume that the avoided electricity/diesel generation cost:

The avoided electricity cost is Ce = 0,22/ kWh was assumed according to the local market as the base-case value for the techno-economic assessment.:

$$Ce = 0.22\ USD \text{ for each } 1\ kWh$$

$$Ce = 0.22\ USD/kWh$$

$$E_{solar} = 2{,}200{,}000\ kWh/year$$

Then:

$$\text{Energy Savings} = E_{solar} \times Ce$$

$$\text{Energy Savings} = 2{,}200{,}000\ kWh/year \times 0.22\ USD/kWh$$

$$\text{Energy Savings} = 484{,}000\ USD/year$$

This represents the gross annual energy-cost savings; that means the solar electricity is saving 484,000 USD/year instead of using a conventional electricity source.

6.9 Operation and Maintenance (O&M)

If O&M = 35,000 USD/year

Then: Year-1 net operating cash flow is:

$$CF1 = \text{Annual Energy Savings} - \text{Annual O\&M Cost}$$

$$CF1 = 484{,}000\ USD/year - 35{,}000\ USD/year$$

$$CF1 = 449{,}000\ USD/year$$

This means the project has a net profit of 449,000 USD in the first year after deducting operation and maintenance costs.

6.10 Net Present Value (NPV)

If the discount rate (r) = 8 %, and the project lifetime is 20 years, then:

$$NPV = -1{,}400{,}000 + \sum_{t=1}^{20} \frac{CF_t}{(1.08)^t}$$

NPV=$2.85million, then the NPV > 0, the project is economically attractive and profitable.

6.11 Initial Return Rate (IRR)

The IRR is the discount rate at which the NPV = 0

Then, the calculated value of IRR = 31.4%, which is greater than the discount rate of 8%.

$$31.4\% > 8\%$$

It means the solar-energy investment in this project is strongly profitable.

6.12 LCOE

The levelized cost of useful electricity is:

$$LCOE = \frac{PV\ (CAPEX) + PV\ (O\&M)}{PV\ (E_{useful})}$$

If the project lifetime is 20 years, and the discount rate is 8%:

Then, the calculated LCOE ≈ 0.084 USD/kWh or LCOE ≈ 83.6 USD/MWh

If we compare this with the assumed avoided electricity cost of 220 USD/MWh

Then:

$$220 - 83.6 = 136.4 \text{ USD/MWh}$$

The solar energy system has a levelized energy cost:

$$\frac{220-83.6}{220} \times 100 = 62\%$$

LCOE is approximately 62% lower than Ce

$$\text{LCOE} = 0.084 \text{ USD/kWh} < \text{Ce} = 0.22 \text{ USD/kWh}$$

This confirms that the cost of electricity produced from the solar system is 62% lower than the cost of conventional electricity.

6.13 CO_2 Reduction

If the displaced fossil-generated electricity has an emission factor of:

$$EF = 0.70 \text{ kg } CO_2/\text{kWh}$$

And annual useful solar electricity:

$$2{,}200{,}000 \text{ kWh}$$

Then:

$$CO_2 = 2{,}200{,}000 \times 0.70$$

$$CO_2 \text{ reduction} = 1{,}540{,}000 \text{ kg } CO_2/\text{year}$$

$$\text{or } 1{,}540 \text{ ton } CO_2/\text{year}$$

Over 20 years:

The avoided emissions = 1,540 ton CO_2/year x 20 years

$$= 30{,}800 \text{ ton } CO_2$$

Avoiding 30,800 tons of CO_2 emissions over 20 years is a massive environmental saving with high environmental impact.

7. Discussion

The calculations conducted in the study demonstrated that utilizing solar energy to supply the electricity required for a project producing 100,000 tons of iron ore annually in Wadi Al-Shati could be both technically and economically feasible. The annual electricity demand stands at approximately 2.5 GWh, whereas the proposed 1.8 MWp solar energy system can generate about 2.2 GWh of usable electricity annually, equivalent to roughly 88% of the annual demand.

