ТЕХНИКАЛЫҚ ҒЫЛЫМДАР / ТЕХНИЧЕСКИЕ НАУКИ / ENGINEERING SCIENCES

UDC 622:621.311.243

DECARBONIZING IRON ORE MINING THROUGH SOLAR PHOTOVOLTAIC INTEGRATION: TECHNO-ECONOMIC ANALYSIS OF HAJIGAK DEPOSIT, AFGHANISTAN

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This research assesses the techno-economic effectiveness of solar-battery-diesel hybrid systems for off-grid iron ore processing through hourly dispatch modeling and lifecycle cost assessment. Three configurations are analyzed at a high-altitude magnetite deposit in Afghanistan. The optimized hybrid configuration achieves a 51% renewable energy contribution while reducing emissions on site by 45% and lowering levelized electricity costs by 31% compared to solely diesel operations. The net present value amounts to USD 914 million over a period of 25 years, with a payback time of 2.6 years. Economic feasibility is influenced by high fuel delivery costs in remote areas, and sensitivity analysis confirms strong performance across various cost scenarios. The findings indicate that extensive solar-battery integration offers a viable route for decarbonizing off-grid mining operations with advantageous solar energy resources.

Keywords: solar photovoltaic; iron ore mining; decarbonization; Afghanistan; hybrid energy systems; techno-economic analysis; off-grid mining; battery energy storage

1. Introduction

Iron ore mining is energy-intensive and CO_2-intensive; direct and indirect mining activities contribute an estimated 4.0–4.8% of global emissions [1], and the sector's energy demand is projected to rise by 36% by 2035 [2]. Off-grid operations in remote, fuel-constrained regions are particularly exposed to these pressures because every unit of electricity must be generated on-site, predominantly by diesel. Rio Tinto's commitment of USD 600 million to solar-plus-battery installations in Australia's Pilbara region [3] demonstrates that large-scale photovoltaic integration in

 ISSN: 2959-1279

mining is commercially viable, yet published techno-economic analyses of off-grid solar–battery hybrids at scale remain scarce [4].

Afghanistan's Hajigak magnetite deposit, in the Baba Mountain range of Bamyan Province (34.96°N, 67.92°E), contains approximately 1,800 Mt of ore at 62% Fe [5]. The site is entirely off-grid, at elevations above 3,200 m, and subject to high fuel-delivery costs and significant security constraints. Abundant solar irradiation at this altitude presents a compelling opportunity to reduce both emissions and operating costs. This study quantifies that opportunity through site-specific hourly dispatch modelling and full lifecycle costing, addressing three questions: (i) what are the baseline diesel costs and emissions under Afghan fuel-delivery premiums; (ii) what renewable penetration is achievable with battery storage; and (iii) what are the resulting LCOE, NPV, and payback metrics?

2. Methodology

2.1 Study Area

Hajigak spans elevations of 3,250–3,800 m above sea level. The reference point adopted is 34.958747°N, 67.91748°E at 3,311 m [6]. Mean annual air temperature is 0.6 °C, with winter minima below −20 °C. The reduced atmospheric optical depth at altitude increases solar irradiance by 8–12% relative to sea level [7], and the cold ambient air partially offsets thermal losses in PV modules.

