

Integrated Co-Valorization of Phosphate and Oil Shale Resources: A Circular Economy Strategy for the Al Abiad Region, Central Jordan

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Abstract

High overburden-to-ore ratios and complex lithostratigraphic heterogeneity increasingly limit the economic viability of sedimentary phosphate deposits. This study evaluates the techno-economic prefeasibility of shifting from a traditional single-commodity extraction to an integrated dual-commodity strategy at the Al Abiad deposit. Geological characterization shows a clear inverse spatial relationship between the primary phosphate horizons and the overlying bituminous marls (oil shale), creating rigid boundaries that challenge traditional mine planning. The assessment shows that a single-commodity approach yields a prohibitive average Stripping Ratio (SR) of 10.7:1. In contrast, the proposed dual-extraction strategy reclassifies the oil shale from waste to ore, capturing an additional 21.99 million m³ of energy resources and reducing the effective SR by approximately 44% to a sustainable 6.0:1. To address the valuation challenge of the non-traded oil shale, a Netback Electricity Pricing Model (NEPM) was developed, deriving the resource's intrinsic value from regulated electricity tariffs rather than standard fossil fuel benchmarks. The analysis identifies a break-even electricity tariff of US \$0.122/kWh, below which the resource has no economic value. Under current tariff structures, the co-extraction model is projected to increase net income by 19% to 28.7% compared to the baseline. These findings confirm the integrated mining model as a robust approach to reducing resource sterilization, mitigating market volatility, and advancing circular economy principles in the extractive industries.

Keywords

Phosphate, Oil Shale (Bituminous Marl), Circular Economy, Stripping Ratio

1. Introduction

The global mining industry faces significant pressure to sustainably supply essential raw materials, a necessity driven by population growth and the rapid expansion of clean energy technologies [1]. This challenge is especially critical in extracting phosphate rock, a non-substitutable input for global food security, where reserves are showing declining grades and increased geological complexity [2]. The transition from high-grade to complex, low-grade ores requires moving exponentially greater volumes of rock, leading to perpetually rising stripping ratios (SR) [3]. The resulting environmental burden is critically assessed by the rock-to-metal ratio, a key metric that emphasizes the widening gap between the mass of rock excavated and the volume of marketable product recovered [4].

In this context, the traditional linear mining model (mine, process, and dispose) has been shown to be both economically unsustainable and environmentally unacceptable [5] [6]. The industry's strategic response is the accelerated adoption of circular economy (CE) principles, which seek to redefine waste materials as valuable resources [7]. The shift from waste management to resource valorization is crucial for reducing the projected accumulation of billions of tonnes of solid mine waste, effectively turning an environmental liability into an economic asset [5]. The valorization of co-existing resources within the overburden, often termed a "neo-mine" approach, is recognized as a key pathway to enhancing operational efficiency and lowering the effective SR [6].

A good example of investigating this concept is found in the Upper Cretaceous sedimentary basin of Jordan. In fact, it provides a critical case study for this multi-resource imperative. Jordan is a major global player in phosphate production, yet phosphate horizons are interlayered with extensive deposits of bituminous marl, known as oil shale [8] [9]. Historically, the conventional mining strategy at deposits like the Al Abiad mine has treated this oil shale as barren waste, leading to its sterilization and artificially inflating the SR to economically marginal levels (often exceeding 10:1 in deeper sectors).

This research evaluates a novel transformative strategy for the Al Abiad deposit: an integrated, dual-extraction operation that systematically co-valorizes both the primary phosphate ore and the co-located oil shale. The prefeasibility scope of this investigation is guided by three pivotal questions critical to modern mining sustainability: First, how does the inverse geological relationship between phosphate thickness and oil shale presence compel a shift from bulk mining to a more selective, multi-commodity scheduling approach? Second, to what extent can reclassifying oil shale from waste to an ore body meaningfully reduce the effective SR and enhance overall resource efficiency? And third, how can the economic potential of a non-traded energy commodity, such as oil shale, be accurately quantified

within a mining project's financial framework using a novel and promising approach?

By integrating high-fidelity resource characterization with advanced, scenario-based techno-economic investigation, this study demonstrates that modern multi-component analysis is indispensable for capturing the synergistic, non-linear economic benefits of a diversified output strategy [1]. The findings aim to provide a practical blueprint for the sustainable development of similarly complex poly-resource deposits worldwide.

2. Literature Review

Sustainable mining has progressed beyond meeting environmental regulations, shifting from treating deposits as single-commodity resources to treating them as complex multi-asset systems. This change marks a transition from a linear approach that emphasized extracting high-grade materials and treated environmental stewardship as a post-closure concern [10] [11] toward a model based on the triple bottom line and the Social License to Operate (SLO) [12] [13]. Moreover, modern holistic mining views the mine not merely as an extraction site but as a connected component within a broader industrial network [1] [7] [11] [14]. Central to this perspective is the circular economy (CE), which urges the sector to eliminate waste and keep materials in use [15]. From a CE perspective, resource efficiency encompasses more than metallurgical recovery rates; it also involves reducing stripping ratios (SR) and rock-to-metal ratio while optimizing overall yield from a specific geological resource [4].

As a result, the poly-resource deposit has become an area of interest. Examining deposits from a single-commodity perspective often leads to the economic neglect of associated resources, a practice increasingly seen as outdated in the context of an unsustainable linear economy [6] [16]. The purposeful exploitation of a deposit's makeup is now more than an efficiency strategy; it is essential for contemporary resource security. This is clearly seen worldwide in the creation of secondary products such as gallium from zinc deposits or cobalt from copper deposits, enhancing both the financial viability of projects and the robustness of supply chains [17]-[20]. Additionally, redefining tailings and waste rock as man-made ore sources underscores the considerable value hidden in previously mined-out waste [5]. As ore grades decrease globally, the rising financial and environmental costs associated with waste management render such efficiency a necessity [21].

Jordan provides an example of these intricate issues. Although Jordan is a global phosphate producer, it faces strategic pressure to optimize the use of its domestic resources in a market heavily influenced by Moroccan reserves [22]. Currently, more than 11 million tonnes of phosphate ore are produced at three major mines in Jordan: Eshidiya, Al Hassa, and Al Abiad. The proven geological reserve in Al Abiad exceeds 2.8 million m³. Surface mining procedures (drilling, blasting, and excavation) are used to extract phosphate ore. Overburden and interbedded non-phosphate layers are scraped away and discarded in dumping areas. The phos-

phate ore produced at these mines is transported by truck to the Aqaba port for export, as well as to the industrial complex in Aqaba, where it is distributed to associated companies and the local market [23].

On the other hand, oil shale is the country's largest proven fossil fuel resource, with reserves of about 40 - 70 billion tonnes [24]-[26]. This situation is distinctive because the oil shale is geologically intertwined with phosphate layers [24]-[26]. Jordanian oil shale is also unique in its properties. It is characterized by limestone containing a substantial amount of organic material (~10%) and notable sulfur levels (1.18% - 8.94%), making it both a valuable energy resource and an environmental challenge [8] [9] [27]. In the Al Abiad region, the Al Hisa (also known as Al Hassa) Phosphorite Formation (AHP), rich in phosphate, is immediately overlaid by the Muwaqqar Chalk Marl Formation (MCM), which contains the oil shale [8] [9] [28]-[31]. Such close geological interweaving requires an integrated extraction approach to avoid resource loss and control stripping ratios that often surpass 10:1.

Tapping into this poly-resource capability requires a techno-economic approach. Technically, the variability of interlayered phosphate and oil shale calls for a shift to targeted extraction. Sensor-based ore sorting (SBS), leveraging AI and advanced sensing technologies, is crucial for processing and waste reduction, ensuring accurate segregation before energy-intensive treatment [32] [33]. Regarding oil shale valorization, Direct Combustion (DC) via Circulating Fluidized Bed (CFB) technology is currently among the best available techniques for oil shale burning, offering in-situ SO₂ capture through limestone injection to mitigate primary pollutants [34].