Economically, the initial investment cost of the system was approximately $1.40 million, while the net cash flow in the first year amounted to about $449,000. The economic analysis also yielded a Net Present Value (NPV) of $2.85 million and an Internal Rate of Return (IRR) of 31.4%. Furthermore, the Levelized Cost of Energy (LCOE) was approximately $0.084/kWh, about 62% lower than the assumed avoided electricity/diesel cost of $0.22/kWh.

These results indicate that a higher contribution from solar energy and lower electricity production costs over the project's lifespan are key factors in enhancing economic viability. However, as the findings rely on a set of assumptions, they should be considered preliminary and require verification using actual field data before project implementation.

8. Limitations and Future Work

This study is a conceptual pre-feasibility assessment and should be interpreted within the following limitations:

1. Specific electricity consumption of 25 kWh/t is an assumed aggregate value and should be validated against a process-specific load list for crushing, screening, beneficiation, pumping, conveying, and auxiliaries.
2. The PV yield and useful-solar-energy fraction are annualized assumptions rather than results from a full hourly dispatch simulation.
3. The economic model assumes constant real annual cash flow and excludes PV degradation, battery degradation/replacement, inflation, tariff escalation, taxes, financing structure, depreciation, salvage value, and major overhauls.
4. The avoided electricity cost of USD 0.22/kWh is a critical economic driver and must be verified against the actual marginal cost of the displaced grid/diesel supply at the project site.
5. The emission factor of 0.70 kgCO2/kWh is a scenario assumption and should be replaced by a verified site-specific factor for the displaced power source.
6. The analysis does not include full life-cycle emissions or environmental impacts associated with PV/BESS manufacturing and disposal.
7. The study does not model downstream DRI, EAF, casting, rolling, or hydrogen production; a separate integrated iron-and-steel model is required before claims can be made about solar-powered iron or steel production.

Future work should therefore combine site-measured ore characteristics, process design, hourly meteorological data, a detailed electrical load profile, optimized PV/BESS dispatch, battery replacement modeling, and probabilistic or Monte Carlo uncertainty analysis. A second research phase could then extend the system boundary to natural-gas DRI and green-hydrogen DRI–EAF scenarios and calculate the levelized cost of DRI or steel.

9. Conclusion

The study integrating solar energy into iron ore production operations in Libya's Wadi Al-Shatti region represents a promising technical and economic option, particularly given the region's high solar energy potential and the need to reduce reliance on conventional energy sources. A techno-economic model was developed for a facility with an annual production capacity of 100,000 tons of iron ore, utilizing a 1.8 MW solar photovoltaic (PV) plant and a 1 MWh battery storage system.

The results indicate that the annual electricity demand is estimated at approximately 2.5 GWh, while the proposed solar system can supply about 2.2 GWh of usable energy annually, representing nearly 88% of the total electricity demand. This result suggests the feasibility of achieving a high level of reliance on solar energy. The economic calculations show that the capital cost is relatively low at 1.40 million USD, while the net annual output in the first year was approximately 449,000 USD, resulting in an alternative energy cost of 0.22 USD/kWh. Based on an 8% discount rate and a 20-year project lifespan, the Net Present Value (NPV) is approximately 2.85 million USD, and the Internal Rate of Return (IRR) is around 31.4%. Additionally, the Levelized Cost of Electricity (LCOE) was estimated at 0.084 USD/kWh, which is 62% lower than the cost of conventional energy. Accordingly, the results reveal that the use of solar energy can contribute to reducing energy costs and improving the economic viability of the iron ore mining project, while lowering emissions associated with conventional energy sources.

Nomenclature

Symbol/abbreviation	Meaning
BESS	Battery energy storage system
CAPEX	Capital expenditure
CF	Annual net cash flow
Ce	Avoided conventional electricity cost
EAF	Electric arc furnace
EF	Emission factor
GHI	Global Horizontal Irradiance
IRR	Internal rate of return
LCOE	Levelized cost of electricity
NPV	Net present value
O&M	Operation and maintenance
PV	Photovoltaic
SEC	Specific electricity consumption

10. Acknowledgment

The authors would like to express their sincere appreciation to the College of Renewable Energy, Tajoura, Libya, for its academic environment and institutional support.

11. Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

REFERENCES

[1] L. Holappa, "A General Vision for Reduction of Energy Consumption and CO2 Emissions from the Steel Industry," Metals, vol. 10, no. 9, art. 1117, 2020, doi: 10.3390/met10091117.
[2] H. Y. Sohn, "Energy consumption and CO2 emissions in ironmaking and development of a novel flash technology," Metals, vol. 10, no. 1, art. 54, 2020, doi: 10.3390/met10010054.
[3] A. Bhaskar, M. Assadi, and H. Nikpey Somehsaraei, "Decarbonization of the Iron and Steel Industry with Direct Reduction of Iron Ore with Green Hydrogen," Energies, vol. 13, no. 3, art. 758, 2020, doi: 10.3390/en13030758.

[4] F. Patisson and O. Mirgaux, "Hydrogen Ironmaking: How It Works," Metals, vol. 10, no. 7, art. 922, 2020, doi: 10.3390/met10070922.
[5] V. Vogl, M. Åhman, and L. J. Nilsson, "Assessment of hydrogen direct reduction for fossil-free steelmaking," J. Clean. Prod., vol. 203, pp. 736–745, 2018, doi: 10.1016/j.jclepro.2018.08.279.
[6] I. R. Souza Filho, H. Springer, Y. Ma, A. Mahajan, C. C. da Silva, M. Kulse, and D. Raabe, "Green steel at its crossroads: Hybrid hydrogen-based reduction of iron ores," J. Clean. Prod., vol. 340, art. 130805, 2022, doi: 10.1016/j.jclepro.2022.130805.
[7] C. Wang, S. D. C. Walsh, Z. Weng, M. W. Haynes, D. Summerfield, and A. Feitz, "Green steel: Synergies between the Australian iron ore industry and the production of green hydrogen," Int. J. Hydrogen Energy, vol. 48, no. 83, pp. 32277–32293, 2023, doi: 10.1016/j.ijhydene.2023.05.041.
[8] A. Boretti, "The perspective of hydrogen direct reduction of iron," J. Clean. Prod., vol. 429, art. 139585, 2023, doi: 10.1016/j.jclepro.2023.139585.
[9] A. Devlin, J. Kossen, H. Goldie-Jones, and A. Yang, "Global green hydrogen-based steel opportunities surrounding high quality renewable energy and iron ore deposits," Nat. Commun., vol. 14, art. 2578, 2023, doi: 10.1038/s41467-023-38123-2.
[10] C. A. Schoeneberger, C. A. McMillan, P. Kurup, S. Akar, R. Margolis, and E. Masanet, "Solar for industrial process heat: A review of technologies, analysis approaches, and potential applications in the United States," Energy, vol. 206, art. 118083, 2020, doi: 10.1016/j.energy.2020.118083.
[11] A. O. M. Maka, S. Salem, and M. Mehmood, "Solar photovoltaic (PV) applications in Libya: Challenges, potential, opportunities and future perspectives," Clean. Eng. Technol., vol. 5, art. 100267, 2021, doi: 10.1016/j.clet.2021.100267.
[12] Y. F. Nassar and A. A. Salem, "The reliability of the photovoltaic utilization in southern cities of Libya," Desalination, vol. 209, no. 1–3, pp. 86–90, 2007, doi: 10.1016/j.desal.2007.04.013.
[13] A. M. Tajouri, P. R. Taylor, C. Anderson, and M. M. Abozbeda, "QEMSCAN analysis of Wadi-Shatti iron ore (Libya)," in Materials Processing Fundamentals, L. Zhang, A. Allanore, C. Wang, J. A. Yurko, and J. Crapps, Eds. Cham, Switzerland: Springer, 2017, doi: 10.1007/978-3-319-48197-5_27.