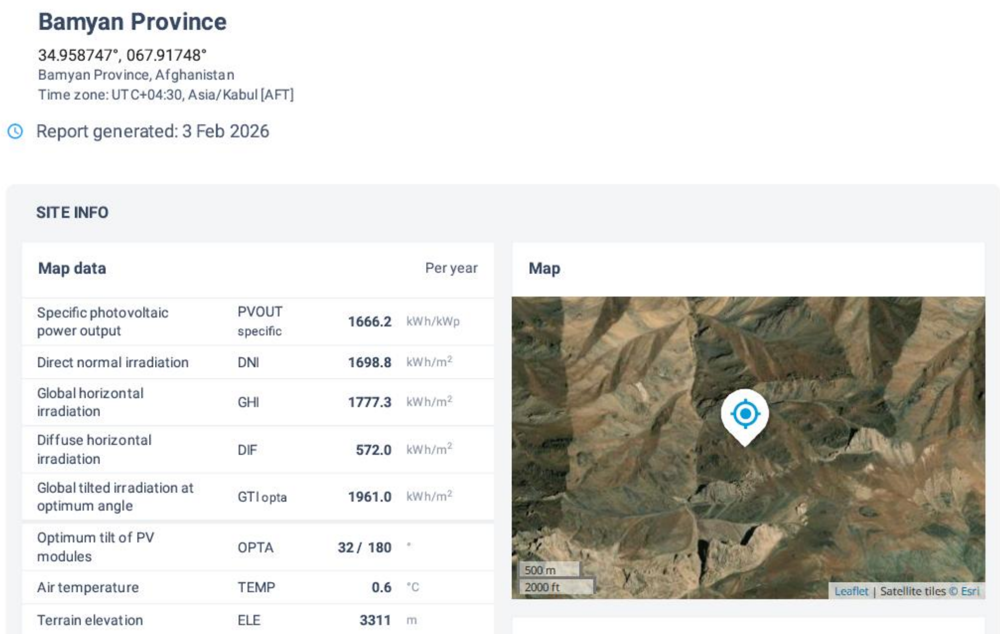


Figure 1. Location of Hajigak deposit, Bamyan Province, Afghanistan (3,311 m elevation). Source: Global Solar Atlas

2.2 PV Technology Selection

Monocrystalline silicon (mono-Si) was selected on the basis of highest commercial efficiency (20–23%), a favorable temperature coefficient (−0.30 to −0.40

%/°C) [8], and the most compact footprint per unit capacity — all critical at a constrained high-altitude site. The altitude-driven irradiance enhancement further favors high-efficiency modules over thin-film alternatives.

2.3 Solar Resource Assessment

Solar data were obtained from the Global Solar Atlas (World Bank / Solargis) [6] and cross-validated with NASA POWER [9], the only available sources for this region. Key metrics are given in Table 1.

Table 1. Solar resource metrics for Hajigak (sources: Global Solar Atlas [6]; NASA POWER [9]).

Parameter	Value	Unit
Global Horizontal Irradiation (GHI)	1,777.3	kWh/m²/yr
Direct Normal Irradiation (DNI)	1,698.8	kWh/m²/yr
Diffuse Horizontal Irradiation (DIF)	572.0	kWh/m²/yr
Global Tilted Irradiation (GTI, 32° tilt)	1,961.0	kWh/m²/yr
Effective PV Yield (derated)	1,645	kWh/kWp/yr
Optimum Tilt Angle	32	degrees