Nonetheless, technological feasibility alone does not ensure profitability. The practicality of adopting traditional energy forms such as oil shale is often influenced more by the synthetic value created through regulatory mechanisms, including Power Purchase Agreements (PPAs), than by free market forces [35] [36]. This creates a regulatory valuation paradox in which plentiful resources remain untapped without policy intervention. Thorough project evaluation should consequently employ tools such as the Netback Electricity Pricing Model (NEPM) to assess the risk-adjusted value of energy minerals within their regulatory framework [37]. At the end, transitioning from prescriptive to performance-driven regulation continues to facilitate these comprehensive projects [38]. The co-valorization of phosphate and oil shale in the Al Abiad area thus represents a convergence of circular economy principles, strategic resource management, and sustainable policy, a nonlinear approach that this study aims to model.

3. Methodology

3.1. Study Area (Al Abiad, Central Jordan)

The study area is in central Jordan, approximately 135 km south of Amman, as shown in **Figure 1**. The climate in this desert region is arid to semi-arid, with rainfall less than 100 mm and elevations ranging from 788 to 840 meters above

sea level. From a geological perspective, the Al Abiad deposit consists of limestone, marl, chert, shale, and phosphates dating to the Campanian-Maastrichtian periods. **Table 1** summarizes the stratigraphic positions of the primary ore (phosphate) and the secondary ore (oil shale) in central Jordan.

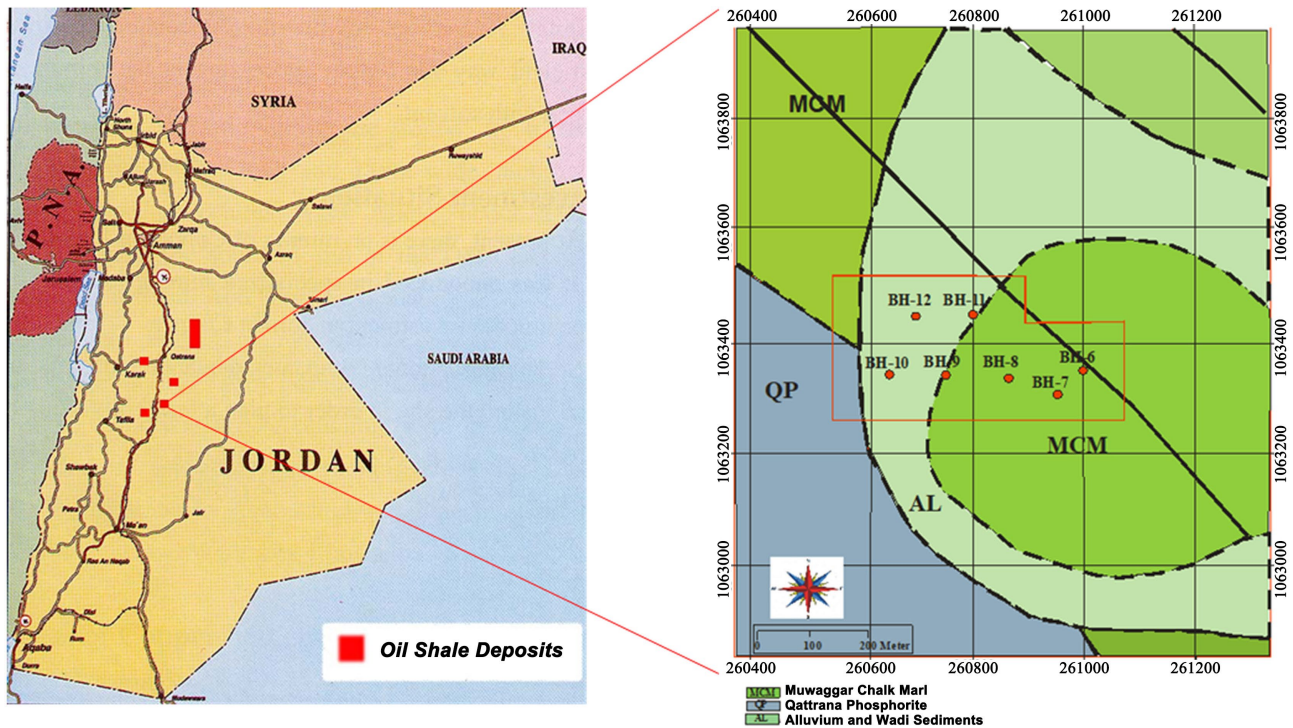


Figure 1. Distribution of oil shale deposits in Jordan (left) and a detailed geological map of the study area showing lithostratigraphic units and borehole locations (right). The map is based on the Jabal Al-Mutarammil Map Sheet No. 3252 III [39].

Table 1. Stratigraphical position of phosphate and oil shale in central Jordan.

Period	Epoch	Group	Formation	Unit [40]
Upper Cretaceous	Paleocene (Danian)-Maastrichtian	Belqa Group (B)	Muwaqqar	Chalk-marl
	Maastrichtian		Hisa (Hassa)	Phosphate
	Campanian-Santonian		Amman	Silicified Limestone
	Santonian-Coniacian		Wadi Umm Ghudran	Chalk
	Turonian	Ajlun (A)	Wadi As Sir	Massive Limestone

The surface geology of the investigated area (**Figure 1**) reveals a gently eastward-dipping sedimentary succession, with the economic Qattrana Phosphorite (QP) unit exposed along the western margin of the tenement. As the stratigraphy progresses eastward, the phosphate is conformably overlain by the MCM, a thick sequence of bituminous marl and chalky limestone that hosts the oil shale resources discussed in this study.

Structural mapping indicates a significant discontinuity; a series of NW-SE-trending faults displace lithologic contacts, creating a compartmentalized struc-

tural block. The exploration boreholes (BH.6 through BH.12) were collared primarily within the MCM and Quaternary Alluvium (AL) zones to intersect the underlying mineralized horizons at depth. This structural and stratigraphic configuration directly influences mine planning parameters, particularly variations in overburden thickness and stripping ratios across the deposit.

3.2. Data Acquisition, Site Characterization, and Stratigraphic Analysis

The geological foundation of this study relies on primary exploration data from the archives of the Jordan Phosphate Mines Company (JPMC), specifically for the Al Abiad phosphate deposit. The dataset comprises detailed lithological logs and assay results from a targeted drilling campaign, focusing on seven representative boreholes (BH.6 - BH.12) that delineate the stratigraphic profile of the deposit's expansion area (Table 2).

The provided borehole records include high-precision Easting/Northing coordinates and elevation data relative to mean sea level. These records were digitized and validated to create a reliable spatial database for the subsequent resource investigation. The stratigraphic logging provided the vertical resolution needed to differentiate between the overburden units (Upper Cretaceous marl and chert), the potential energy resource (oil shale), and the economic phosphate horizon.

Table 2. Borehole data in the Al Abiad area carried out by JPMC.

Borehole thickness (m)							Lithology Description
BH.6	BH.7	BH.8	BH.9	BH.10	BH.11	BH.12	
2.00	0.50	0.50	0.50	0.50	0.50	2.50	Alluvium & Loose cuttings (Drift)
12.00	12.50	12.50	11.50	11.50	12.00	12.50	Marl, Chert & Limestone
10.50	10.50	9.00	9.10	8.50	9.00	8.00	Marl, Clay, Limestone & Interbedded Phosphate
1.00	0.80	1.00	0.90	2.20	1.10	1.00	Phosphate
8.50	8.20	7.00	8.00	10.80	10.90	7.50	Marl, Limestone & Clay
5.00	4.00	5.00	2.50	^a	^a	2.00	Oil Shale
0.50	1.50	0.50	1.00	^b	^b	1.50	Clay
1.50	0.50	0.50	0.50	0.25	1.25	0.40	Phosphate
0.25	1.50	1.50	1.00	5.75	1.00	5.10	Marl, Chert & Limestone
0.75	0.50	1.00	1.00	0.50	1.25	1.00	Phosphate
3.50	3.30	3.50	4.00	0.25	4.50	3.00	Marl, Chert, Limestone & Phosphate
0.75	0.70	0.75	0.75	0.25	3.50	0.40	Phosphate
3.75	5.50	7.25	9.25	9.50	5.00	5.10	Marl, Chert, Limestone & Phosphate

^aNo oil shale layer. ^bNo clay layer.