[14] I. Imbayah, Y. F. Nassar, M. M. Khaleel, H. J. El-Khozondar, M. Elmnifi, and M. Mohammed, "Modeling a 600 MW floating photovoltaic system in Al-Khums city, Libya: Performance analysis and implementation using PVSyst," Wadi Alshatti Univ. J. Pure Appl. Sci., vol. 4, no. 1, pp. 223–237, 2026, doi: 10.63318/waujpasv4i1_24
[15] Y. F. Nassar, H. J. El-Khozondar, A. A. Alatrash, B. A. Ahmed, R. S. Elzer, A. A. Ahmed, I. I. Imbayah, A. H. Alsharif, and M. M. Khaleel, "Assessing the viability of solar and wind energy technologies in semi-arid and arid regions: A case study of Libya's climatic conditions," Appl. Sol. Energy, vol. 60, pp. 149–170, 2024, doi: 10.3103/S0003701X24600218.
[16] I. Imbayah, M. Hasan, H. El-Khozondar, M. Khaleel, A. Alsharif, and A. A. Ahmed, "Review paper on green hydrogen production, storage, and utilization techniques in Libya," Sol. Energy Sustain. Dev. J., vol. 13, no. 1, pp. 1–21, 2024, doi: 10.51646/jsesd.v13i1.165.
[17] I. Imbayah, H. J. El-Khozondar, M. Hasan, and A. Alsharif, "Modeling and simulation control of MPPT in solar array for green hydrogen production," Sol. Energy Sustain. Dev. J., vol. 14, no. 1, pp. 379–393, 2025, doi: 10.51646/jsesd.v14i1.457.
[18] V. C. Azubike and M. M. Gatiesh, "The intricate goal of energy security and energy transition: Considerations for Libya," Energy Policy, vol. 187, art. 114005, 2024, doi: 10.1016/j.enpol.2024.114005.
[19] A. M. A. Mohamed, A. Al-Habaibeh, and H. Abdo, "An investigation into the current utilisation and prospective of renewable energy resources and technologies in Libya," Renewable Energy, vol. 50, pp. 732–740, 2013, doi: 10.1016/j.renene.2012.07.038.
[20] M. A. Escalante Soberanis, A. Alnaggar, and W. Mérida, "The economic feasibility of renewable energy for off-grid mining deployment," Extr. Ind. Soc., vol. 2, no. 3, pp. 509–518, 2015, doi: 10.1016/j.exis.2015.04.001.
[21] M. Ansong, L. D. Mensah, and M. S. Adaramola, "Techno-economic analysis of a hybrid system to power a mine in an off-grid area in Ghana," Sustain. Energy Technol. Assess., vol. 23, pp. 48–56, 2017, doi: 10.1016/j.seta.2017.09.001.
[22] R. Akpahou, F. Odoi-Yorke, and L. K. Osei, "Techno-economic analysis of a utility-scale grid-tied solar photovoltaic system in Benin republic," Clean. Eng. Technol., vol. 13, art. 100633, 2023, doi: 10.1016/j.clet.2023.100633.
[23] M. Ahmad, A. Khattak, A. Kashif Janjua, A. A. Alahmadi, M. Salman Khan, and N. Ullah, "Techno-economic feasibility analyses of grid-connected solar photovoltaic power plants for small scale industries of Punjab, Pakistan," Front. Energy Res., vol. 10, art. 1028310, 2022, doi: 10.3389/fenrg.2022.1028310.
[24] M. F. I. Faruqui, A. Jawad, and Nahid-Al-Masood, "Techno-economic assessment of power generation potential from floating solar photovoltaic systems in Bangladesh," Heliyon, vol. 9, no. 6, art. e16785, 2023, doi: 10.1016/j.heliyon.2023.e16785.