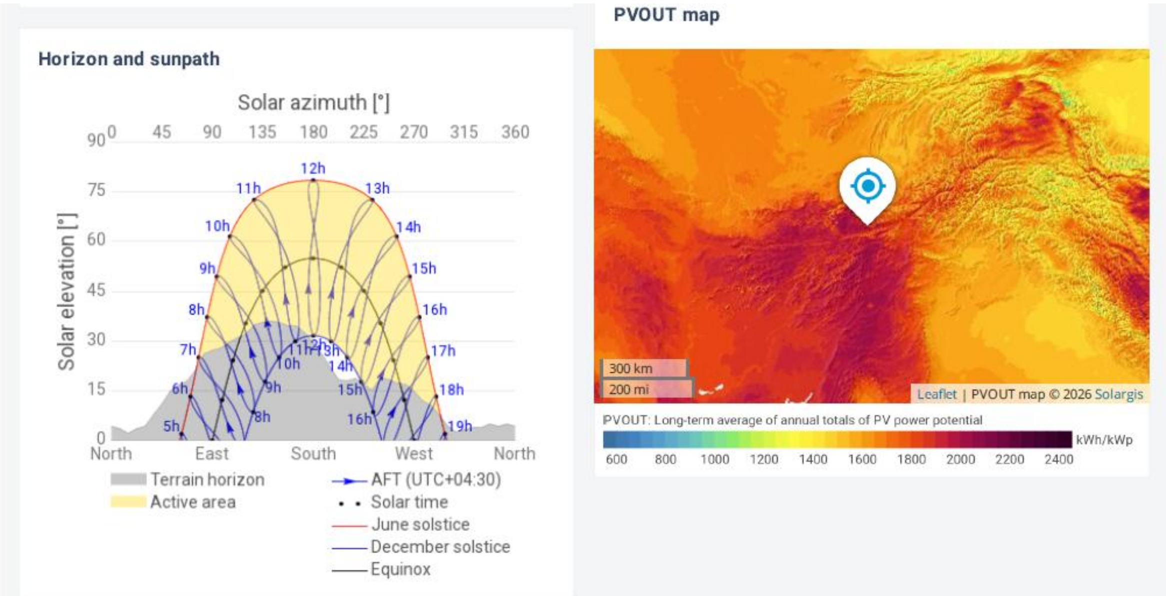
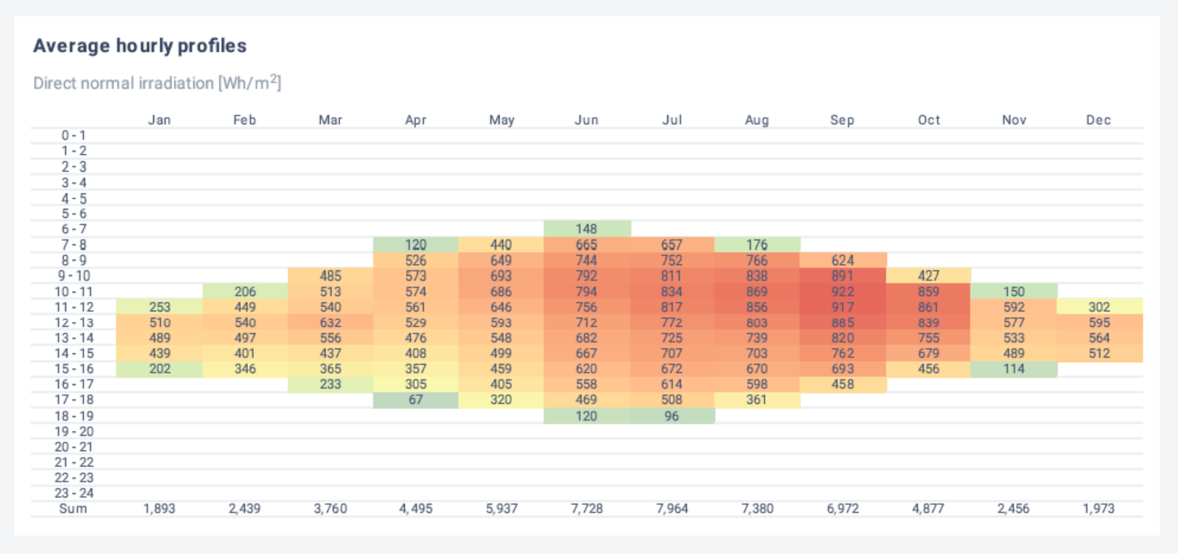


Figure 2. PV power output distribution at Hajigak. Source: Global Solar Atlas

2.3.1 System Derating

Standard derating factors for soiling, wiring losses, inverter efficiency, thermal effects, and array mismatch result in a combined system efficiency of 83.9%. This yields an effective PV output of 1,645 kWh/kWp/yr at Hajigak, accounting for the site's high-altitude solar resource (GTI = 1,961 kWh/m²/yr at 32° tilt).