To translate the raw borehole data into a coherent geological model, a stratigraphic reinterpretation was performed to correlate lithologic units across the

study area. The analysis focused on quantifying the vertical thickness of four key horizons: Overburden (consisting of Quaternary sediments and massive limestone); Inter-waste (the calcareous waste rock separating the energy and mineral horizons); Oil shale (the bituminous marl layer, evaluated here for its co-extraction potential); and phosphate (the primary economic target).

Spatial analysis was conducted using the polygon-of-influence method in ArcGIS software. This geometric approach assigns an area of influence to each borehole (ranging from 8.2 to 18.6 million m²) to calculate volumetric reserves. This method was chosen to account for the lateral geological heterogeneity observed in the JPMC logs, such as the pinch-out of the oil shale unit in some sectors of the deposit (BH.10 and BH.11).

The use of seven boreholes to characterize a 94.6 km² domain is a primary constraint on the statistical reliability of volumetric estimates. With an average sampling density of one borehole per 13.5 km², spatial correlation between data points cannot be rigorously quantified via variography, necessitating the use of the geometric polygon-of-influence method. This sparsity introduces two primary sources of uncertainty: Geological continuity risk and smoothing bias. The method assumes linear continuity of phosphate and oil shale thickness between boreholes. However, observed pinch-outs in BH.10 and BH.11 suggest that the deposit geometry may be more complex, potentially leading to local overestimation of volumes in areas distal to the drill collars. Also, the limited data preclude capturing small-scale stratigraphic variations or fault-induced offsets that might affect the stripping ratio. Consequently, the reserves calculated herein are classified as Inferred Resources under standard reporting codes. While sufficient for the preliminary scope of this study and for identifying broad economic trends, these results should be viewed as a baseline for future high-density infill drilling campaigns required to elevate the resource to a “Measured” or “Indicated” confidence level.

3.3. Mineable Reserve, Life of Mine and Production Rate Calculations

The geological reserve was calculated by multiplying the area of influence for the boreholes with the average thickness of each block. By calculating the total volume of the influenced boreholes, the tonnage formula can be used as the fundamental building block for estimating ore reserves by multiplying with the specific gravity of the ores. Once tonnage is calculated the mineable reserve can be estimated by taking into consideration the recovery rate (90%) and the dilution factor (5%) for open pit mining as specified by [41]. The life of mine can be estimated by dividing the mineable reserves by the total annual production rate of the ores. Here, the annual production rates (P_i) were set based on JPMC’s operational data and mining expert opinions ($P_1 = 700,000$ m³/year for phosphate, and $P_2 = 500,000$ m³/year for oil shale) [23]. The mine capacity (C) (extracting both ore and waste, m³/year) is calculated using the following formula [41]:

$$C = (\text{SR} + 1) \times \sum_{i=1}^n P_i \quad (1)$$

where SR is calculated as the volume of total waste divided by the total ore volume, i is the i^{th} ore, depending on the scenario under consideration ($i = 1$ for phosphate and $i = 2$ for oil shale), and n is the total economic ore; here, $n = 2$. Two scenarios can be drawn in this study:

- Scenario I: the traditional mining option of assuming that the economic ore under concern is only phosphate.
- Scenario II: where the target is to minimize waste and valorize all possible resources in line with circular economy principles, the oil shale is redefined as a potential economic energy resource.

3.4. Equipment Selection and Fleet Sizing

Accurately determining the capacity and fleet size of mining equipment is crucial for establishing the project's capital expenditure (CAPEX) profile. After outlining the total mineral reserves, a comprehensive mine development plan was created. This plan incorporates spatial constraints, such as the optimal placement of stockpiles and external and overburden dump sites, which directly affect cycle times and equipment mobility, as shown in **Figure 2**.

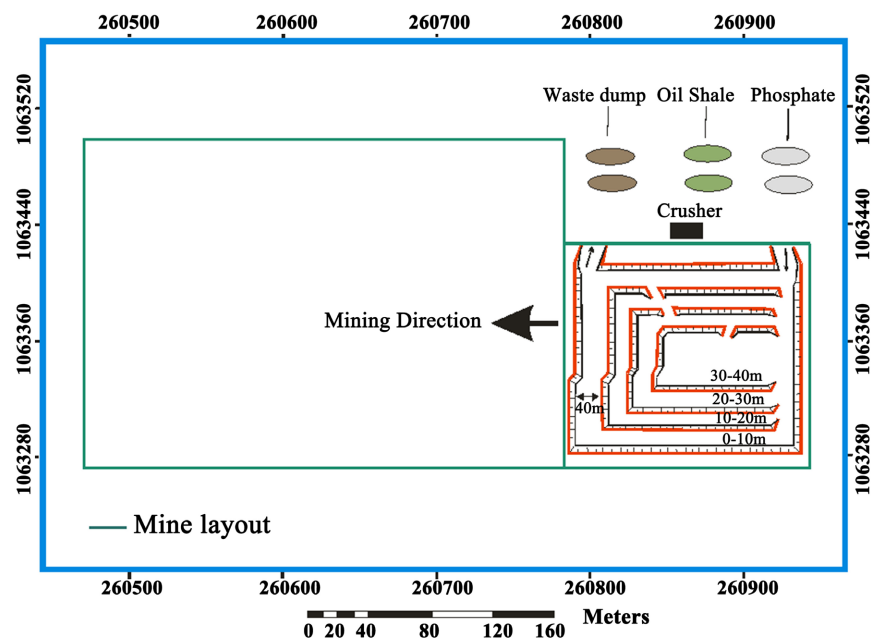


Figure 2. Mine layout sketch for the proposed study area.

The operational framework for both scenarios comprises standard mining unit operations: ripping/dozing, drilling, blasting, loading, and haulage [42]. To achieve the target annual production capacity of 8.4 million m^3 , the required machinery was dimensioned using the specific algorithmic methodology detailed in our previous work [43]. Crucially, theoretical production rates were adjusted to reflect operational realism by applying specific coefficients for mechanical availability and effective utilization. This approach is further substantiated by established equipment selection principles and empirical performance metrics defined by

[44]-[46].

3.5. Economics Calculations

CAPEX and operational expenditure (OPEX), including fuel, salaries, maintenance, and drilling/blasting, were estimated using vendor quotes, contractor estimates, and expert input from the Jordanian mining sector [23] [47] [48]. Revenues from phosphate were calculated using current commodity prices [49], while the economic value of oil shale was estimated here using the netback electricity pricing model (NEPM), as detailed below.

Valuation of Oil Shale Using NEPM

The economic assessment of oil shale is difficult because there is no market for the unprocessed resource and no transparent spot price for raw oil shale. Conventional oil-equivalence approaches are primarily used in processes that produce shale oil [50]-[52]. However, when oil shale is used for power generation, as in the case of the Attarat power plant (APCO), NEPM is proposed. This framework derives the intrinsic economic value of the in-situ ore body not from its theoretical hydrocarbon content, but from the realized revenues of selling the generated electricity, the final commercial product.

To obtain a realistic estimate, the model was calibrated against APCO's operational parameters, assuming a baseload capacity of 470 MW to generate approximately 3700 GWh annually (representing ~15% of Jordan's electricity demand) [53]-[55]. The mass balance calculation relied on the specific calorific value of the Jordanian oil shale reserve (7.5 MJ/kg) [56]. Based on APCO data, this generation scale required an annual throughput of 10 million metric tons (Mt) of raw shale (equivalent to 0.3 Mt of oil equivalent). And, at the current PPA rate of US\$0.17 per kWh [53]-[55] [57] the estimated annual revenue from selling the generated electricity was about \$629 million (based on APCO benchmark capacity of 10Mt). This, consequently, predicts a gross value of oil shale of about \$62.9 per ton. The NEPM model showed that the resource had no value if the electricity rate fell below \$0.122/kWh (equivalent to \$45/t), the break-even point. If the levelized processing cost was estimated at \$45 per ton, the net intrinsic value was roughly \$17.90 per ton. The current PPA rate encourages the use of oil shale; however, to ensure the project's long-term viability, tariff prices should be regulated.