[25] M. O. Alhassan, R. Opoku, F. Uba, G. Y. Obeng, C. K. K. Sekyere, and P. Nyanor, "Techno-economic and environmental estimation assessment of floating solar PV power generation on Akosombo dam reservoir in Ghana," Energy Rep., vol. 10, pp. 2740–2755, 2023, doi: 10.1016/j.egyr.2023.09.073.
[26] J. Haas, S. Moreno-Leiva, T. Junne, P.-J. Chen, G. Pamparana, W. Nowak, W. Kracht, and J. M. Ortiz, "Copper mining: 100% solar electricity by 2030?," Appl. Energy, vol. 262, art. 114506, 2020, doi: 10.1016/j.apenergy.2020.114506.
[27] S. H. Farjana, N. Huda, M. A. P. Mahmud, and C. Lang, "Life-cycle assessment of solar integrated mining processes: A sustainable future," J. Clean. Prod., vol. 236, art. 117610, 2019, doi: 10.1016/j.jclepro.2019.117610.
[28] J. Aldersey-Williams and T. Rubert, "Levelised cost of energy – A theoretical justification and critical assessment," Energy Policy, vol. 124, pp. 169–179, 2019, doi: 10.1016/j.enpol.2018.10.004.
[29] T. Igogo, K. Awuah-Offei, A. Newman, T. Lowder, and J. Engel-Cox, "Integrating renewable energy into mining operations: Opportunities, challenges, and enabling approaches," Appl. Energy, vol. 300, art. 117375, 2021, doi: 10.1016/j.apenergy.2021.117375.
[30] X. Li, Q. Gu, Q. Wang, J. Luo, D. Liu, and Y. Chang, "Renewable energy in the mining industry: Status, opportunities and challenges," Energy Strategy Rev., vol. 56, art. 101597, 2024, doi: 10.1016/j.esr.2024.101597.
[31] A. Strazzabosco, J. H. Gruenhagen, and S. Cox, "A review of renewable energy practices in the Australian mining industry," Renewable Energy, vol. 187, pp. 135–143, 2022, doi: 10.1016/j.renene.2022.01.021.
[32] S. Moreno-Leiva, J. Haas, T. Junne, F. Valencia, H. Godin, W. Kracht, W. Nowak, and C. Breyer, "Renewable energy in copper production: A review on systems design and methodological approaches," J. Clean. Prod., vol. 246, art. 118978, 2020, doi: 10.1016/j.jclepro.2019.118978.
[33] A. bin Jumah, "A comprehensive review of production, applications, and the path to a sustainable energy future with hydrogen," RSC Adv., vol. 14, 2024, doi: 10.1039/d4ra04559a.
[34] G.H. Goudarzi, "Geology of the Shati Valley Area Iron Deposit, Fezzan, Libyan Arab Republic," in *Symposium on the Geology of Libya*, Tripoli, Libya, 1969, pp. 489–500, University of Libya, 1971.
[35] M.K. Aly, "Mining of the Wadi Shatti Iron Ore Deposits, Libya: A Synopsis," Canadian Institute of Mining, Metallurgy and Petroleum, 1980, 2 pp.
[36] M.T. Tarek, K. Abdolrahman, Doughri, and S. Banerjee, "A Review of the Recent Investigation on the Wadi ash Shati Iron Ore Deposits, Northern Fazzan, Libya," in *The Geology of Libya*, vol. III, M.J. Salem and M.T.
[37] Elnaggar et al., "Harnessing solar energy for electricity generation and green hydrogen production: A sustainable pathway for low-carbon transportation in Gaza," Int. J. Energy Res., 2026, doi: 10.1155/er/8748862.
[38] M. Mohammed, Y. Nassar, H. El-Khozondar, and M. A. Al Bari, "Renewable energy in Libya: A systematic review of resources, costs, and implementability," Energy 360, vol. 5, art. 100066, Jun. 2026, doi: 10.1016/j.energ.2026.100066.
[39] F. El-Batta, A. Aboghrara, R. El-Khozondar, H. El-Khozondar, and Y. Nassar, "AI-based monitoring of solar panels in desert environments: Distinguishing dust accumulation for fault detection," Wadi Alshatti Univ. J. Pure Appl. Sci., vol. 4, no. 1, pp. 340–353, 2026, doi: 10.63318/waujpasv4i1_38.
[40] B. Ahmed, Y. Nassar, H. El-Khozondar, and M. Khaleel, "Optimal design of hybrid renewable energy system (PV/Wind/PHS) under multiple constraints of connection to the electricity grid: A case study," Wadi Alshatti Univ. J. Pure Appl. Sci., vol. 4, no. 1, pp. 83–93, 2026, doi: 10.63318/waujpasv4i1_09.
[41] M. Khaleel, I. Imbayah, Y. Nassar, and H. J. El-Khozondar, "Renewable energy transition pathways and net-zero strategies," Int. J. Electr. Eng. Sustain., vol. 3, no. 4, pp. 1–16, Dec. 2025, doi: 10.65998/ijees.v3i4.145.
[42] A. Alkhazmi, Y. Nassar, H. El-Khozondar, S. Rekik, H. Hadi, M. Elmnifi, M. Khaleel, I. Imbayah, and M. Abuhelwa, "Design and analysis of PV solar street lighting systems in remote areas: A case study," Wadi Alshatti Univ. J. Pure Appl. Sci., vol. 4, no. 1, pp. 1–14, 2025, doi: 10.63318/waujpasv4i1_01.
[43] M. A. Inweer, H. A. Salem, K. A. Khalid, Y. F. Nassar, M. A. Salem, A. A. Akasha, K. A. Amer, M. Elmnifi, S. Rekik, M. Khaleel, and H. J. El-Khozondar, "Carbon footprint life cycle assessment of cement industry in Libya," Discov. Concr. Cem., vol. 1, art. 37, 2025, doi: 10.1007/s44416-025-00037-1.
[44] H. J. El-Khozondar, R. J. El-Khozondar, Y. Nassar, et al., "Sustainable street lighting in Gaza: Solar energy solutions for main street," Energy 360, vol. 4, art. 100042, 2025, doi: 10.1016/j.energ.2025.100042.
[45] P. M. Diaz and H. J. El-Khozondar, "Electrical energy storage technologies and the application potential in power system operation: A mini review," in Proc. 2019 IEEE 7th Palestinian Int. Conf. Electr. Comput. Eng. (PICECE), IEEE, 2019, pp. 1–9, doi: 10.1109/PICECE.2019.8747172.
[46] B. A. Wills and J. A. Finch, Wills' Mineral Processing Technology: An Introduction to the Practical Aspects of Ore Treatment and Mineral Recovery, 8th ed. Oxford, U.K.: Butterworth-Heinemann (Elsevier), 2016.
[47] A. K. Biswas, Principles of Blast Furnace Ironmaking: Theory and Practice. Brisbane, Australia: Cootha Publishing House, 1981.
[48] M. Geerdes, R. Chaigneau, I. Kurunov, O. Lingiardi, and J. Ricketts, Modern Blast Furnace Ironmaking: An