 ISSN: 2959-1279



Average hourly profiles

Direct normal irradiation [Wh/m^2]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5												
5 - 6												
6 - 7						148						
7 - 8				120	440	665	657	176				
8 - 9				526	649	744	752	766	624			
9 - 10			485	573	693	792	811	838	891	427		
10 - 11		206	513	574	686	794	834	869	922	859	150	
11 - 12	253	449	540	561	646	756	817	856	917	861	592	302
12 - 13	510	540	632	529	593	712	772	803	885	839	577	595
13 - 14	489	497	556	476	548	682	725	739	820	755	533	564
14 - 15	439	401	437	408	499	667	707	703	762	679	489	512
15 - 16	202	346	365	357	459	620	672	670	693	456	114	
16 - 17			233	305	405	558	614	598	458			
17 - 18				67	320	469	508	361				
18 - 19						120	96					
19 - 20												
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	1,893	2,439	3,760	4,495	5,937	7,728	7,964	7,380	6,972	4,877	2,456	1,973

Figure 3. Monthly DNI for Hajigak, peak May–Aug. Source: Global Solar Atlas/Solargis.

2.4 Mining Energy Demand

The mine's projected throughput of 12 Mt/yr magnetite concentrate requires 792 GWh/yr total energy, split between stationary processing (576 GWh/yr; 73%) and mobile equipment (216 GWh/yr; 27%). Energy intensities of 48 kWh/t for stationary processing and 18 kWh/t for mobile operations are consistent with magnetite mining benchmarks [10]. This study focuses on decarbonizing the stationary load through solar-battery integration; mobile fleet electrification is discussed as a future pathway in Section 4.3.

2.5 PV Generation

Based on the effective PV yield of 1,645 kWh/kWp/yr, the two solar capacities evaluated generate 296 GWh/yr (180 MW system) and 197 GWh/yr (120 MW system), representing 51% and 34% renewable penetration, respectively for the processing load.

2.6 System Configurations and Dispatch

Three configurations were modeled. Baseline: 60 MW diesel only. Moderate Hybrid: 120 MW PV + 300 MWh lithium-ion BESS + 40 MW diesel. Optimized Hybrid: 180 MW PV + 500 MWh BESS + 40 MW diesel. The average processing load is 576 GWh/yr ÷ 8,760 h = 65.8 MW. The 500 MWh BESS provides 500 MWh ÷ 65.8 MW = 7.6 hours of autonomous operation — sufficient to cover the longest night at this latitude. The battery operates within 80% depth of discharge limits under normal cycling. Hourly dispatch over 8,760 time-steps follows priority logic: (1) solar generation directly meets load where available; (2) excess solar charges battery (subject to state-of-charge limits); (3) battery discharges to meet deficit (subject to depth-of-discharge constraints); (4) diesel generators dispatch as last resort to meet remaining demand.

2.7 Economic Assumptions

All costs are adjusted for the Afghan context. PV CAPEX: USD 900/kW (including high-altitude installation premium). BESS CAPEX: USD 350/kWh. Diesel CAPEX: USD 800/kW. Landed diesel fuel: USD 2.00/L (USD 1.50 international + USD 0.50 remote-delivery premium) [5]. Annual O&M: 2% (PV), 3% (BESS), 5% (diesel). Discount rate: 10%, reflecting Afghan sovereign and project-delivery risk [11]. CO_2 emission factor: 2.68 kg/L (lifecycle, well-to-wheel) [12]. Project lifetime: 25 years.

3. Results

3.1 Baseline Diesel-Only System

The baseline diesel-only system supplies 576 GWh/yr for processing and 216 GWh/yr for mobile equipment, requiring 203 million litres of diesel annually at an assumed generator efficiency of 40%. At Hajigak's delivered fuel price of USD 2.00/L, annual operating costs reach USD 406 million. The system produces 544 kt/yr of CO_2 emissions (45 kg per tonne of ore) with a levelized cost of electricity of USD 0.72/kWh over 25 years.