4. Results and Discussion

In this work, the Al Abiad deposit was assessed with respect to lithostratigraphic variability, potential resource reserves, mining operations, and techno-economic analysis. A combined dual-commodity approach is shown to offer both practical and significant enhancements to the project's outlook, primarily by substantially lowering the effective stripping ratio and improving economic viability. Additionally, a financial framework for appraising oil shale is proposed, revealing that its profitability hinges crucially on controlled electricity prices rather than on standard oil-market conditions.

4.1. General Geology and Borehole Analysis

Investigating the geological record in borehole data logs (BH6 - BH12) is vital for characterizing subsurface stratigraphy and revealing the spatial distribution of resources. Borehole data analysis indicates that the sedimentary formation spans an estimated area of 94.6 km², as shown in Table 3. Although the overlying layers show lateral uniformity, the economic strata exhibit structural variability (Figure 3). Quaternary alluvium and Upper Cretaceous limestone/marl formations are the main constituents of the cover layer, with a relatively consistent depositional pattern and thicknesses ranging from 20.5 to 24.5 m in BH.10 and BH.6, respectively. This suggests a quiet, uniform depositional rate that caused horizontal uniformity.

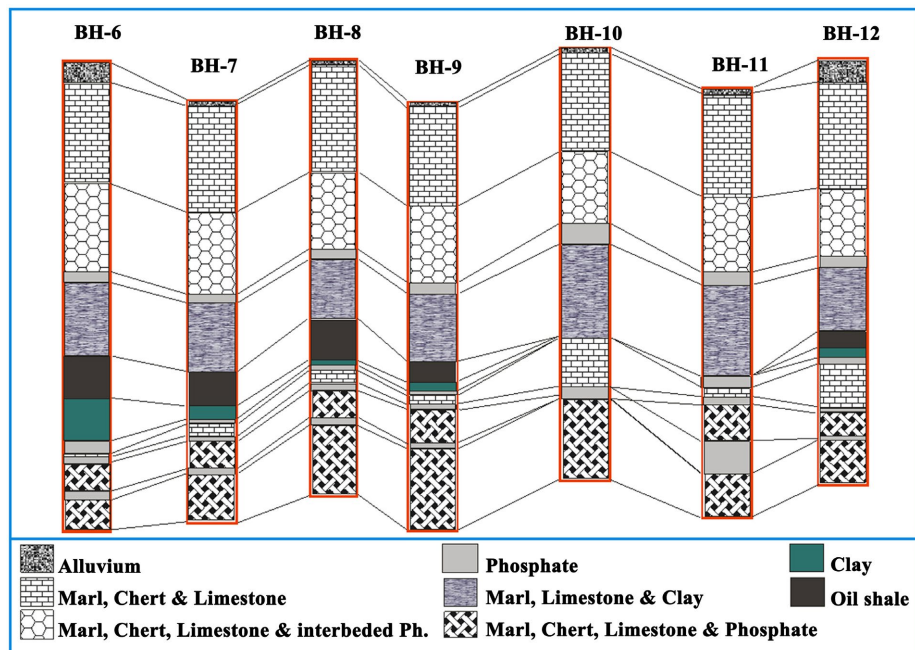


Figure 3. Subsurface lithology distribution based on borehole data.

Table 3. Borehole analysis illustrates the influence area and material thicknesses.

BH ID.	Coordinates ^a		Elevation ^a	Influence area (m ²)	Layer Thickness (m)			
	East	North			Overburden	Interwaste	Oil Shale	Phosphate
BH.6	260999.8	1063353.1	810.1040	12,127,000	24.5	12.75	5.0	4
BH.7	260951.0	1063307.8	809.5090	15,075,000	23.5	14.50	4.0	2.5
BH.8	260853.6	1063346.9	809.4230	18,680,000	22.0	12.50	5.0	3.25
BH.9	260748.4	1063347.3	809.6730	13,119,000	21.1	14.00	2.5	3.15
BH.10	260646.9	1063348.2	810.4640	15,058,000	20.5	16.80	0.0	3.2
BH.11	260800.6	1063455.6	809.3130	8,205,000	21.5	16.40	0.0	7.1
BH.12	260700.0	1063450.0	810.0000	12,336,000	23.0	17.10	2.0	2.8
Total				94,600,000				

^aBorehole coordinates and elevations were obtained from JPMC.

Conversely, the fundamental mineralized zones show geological variability. The primary focus, phosphate, appears in every borehole. Phosphate shows considerable variation in thickness, ranging from 2.5 m in BH.7 to 7.1 m in BH.11. The oil shale layer above is lens-shaped, with notable thicknesses (5.0 m) in BH.6 and BH.8, yet it is completely missing in BH.10 and BH.11. A spatial inverse correlation between the two resources is observed; BH.11, lacking oil shale, contains the phosphate deposit. This irregularity in the depositional pattern may be attributed to paleoenvironmental influences, such as a paleostructural elevation that inhibited the accumulation of lower-energy bituminous marls (oil shale) while concentrating heavier phosphatic pellets. The finding is consistent with regional facies variations observed in the literature [9] [58] [59].

Table 4 presents the estimated volumetric measures of overburden, inter-waste, and the economic resources: phosphate and oil shale. The overall material movement required is substantial, with waste volumes (overburden and inter-waste) totaling 351.14 million m³, compared with 34.88 million m³ of phosphate and 23.27 million m³ of oil shale. This difference calls for an examination of the SR, which serves as the main metric for assessing economic viability in open-pit mining [3] [4]. In Scenario I, with oil shale treated as waste, the mean SR is 10.7, peaking at 16.8 in BH.7. These levels often make low-to-medium-grade deposits economically unviable because of high waste-handling expenses [41]. However, in Scenario II, which redefines oil shale as ore, the average SR drops to 6.0, representing a reduction of about 44%. The most significant reduction occurs in BH.7, where the SR falls from 16.8 to 5.8. This tactical change aligns with the idea that sustainable resource efficiency serves as an economic motive [60].

Table 4. Reserve analysis for the two scenarios.

BH ID.	Total overburden and inter-waste volume (million m ³)	Total oil shale volume (million m ³)	Total phosphate volume (million m ³)	Stripping Ratio	
				Scenario I	Scenario II
BH.6	46.0	6.2	4.9	10.6	4.1
BH.7	31.2	3.3	2.1	16.8	5.8
BH.8	51.6	7.5	4.9	12.2	4.2
BH.9	46.6	3.3	4.2	11.9	6.2
BH.10	68.5	0	5.9	11.7	11.7
BH.11	46.7	0	8.7	5.3	5.3
BH.12	60.7	3.0	4.2	15.0	8.4
Total	351.3	23.3	34.9	-	-
Average stripping ratio				10.7	6.0

However, the observed geological heterogeneity limits the mining techniques used. For example, in areas where oil shale is absent (BH.10 and BH.11), SR remains unchanged across all scenarios. This calls for a targeted mining order rather

than a straightforward borehole-to-borehole approach. Here, adaptive production mixing and cross-subsidy techniques can be employed. This means that blocks with high-profit margins and low SRs (BH.11) should support the development of blocks with negative margins and high SRs (BH.10). Doing so can avoid high-grading and optimize overall resource use [61]. Also, given the variability, the classification of ore versus waste needs to be flexible. Optimization methods, such as mixed-integer linear programming, might be used to schedule extraction, focusing on low-SR blocks first to enhance net present value and generate cash flow to support the later extraction of high-burden zones [62]. Also, the lenticular shape of the oil shale necessitates the use of resilient geostatistical techniques, such as Ordinary Kriging or Conditional Simulation, to avoid overestimation and the deployment of machinery in productive areas [63]. A run-of-mine (ROM) blending stockpile is crucial to reduce the variation discussed and provide a stable and sustained ore input to subsequent operations [64].

4.2. Mining Method and Operational Strategy

The co-extraction of phosphate and oil shale, along with the nature of the geological conditions, necessitates an accurate open-pit mining operation. Also, the inverse relationship between the resource demands techniques that guarantee the distinction of three separate material flows: phosphate ore, oil shale, and waste, such as the bench-cutting approach. This is paramount to reduce any possible contamination and preserve the resources' value.