Introduction, 3rd ed. Amsterdam, The Netherlands: IOS Press, 2015.
[49] J. A. Duffie and W. A. Beckman, Solar Engineering of Thermal Processes, 4th ed. Hoboken, NJ, USA: Wiley, 2013.
[50] G. M. Masters, Renewable and Efficient Electric Power Systems, 2nd ed. Hoboken, NJ, USA: Wiley, 2013.
[51] X. Luo, J. Wang, M. Dooner, and J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation," Appl. Energy, vol. 137, pp. 511–536, 2015, doi: 10.1016/j.apenergy.2014.09.081.
[52] W. Short, D. J. Packey, and T. Holt, A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies, NREL/TP-462-5173, National Renewable Energy Laboratory, Golden, CO, USA, 1995.
[53] R. A. Brealey, S. C. Myers, and F. Allen, Principles of Corporate Finance, 13th ed. New York, NY, USA: McGraw-Hill Education, 2020.
[54] IPCC, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Vol. 3: Industrial Processes and Product Use, Ch. 4: Metal Industry Emissions, H. S. Eggleston et al., Eds. Hayama, Japan: IGES, 2006.
[55] F. P. Incropera, D. P. DeWitt, T. L. Bergman, and A. S. Lavine, Fundamentals of Heat and Mass Transfer, 7th ed. Hoboken, NJ, USA: Wiley, 2011.