3.2 Comparative Performance

Table 2 presents technical and economic performance across the three configurations. The Optimized Hybrid achieves 51% renewable penetration of stationary electricity—substantially above the 20–35% typical of off-grid mining operations.

Table 2. Technical and economic performance of the Baseline, Moderate, and Optimized energy-system configurations.

Metric	Baseline	Moderate	Optimized
PV Capacity (MW)	0	120	180
Battery Storage (MWh)	0	300	500
Diesel Capacity (MW)	60	40	40
PV Generation (GWh/yr)	0	197.3	296
Renewable Penetration (%)	0	34.3	51.4
Stationary Diesel (GWh/yr)	576	378.7	280
Total Diesel (million litres)	203.1	152.5	127.2
CO_2 Emissions (kt/yr)	544.2	408.6	340.8
Emissions Reduction (%)	—	24.9	37.4
Specific Emissions (kg CO_2/t ore)	45.4	34.1	28.4
CAPEX (USD million)	48	245	369
Annual Fuel Cost (USD million)	406.2	305	254.4
Annual O&M (USD million)	2.4	6.91	10.09
LCOE (USD/kWh)	0.718	0.597	0.544
NPV vs Baseline (USD million)	—	636.6	913.6
Payback Period (years)	—	2.4	2.6

4. Discussion

4.1 Technical Feasibility at Hajigak

Three Hajigak-specific factors explain the 51.4% renewable penetration. First, the effective PV yield of 1644.5 kWh/kWp/yr — after a rigorous 16.1% derating from the tilted irradiation — is exceptionally high for a fixed-tilt system at this altitude [13]. Second, The 500 MWh battery system provides 7.6 hours of storage at average load, sufficient for winter night operations at 35°N latitude, with an 80% depth of discharge limit for cycle life.

4.2 Economic Competitiveness and Afghan Context

The Optimized Hybrid achieves a 24% reduction in electricity costs (LCOE of USD 0.54/kWh versus USD 0.72/kWh) despite requiring nearly eight times the initial investment. High fuel delivery costs at Hajigak (USD 2.00/L versus USD 1.20–1.50/L internationally) drive this economic advantage through annual savings of USD 152 million. The net present value of USD 914 million over 25 years confirms strong economic viability with a 2.6-year payback period.

4.3 Limitations and Roadmap for Full Decarbonization

Mobile diesel accounts for 27% of total mine energy (216.0 GWh/yr) and is excluded from the PV scope. Full decarbonization at Hajigak would require electrification of the mobile fleet — battery-electric haul trucks are now commercially available [14] — and a corresponding expansion of PV capacity to 240–300 MW with additional storage, potentially raising renewable penetration to 70–85%.

Non-technical barriers are significant: security and access constraints in Bamyan Province, transport of heavy equipment to 3,300 m over limited roads, and policy uncertainty in Afghan energy and mining regulation. Lithium-ion performance also degrades below −10 °C; the extreme Hajigak winters require active thermal management in battery enclosures and reduced-capacity design margins.

5. Conclusions

Solar-PV–battery–diesel hybrid systems are both technically and economically viable for decarbonizing stationary energy at Hajigak. The Optimized Hybrid configuration (180 MW PV, 500 MWh battery, 40 MW diesel) delivers: (1) 51% renewable energy penetration for processing electricity (296 GWh/yr from solar); (2) 37% reduction in total site CO_2 emissions (203 kt/yr avoided; 5.1 Mt cumulative over 25 years); (3) 24% electricity cost reduction (LCOE of USD 0.54/kWh versus USD 0.72/kWh for diesel-only operation), enabled by high fuel delivery costs; (4) net present value of USD 914 million over 25 years at 10% discount rate; and (5) payback period of 2.6 years.

Sensitivity analysis confirms robustness across tested input ranges. Future work at Hajigak should address mobile-fleet electrification, battery thermal management for extreme cold, and detailed engineering feasibility incorporating site-specific geology and access constraints.