The machinery fleet and mine configuration (**Figure 2**) are designed to implement this approach. The production process involves ripping and dozing for overburden, drilling and blasting for hard caprock, along with specific load-and-haul phases. A control system directs each excavated material to its assigned area (phosphate stockpile, oil shale stockpile, and waste dump), ensuring resource-handling management. This allows an advanced stockpiling and blending approach to maintain a uniform supply of materials for subsequent operations [65].

4.3. Sensitivity Analysis

A sensitivity analysis was conducted to evaluate the elasticity of oil shale's value with respect to market electricity prices (see **Figure 4**). This analysis treated oil shale value as a derivative of the tariff spread rather than global oil prices. **Figure 4** showed that the break-even threshold occurred at a tariff of \$0.122/kWh. Below this price, revenue from using oil shale as a fuel for electricity generation was insufficient to cover mining and processing costs and the capital recovery of the oil shale power plant. This indicated that, in this case, oil shale was economically sterile, with a value of zero or negative. Notably, at grid-parity prices driven by renewable alternatives (such as electricity generated from solar energy using photovoltaic technology (PV) at an assumed price of \$0.06/kWh), theoretical revenues dropped to negative \$22/tonne, resulting in a substantial net loss. This confirmed that the deposit's commercial-grade status was artificial, sustained primarily by

the difference between the fixed PPA tariff and the market rate. The potential to mitigate these high break-even costs is further explored in Scenario II, which examines the economic impact of co-extracting the phosphate deposits alongside oil shale.

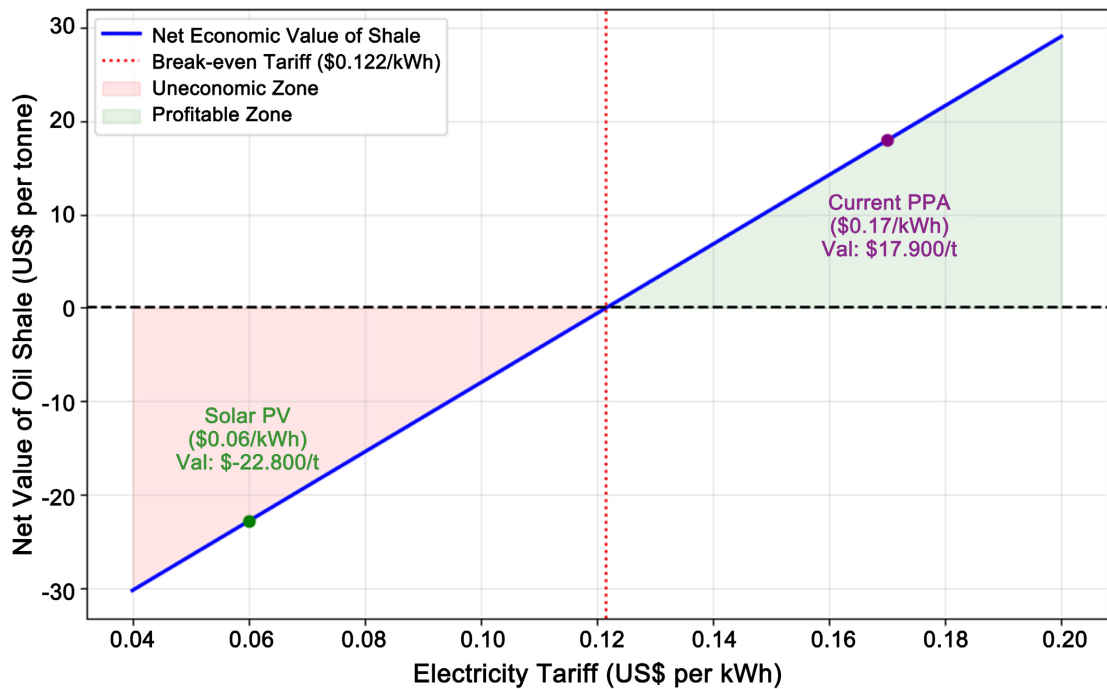


Figure 4. Sensitivity analysis of oil shale net value versus electricity tariff.

4.4. Economic Analysis

The economic analysis of the two proposed scenarios depends on the operational parameters of the mining activities. Table 5 summarizes the key parameters of mining operations. Scenario II shifts the project from being waste-dependent to an effective multi-resource venture. The extractable phosphate reserve remains unchanged at 32.96 million m³. Scenario II also recovers an additional 21.99 million m³ of oil shale, following the principles of circular economy and industrial ecology [66]-[68].

Table 5. Mineable reserves, mine life, and annual production capacity for the two scenarios.

Item	Scenario I ^a	Scenario II	
	Phosphate	Phosphate	Oil Shale
Mineable reserve (million m ³)	32.96	32.96	21.99
Annual production rate (million m ³ /year)	0.7	0.7	0.5
L (year)	47	46	
Total annual mine capacity (million m ³ /year)	8.19	8.4	

^aOil shale is considered waste in Scenario I.

While Scenario II requires about 2.6% of the mine's annual capacity, this operation is more efficient because a large portion is allocated to oil shale, which generates revenue. The mining activities in this project are estimated to last around 45 years in both cases, classifying it as a strategic asset and allowing for extended capital depreciation.

CAPEX and OPEX were calculated as shown in **Table 6**. The overall CAPEX amounts to US\$4.61 million, assuming a 10% straight-line depreciation rate. Yearly OPEX is mainly driven by energy expenses, resulting in on-site OPEX of US \$12.75 million (**Tables 7-9**). Logistics are the cost driver; annual transport expenses to the port of Aqaba and the APCO facility total US\$47.53 million, which is 3.7 times direct mining expenses, underscoring the project's vulnerability to fluctuations in fuel prices and transport distances (**Table 10**).

Table 6. Mining machinery and estimated CAPEX for the Al Abiad deposit.

Item Category	Equipment/ Infrastructure	Quantity	Unit Cost (US\$)	Total Cost (US\$)
Capital Equipment	Grader	2	110,000	220,000
	Bulldozers	3	150,000	450,000
	Drilling Machine	4	120,000	480,000
	Shovels	5	150,000	750,000
	Trucks	10	150,000	1,500,000
	Water Tanker	2	30,000	60,000
	Service Truck	2	25,000	50,000
	Diesel Tanker	2	25,000	50,000
	Explosive Truck	2	25,000	50,000
	Forklift	2	25,000	50,000
	Buses	4	30,000	120,000
	Grease Truck	2	25,000	50,000
	Pickup Trucks	4	25,000	100,000
	1. Subtotal Equipment			
Infrastructure	Fuel Tanks	-	-	4000
	Septic Pool	-	-	10,000
	Fence	-	-	25,000
	Local Roads Opening	-	-	40,000
	Water Tanks	-	-	3,000
	Houses & Offices	-	-	250,000
	Workshop	-	-	250,000
2. Subtotal Infrastructure				582,000
3. Exploration Costs				100,000
TOTAL CAPEX (1 + 2 + 3)				4,612,000
Depreciation (10%)				461,200

Table 7. Estimated annual labor costs (Summary of key personnel).

Category	Count	Monthly Salary (\$)	Annual Cost (million \$)
Management & Admin	8	1500 - 2500	0.205
Engineers & Geologists	8	1800	0.172
Equipment Operators	44	700 - 1400	0.6442
Technical Support (Mech/Elec/Drill)	16	1000 - 1400	0.2204
General Labor & Security	16	600	0.1152
Subtotal Salaries	92		1.36
Benefits (Vacation & Social Security)			0.285

Table 8. Estimated annual fuel and maintenance costs.

Equipment Type	Units	Daily Consumption (L/hr)	Annual Cost (million \$)
Load & Haul (Shovels/Trucks)	15	30 - 35	2.49
Support (Dozers/Graders)	5	30 - 70	1.42
Drilling & Auxiliary.	8+	4 - 40	1.17
Fluids & Maintenance.			0.15
TOTAL FUEL & FLUIDS			5.23

Table 9. Summary of On-Site OPEX.

Cost Center	Annual Cost (Million US\$)
Depreciation (10% of CAPEX)	0.46
Labor (Salaries + Benefits)	1.64
Energy (Fuel, Oil, Lubricants)	5.23
Spare Parts & Maintenance (10% of CAPEX)	0.46
Drilling & Blasting (\$0.55/m ³)	4.95
TOTAL SITE OPEX	12.74

Table 10. Cost of transporting ores to designated destinations.

Item	Total Annual Cost (million \$) ^a
Phosphate Transport (to Aqaba)	37.730
Oil Shale Transport (to APCO)	9.8
Total Logistics Cost	47.53

^aBased on a unit rate of 0.1\$/ (tonne-km).

A comparative economic analysis of the two scenarios is summarized in **Table 11**. Essentially, Scenario I is expected to generate gross revenue of about US \$231 million from the sale of 1.54 million tons of phosphate at US \$150 per ton. The estimated net income is US \$126.4 million after deducting OPEX, transportation

costs, and the 30% mining tax. However, adding oil shale valorization expands the income base. Using the NEPM-based price range (US \$45.00 - 62.90 per ton of oil shale) yields net income of approximately US\$150.4 million to US \$162.4 million, representing about a 19% to 28.7% increase over the baseline scenario. Even at the intrinsic value of oil shale (US \$17.9 per ton), net income rises by about 4.3%.

Table 11. Comparative economic analysis of extraction scenarios (in Million US\$).

Economic Indicator	Scenario I (Phosphate only)	Scenario II (Phosphate + oil shale ^a)
Production Volume	1.54 million tonne	1.54 million tonne (Phosphate) + 0.98 million tonne (Oil Shale)
Gross Revenue	231.0	275.1 - 292.6
Pre-tax Profit	180.5	214.8 - 232.3
Mining Tax (30%)	(54.2)	(64.4 - 69.7)
Net Income	126.4	150.4 - 162.6
Increase over baseline	—	+19.0% to +28.7%

^aRange based on oil shale price sensitivity (\$45 - \$62.9/tonne).

While this study provides a targeted evaluation of the sensitivity of oil shale value to fluctuations in electricity tariffs, it is important to contextualize these findings within the broader economic landscape of the project. The projected increases in net income (19% - 28.7%) isolate the impact of energy pricing to demonstrate the resource's value elasticity. However, in a full-scale operational environment, other significant variables, most notably fuel prices affecting logistics (the largest OPEX component), commodity price volatility, and CAPEX adjustments, would introduce additional layers of risk. While a multi-variable risk assessment was outside the immediate scope of this energy-focused analysis, these factors remain critical for future site-specific feasibility studies. These results should therefore be interpreted as an indicator of energy-price sensitivity rather than an absolute financial forecast across all market conditions.

In summary, the co-extraction strategy significantly improves the project's economic outlook and resilience. It not only aims to lower SR and related costs but also generates additional income as a hedge against fluctuations in the phosphate market. This is especially important because it helps keep the mine operational and employment stable even during commodity downturns, which is vital for sustainable mining. This study presents a practical approach for applying sustainable material management and circular economy principles. The Al Abiad project shows that the viability of marginal phosphate deposits in Jordan heavily relies on co-extracting the overlying oil shale. Scenario II transforms the operation into a resilient industrial complex, balancing logistical costs with dual revenue streams. Future research should focus on expanding borehole activities to produce detailed geostatistical conditional simulations of the precise boundaries between ore and waste, helping to define the size of selective mining units better and optimize the

ROM homogenization stockpiles needed for consistent plant feed [5] [7] [32] [33].

5. Conclusions

The investigation into the Al Abiad deposit underscores the critical need to transition from conventional mono-commodity extraction to an integrated poly-resource mining model in complex sedimentary basins. This study synthesizes lithostratigraphic characterization with techno-economic modeling to demonstrate that sustainable resource management is not merely an environmental compliance mechanism, but the primary driver of economic feasibility in high-stripping-ratio deposits.

Geological Constraints and Selective Mining Implications: The borehole analysis reveals a depositional environment defined by significant lateral heterogeneity. While the calcareous overburden is geometrically consistent, the economic horizons exhibit a distinct inverse thickness relationship; notably, the phosphate resource thickens (up to 7.1 m) in zones where the oil shale is absent (e.g., BH.11). This suggests localized high-energy paleo-environmental controls that winnowed lighter bituminous sediments while concentrating phosphatic pellets. Consequently, a linear, block-by-block mining sequence is operationally flawed. The study confirms that blind bulk mining would result in significant resource sterilization and negative margins in high-burden sectors like BH.10. Instead, the operation requires a stochastic scheduling approach that uses dynamic blending and cross-subsidization, with high-yield blocks (BH.11) supporting the development of high-stripping-ratio zones.

The Decoupling of Waste and Value: The most transformative finding of this research is the quantification of the circular economy effect on mine geometry. Under the conventional mono-commodity scenario (Scenario I), the project faces a prohibitive average SR of 10.7:1, rendering it economically marginal. By reclassifying the oil shale from waste to energy ore (Scenario II), the effective SR is reduced by 44% to 6.0:1. This operational shift aligns with industrial ecology principles, proving that co-valorization significantly reduces the environmental footprint by minimizing ex-pit waste volumes while simultaneously enhancing the net income by approximately 19% - 29%.

Valuation via the NEPM: This paper introduces the NEPM as a novel framework for valuing non-traded energy commodities, such as oil shale. The sensitivity analysis demonstrates that the commercial grade of the oil shale is synthetic, derived not from its geological calorific value, but from the regulatory electricity tariff. The resource holds positive economic value (\$17.90/t) only when sustaining a PPA tariff above the break-even threshold of US \$0.122/kWh. Below this threshold, or at grid-parity prices with solar PV (\$0.06/kWh), the resource becomes an economic liability. Thus, the feasibility of the dual-extraction model is contingent upon long-term, fixed-tariff offtake agreements that insulate the operation from market spot-price volatility, as is the case in APCO.

Strategic Outlook: In conclusion, Al Abiad project demonstrates that the via-

bility of marginal phosphate deposits in Jordan is inextricably potential to the co-extraction of overlying oil shale. The proposed Scenario II transforms the operation into a resilient industrial complex where the logistical costs—dominating OPEX at a factor of 3.7 times the mining cost—are offset by dual revenue streams. Future work should focus on the rigorous geostatistical conditional simulation of the hard boundaries between ore and waste to further refine the selective mining unit sizing and optimize the ROM homogenization stockpiles required for consistent plant feed.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Ryter, J., Bhuwalka, K., Roth, R., Olivetti, E., Buarque-Andrade, L., Frenzel, M., *et al.* (2025) Modeling Interconnected Minerals Markets with Multicommodity Supply Curves: Examining the Copper-Cobalt-Nickel System. *Nature Communications*, **16**, Article No. 7302. <https://doi.org/10.1038/s41467-025-62570-8>
- [2] Scholz, R.W., Ulrich, A.E., Eilittä, M. and Roy, A. (2013) Sustainable Use of Phosphorus: A Finite Resource. *Science of the Total Environment*, **461**, 799-803. <https://doi.org/10.1016/j.scitotenv.2013.05.043>
- [3] Holden, J. (2025) Gold Mine Stripping Ratios Rise on High Prices, Grades Continue Declining. S&P Global Market Intelligence. <https://www.spglobal.com/market-intelligence/en/news-insights/research/gold-mine-stripping-ratios-rise-on-high-prices-grades-continue-declining>
- [4] Nassar, N.T., Lederer, G.W., Brainard, J.L., Padilla, A.J. and Lessard, J.D. (2022) Rock-To-Metal Ratio: A Foundational Metric for Understanding Mine Wastes. *Environmental Science & Technology*, **56**, 6710-6721. <https://doi.org/10.1021/acs.est.1c07875>
- [5] Kinnunen, P.H.-. and Kaksonen, A.H. (2019) Towards Circular Economy in Mining: Opportunities and Bottlenecks for Tailings Valorization. *Journal of Cleaner Production*, **228**, 153-160. <https://doi.org/10.1016/j.jclepro.2019.04.171>
- [6] Lèbre, É., Corder, G. and Golev, A. (2017) The Role of the Mining Industry in a Circular Economy: A Framework for Resource Management at the Mine Site Level. *Journal of Industrial Ecology*, **21**, 662-672. <https://doi.org/10.1111/jiec.12596>
- [7] Antony Jose, S., Calhoun, J., Renteria, O.B., Mercado, P., Nakajima, S., Hope, C.N., *et al.* (2024) Promoting a Circular Economy in Mining Practices. *Sustainability*, **16**, Article 11016. <https://doi.org/10.3390/su162411016>
- [8] Alnawafleh, H. (2007) Geological Factors Controlling the Variability of Maastrichtian Bi-tuminous Rocks in Jordan. Ph.D. Thesis, The University of Nottingham.
- [9] Muhaisen Alnawafleh, H. (2015) Jordanian Oil Shales: Variability, Processing Technologies, and Utilization Options. *Journal of Energy and Natural Resources*, **4**, 52-55. <https://doi.org/10.11648/j.jenr.20150404.11>