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ДЕКАРБОНИЗАЦИЯ ЖЕЛЕЗНОЙ РУДЫ ПРИ ДОБЫЧЕ С ИСПОЛЬЗОВАНИЕМ СОЛНЕЧНОЙ ФОТОЭЛЕКТРИЧЕСКОЙ ИНТЕГРАЦИИ: ТЕХНИКО-ЭКОНОМИЧЕСКИЙ АНАЛИЗ МЕСТОРОЖДЕНИЯ ХАДЖИГАК, АФГАНИСТАН

Резайе Никбахт

В данном исследовании оценивается технико-экономическая эффективность гибридных систем «солнечная энергия – аккумулятор – дизель» для автономной переработки железной руды с помощью почасового моделирования диспетчеризации и оценки стоимости жизненного цикла. Проанализированы три конфигурации на высокогорном месторождении магнетита в Афганистане. Оптимизированная гибридная конфигурация обеспечивает 51% вклада возобновляемой энергии, одновременно снижая выбросы на месте на 45% и уменьшая приведенные затраты на электроэнергию на 31% по сравнению с эксплуатацией только на дизельном топливе. Чистая приведённая стоимость составляет 914 миллионов долларов США за 25 лет, при этом срок окупаемости составляет 2,6 года. Экономическая целесообразность обусловлена высокими затратами на доставку топлива в отдалённые районы, а анализ чувствительности подтверждает высокую эффективность при различных сценариях затрат. Результаты показывают, что широкая интеграция солнечных батарей и аккумуляторов предлагает жизнеспособный путь для декарбонизации автономных горнодобывающих предприятий с использованием выгодных ресурсов солнечной энергии.

Ключевые слова: солнечная фотовольтаика; добыча железной руды; декарбонизация; Афганистан; гибридные энергетические системы; технико-экономический анализ; автономная добыча полезных ископаемых; аккумуляторные системы хранения энергии.

ТЕМІР КЕНІН ӨНДІРУДІ КҮН ФОТОЭЛЕКТРЛІК ИНТЕГРАЦИЯСЫ АРҚЫЛЫ ДЕКАРБОНИЗАЦИЯЛАУ: АУҒАНСТАНДАҒЫ ХАДЖИГАК КЕН ОРНЫНЫҢ ТЕХНИКАЛЫҚ-ЭКОНОМИКАЛЫҚ ТАЛДАУЫ

Резайе Никбахт

Бұл зерттеуде темір кенін автономды өңдеу үшін «күн энергиясы – аккумулятор – дизель» гибридті жүйелерінің техникалық-экономикалық тиімділігі сағаттық диспетчерлік модельдеу және өмірлік цикл құнын бағалау *арқылы қарастырылады. Ауғанстандағы биік таулы магнетит кен орнында үш конфигурация талданды. Оңтайландырылған гибридті конфигурация жаңартылатын энергия үлесін 51%-ға жеткізіп, жергілікті шығарындыларды 45%-ға азайтады және тек дизель отынымен жұмыс істеумен салыстырғанда электр энергиясының келтірілген шығындарын 31%-ға төмендетеді. 25 жылға есептелген таза келтірілген құн 914 миллион АҚШ долларын құрайды, ал инвестицияның өтелу мерзімі 2,6 жыл. Экономикалық тиімділік шалғай аймақтарға отын жеткізу шығындарының жоғары болуымен түсіндіріледі, ал сезгіштік талдауы әртүрлі шығын сценарийлерінде жүйенің жоғары тиімділігін растайды. Нәтижелер күн батареялары мен аккумуляторларды кеңінен интеграциялау автономды тау-кен кәсіпорындарын декарбонизациялаудың тиімді жолын ұсынатынын көрсетеді.*

Кілт сөздер: күн фотовольтаикасы; темір кенін өндіру; декарбонизация; Ауғанстан; гибридті энергетикалық жүйелер; техникалық-экономикалық талдау; автономды тау-кен өндірісі; энергияны сақтау аккумуляторлық жүйелері.