- [10] Hilson, G. (2002) Promoting Sustainable Development in Ghanaian Small-Scale Gold Mining Operations. *Environmentalist*, **22**, 51-57. <https://doi.org/10.1023/a:1014572009016>
- [11] Hilson, G., Bartels, E. and Hu, Y. (2022) Brick by Brick, Block by Block: Building a Sustainable Formalization Strategy for Small-Scale Gold Mining in Ghana. *Environmental Science & Policy*, **135**, 207-225. <https://doi.org/10.1016/j.envsci.2022.04.006>
- [12] Elkington, J. (1998) Partnerships from Cannibals with Forks: The Triple Bottom Line of 21st-Century Business. *Environmental Quality Management*, **8**, 37-51. <https://doi.org/10.1002/tqem.3310080106>
- [13] Sícoli Pósleman, C. and Sallan, J.M. (2019) Social License to Operate in the Mining Industry: The Case of Peru. *Impact Assessment and Project Appraisal*, **37**, 480-490. <https://doi.org/10.1080/14615517.2019.1585142>
- [14] Koval, V., Kryshtal, H., Udovychenko, V., Soloviova, O., Froter, O., Kokorina, V., et al. (2023) Review of Mineral Resource Management in a Circular Economy Infrastructure. *Mining of Mineral Deposits*, **17**, 61-70. <https://doi.org/10.33271/mining17.02.061>
- [15] Kirchherr, J., Reike, D. and Hekkert, M. (2017) Conceptualizing the Circular Economy: An Analysis of 114 Definitions. *Resources, Conservation and Recycling*, **127**, 221-232. <https://doi.org/10.1016/j.resconrec.2017.09.005>
- [16] Lottermoser, B.G. (2011) Recycling, Reuse and Rehabilitation of Mine Wastes. *Elements*, **7**, 405-410. <https://doi.org/10.2113/gselements.7.6.405>
- [17] Frenzel, M., Ketris, M.P., Seifert, T. and Gutzmer, J. (2016) On the Current and Future Availability of Gallium. *Resources Policy*, **47**, 38-50. <https://doi.org/10.1016/j.resourpol.2015.11.005>
- [18] Gunn, G. (2014) Front Matter. In: Gunn, G., Ed., *Critical Metals Handbook*, John Wiley & Sons, I-XIII. <https://doi.org/10.1002/9781118755341.fmatter>
- [19] Hagelüken, C. (2014) Recycling of (Critical) Metals. In: Gunn, G., Ed., *Critical Metals Handbook*, John Wiley & Sons, 41-69. <https://doi.org/10.1002/9781118755341.ch3>
- [20] Humphreys, D. (2014) The Mining Industry and the Supply of Critical Minerals. In: Gunn, G., Ed., *Critical Metals Handbook*, John Wiley & Sons, 20-40. <https://doi.org/10.1002/9781118755341.ch2>
- [21] Calvo, G., Mudd, G., Valero, A. and Valero, A. (2016) Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issue or a Global Reality? *Resources*, **5**, Article 36. <https://doi.org/10.3390/resources5040036>
- [22] USGS (2025) Mineral Commodity Summaries 2025: Phosphate Rock. <https://pubs.usgs.gov/periodicals/mcs2025/mcs2025-phosphate.pdf>
- [23] JPMC (2025) Sustainability Reports. JPMC. <http://www.jpmmc.com/jo/en/annual-report/sustainability>
- [24] Abu-Hamattah, Z.S.H. and Al-Shawabkeh, A.F. (2008) An Overview of the Jordanian Oil Shale: Its Chemical and Geologic Characteristics, Exploration, Reserves and Feasibility for Oil and Cement Production. *Central European Geology*, **51**, 379-395. <https://doi.org/10.1556/ceugeol.51.2008.4.6>
- [25] Alali, J., Abu Salah, A., Yasin, S. and Al Omari, W. (2015) Mineral Status and Future Opportunity: Oil Shale. Ministry Of Energy and Mineral Resources (MEMR). https://madar-ju.com/storage/images/files/file_1738774858ObEYV.pdf
- [26] Alhilu, G. (2019) Jordanian Oil Shale 2019. Ministry Of Energy and Mineral Resources (MEMR). https://www.memr.gov.jo/EBV4.0/Root_Storage/EN/Project/Oil_Shale.pdf

- [27] Khalil M Ibrahim, and Hanan B. Abdel Rahman, (2024) Uranium and Organic Geochemistry of Oil Shale in Attarat Um Ghudran, Jordan. *Iraqi National Journal of Earth Science (INJES)*, **24**, 271-289. <https://doi.org/10.33899/earth.2023.142670.1133>
- [28] Alnawafleh, H., Tarawneh, K. and Alrawashdeh, R. (2013) Geologic and Economic Potentials of Minerals and Industrial Rocks in Jordan. *Natural Science*, **5**, 756-769. <https://doi.org/10.4236/ns.2013.56092>
- [29] Tarawneh, K. (2008) Jordanian Phosphate Mining History. *Fifth International Conference of Beneficiation of Phosphates*, Rio de Janeiro. <https://minedocs.com/23/JPMC-PR-07012011.pdf>
- [30] Tarawneh, K.A. (2016) A Comprehensive Outlook of Mining Industry in Jordan, Opportunities and Threats. *Open Journal of Geology*, **6**, 1137-1148. <https://doi.org/10.4236/ojg.2016.69084>
- [31] Tarawneh, K. and Moumani, K. (2006) Petrography, Chemistry and Genesis of Phosphorite Concretions in the Eocene Umm Rijam Chert Limestone Formation, Ma'an Area, South Jordan. *Journal of Asian Earth Sciences*, **26**, 627-635. <https://doi.org/10.1016/j.jseaes.2004.12.006>
- [32] Peukert, D., Xu, C. and Dowd, P. (2022) A Review of Sensor-Based Sorting in Mineral Processing: The Potential Benefits of Sensor Fusion. *Minerals*, **12**, Article 1364. <https://doi.org/10.3390/min12111364>
- [33] Robben, C. and Wotruba, H. (2019) Sensor-Based Ore Sorting Technology in Mining—Past, Present and Future. *Minerals*, **9**, Article 523. <https://doi.org/10.3390/min9090523>
- [34] Al-Makhadmeh, L.A., Batiha, M.A., Maier, J., Rawadih, S.E., Altarawneh, I.S. and Scheffknecht, G. (2018) Effect of Air and Oxyfuel Staged Combustion on Oil Shale Fly Ash Formation with Direct In-Furnace Limestone Addition for Sulphur Retention. *Fuel*, **220**, 192-199. <https://doi.org/10.1016/j.fuel.2018.01.057>
- [35] EASAC (2025) Study on the EU Oil Shale Industry. <https://easac.eu/publications/details/study-on-the-eu-oil-shale-industry>
- [36] Latošov, E., Volkova, A. and Siirde, A. (2011) The Impact of Subsidy Mechanisms on Biomass and Oil Shale Based Electricity Cost Prices. *Oil Shale*, **28**, 140-151. <https://doi.org/10.3176/oil.2011.1s.06>
- [37] Trinks, A., Mulder, M. and Scholtens, B. (2020) An Efficiency Perspective on Carbon Emissions and Financial Performance. *Ecological Economics*, **175**, Article ID: 106632. <https://doi.org/10.1016/j.ecolecon.2020.106632>
- [38] Mendonca Severiano, B., Northey, S.A. and Giurco, D. (2024) Drivers and Barriers of Voluntary Sustainability Initiatives in Mining Raw Materials for Batteries. *The Extractive Industries and Society*, **20**, Article ID: 101552. <https://doi.org/10.1016/j.exis.2024.101552>
- [39] El-Hiyari, M. (1985) The Geology of Jabal Al-Mutarammil: Map Sheet 3252 III. Geology Directorate—Natural Resources Authority.
- [40] Bender, F. (1975) Geology of the Arabian Peninsula: Jordan. US Department of the Interior, Geological Survey. <https://books.google.com/books?hl=en&lr=&id=ieTi4JWCraAC&oi=fnd&pg=PA101&dq=Geology+of+Jordan&ots=Xiy3VbTF-H&sig=euCJFOY-WHB1QaoY1rl8jw1ie4Yw>
- [41] Camm, T. (1991) Simplified Cost Models for Prefeasibility Mineral Evaluations. Vol. 1991, U.S. Bureau of Mines: US Department of the Interior.
- [42] H. Altit, A., O. Alrawashdeh, R. and M. Alnawafleh, H. (2021) Open Pit Mining. In:

- Soni, A., Ed., *Mining Techniques—Past, Present and Future*, IntechOpen.
<https://doi.org/10.5772/intechopen.92208>
- [43] Titi, A. and Rawashdeh, R.A. (2023) Feasibility of Pure Calcium Carbonate Project at Zwizya, Central Jordan. *International Journal of Mining and Mineral Engineering*, **14**, 421-446. <https://doi.org/10.1504/ijmme.2023.137379>
- [44] Hustrulid, W.A., Kuchta, M. and Martin, R.K. (2013) Open Pit Mine Planning and Design, Two Volume Set & CD-ROM Pack. 3rd Edition, CRC Press.
- [45] Novozhilov, M.G., Pchelkin, G.D., Khokhryakov, V.S. and Eskin, V.S. (1971) *Open-pit Mining Technology. Part 2. Open-Pit Mining Technology and Integrated Mechanization* (Vol. 2). Subsoil, Moscow. <https://www.geokniga.org/books/35858>
- [46] Tomakov, P. and Naumov, I. (1992) Technology, Mechanization, and Organization of Open-Pit Mining. Publishing House of the Moscow Mining Institute.
- [47] Nourali, H. and Osanloo, M. (2019) Mining Capital Cost Estimation Using Support Vector Regression (SVR). *Resources Policy*, **62**, 527-540.
<https://doi.org/10.1016/j.resourpol.2018.10.008>
- [48] O'Hara, T. and Suboleski, S. (1992) Chapter 6.3: Costs and Cost Estimation. *SME Mining Engineering Handbook*, **1**, 405-424.
<https://nubeminera.cl/wp-content/uploads/2019/05/Nube-Minera-OHara-Subolewsky.pdf>
- [49] EGT (2025) Phosphate Rock Market July 25: When Ship Routes Speak Louder. Eastern General Trade Co.
<https://easttrades.com/phosphate-rock-market-july-25-when-ship-routes-speak-louder/>
- [50] Tooming, M. (2025) Analysis: Estonia's Oil Shale Plants Kept Price of Electricity 17% Lower in 2024.
<https://news.err.ee/1609638418/analysis-estonia-s-oil-shale-plants-kept-price-of-electricity-17-lower-in-2024>
- [51] Koel, M. (2025) Estonian Oil Shale. <https://www.kirj.ee/public/oilshale/Est-OS.htm>
- [52] Jaber, J.O., Sladek, T.A., Mernitz, S. and Tarawneh, T.M. (2008) Future Policies and Strategies for Oil Shale Development in Jordan. *Jordan Journal of Mechanical and Industrial Engineering*, **2**, 31-44. <https://jjmie.hu.edu.jo/files/V2/004-v2-1.pdf>
- [53] APCO (2025) Attarat Power Company (APCO). Attarat Power Company.
<https://attaratpower.com.jo/>
- [54] APCO (2025) The Plant Project Significance: Meeting Jordan's Energy Demand. Attarat Power Co Website. <https://attaratpower.com.jo/project-significance/>
- [55] BCM (2025) Oil Shale Mining & Exploration—BCM-GROUP. APCO Oil Shale Project—Jordan. <https://www.bcm-group.com/oil-shale-mining-exploration/>
- [56] Qudaih, R., Talab, I., Raza, S., Janajreh, I. and Hamdan, M. (2011) Material Characterization and Gasification of Jordanian Oil Shale. *International Journal of Energy, Environment, and Economics*, **19**, 339-354.
- [57] China Aid Data (2025) China Construction Bank Contributes \$244 Million to Syndicated Buyer's Credit Loan for 554MW Attarat Oil Shale Fired Power Plant Project (Linked to Record ID#64457, ID#72499, ID#72502, and ID#52552). AidData Project.
<https://china.aiddata.org/projects/72500>
- [58] Abed, A. (2000) The Geology of Jordan and Its Environment and Water. Publication of the Jordanian Geologists Association.
<https://www.scirp.org/reference/referencespapers?referenceid=1561524>
- [59] Alnawafleh, H.M. and Fraige, F.Y. (2015) Analysis of Selected Oil Shale Samples from

- El-Lajjun, Central Jordan. *Geomaterials*, **5**, 77-84.
<https://doi.org/10.4236/gm.2015.53008>
- [60] Laurence, D. (2011) Establishing a Sustainable Mining Operation: An Overview. *Journal of Cleaner Production*, **19**, 278-284. <https://doi.org/10.1016/j.jclepro.2010.08.019>
- [61] Mudd, G.M. (2010) The Environmental Sustainability of Mining in Australia: Key Mega-Trends and Looming Constraints. *Resources Policy*, **35**, 98-115.
<https://doi.org/10.1016/j.resourpol.2009.12.001>
- [62] Asad, M.W.A. and Dimitrakopoulos, R. (2013) Implementing a Parametric Maximum Flow Algorithm for Optimal Open Pit Mine Design under Uncertain Supply and Demand. *Journal of the Operational Research Society*, **64**, 185-197.
<https://doi.org/10.1057/jors.2012.26>
- [63] Dimitrakopoulos, R. (2011) Stochastic Optimization for Strategic Mine Planning: A Decade of Developments. *Journal of Mining Science*, **47**, 138-150.
<https://doi.org/10.1134/s1062739147020018>
- [64] Lotter, N.O. (2011) Modern Process Mineralogy: An Integrated Multi-Disciplined Approach to Flowsheeting. *Minerals Engineering*, **24**, 1229-1237.
<https://doi.org/10.1016/j.mineng.2011.03.004>
- [65] Zhao, S., Lu, T., Koch, B. and Hurdsman, A. (2015) Automatic Quality Estimation in Blending Using a 3D Stockpile Management Model. *Advanced Engineering Informatics*, **29**, 680-695. <https://doi.org/10.1016/j.aei.2015.07.002>
- [66] Baca-Neglia, M., Barreto-Pio, C., Virú-Vásquez, P., Badillo-Rivera, E., Césare-Coral, M.F., Castro-Pantoja, J.B., *et al.* (2025) Industry 4.0, Circular Economy and Sustainable Development Goals: Future Research Directions through Scientometrics and Mini-Review. *Sustainability*, **17**, 6468. <https://doi.org/10.3390/su17146468>
- [67] Born, K. (2025) Adoption of Circular Economy Practices in the Mining Sector: Evidence from Chile. *Resources Policy*, **102**, Article ID: 105514.
<https://doi.org/10.1016/j.resourpol.2025.105514>
- [68] Cotrina-Teatino, M.A. and Marquina-Araujo, J.J. (2025) Circular Economy in the Mining Industry: A Bibliometric and Systematic Literature Review. *Resources Policy*, **102**, Article ID: 105513. <https://doi.org/10.1016/j.resourpol.2025.105513>