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Integration of renewable energy and sustainable development with strategic planning in the mining industry

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ABSTRACT

With an increase in the world population, the global demand for minerals is rising, increasing energy consumption. Due to the distance of mines from urban areas, the energy required for mining is highly dependent on fossil fuels. Using renewable energies is an effective solution to reducing this problem. This study examines the challenges and opportunities of integrating renewable energy into mining operations and the impact of this integration on the attainment of Sustainable Development Goals (SDG). The present study also investigates the strategic management of renewable energy use in the mining sector via the Strengths, Weaknesses, Opportunities, and Threats (SWOT) method. The results indicate that despite the high potentialities of renewable energy in mining, much more investigation is required for the technical use of this technology in the mining industry. Using renewable energy can create new jobs, reduce environmental pollution, increase knowledge in the mining area, create a circular economy in the mining industry, and reduce mining operating costs. All mentioned factors can have a positive effect on sustainable development indicators. On the other hand, mine owners' lack of information about the positive effects of renewable energy, high investment, lack of skilled labor, and high maintenance costs can create challenges for using renewable energy in mines. The SWOT strategic management analysis results demonstrate that the strengths and possible opportunities of using this technology in mining outweigh the weaknesses and possible threats. Hence, the aggressive strategy, defined as the maximum use of strengths to benefit from created opportunities optimally, is suggested.

1. Introduction

The mining industry encompasses five critical phases: exploration, extraction, exploitation, processing, and refining. It is a cornerstone industry, providing essential raw materials for many sectors, including transportation, construction, aerospace, high-tech technology, energy, and mining. As the renowned German physicist Max Planck once stated, 'Mining may not be everything, but without mining, everything is nothing.' With the global population steadily increasing and numerous low-income nations aspiring to reach the per capita income levels of middle-income countries, the demand for minerals is poised to experience substantial growth [1]. Nowadays, developed countries have devoted more attention to mineral recycling. However, the critical role of the mining industry as the main source of raw material production is indisputable [2]. Mineral production is regarded as one of the most significant indicators of economic growth in various countries [3]. More energy is needed to produce the required materials because of increased demand for raw materials and a decrease in high-grade resources. More energy consumption potentially boosts the amount of greenhouse gas emissions [4], which signifies the adverse impacts of mining activities on the environment. Therefore, exploring and identifying and identifying these environmental effects and taking measures to eliminate them is paramount. Efficient energy utilization throughout mining operations, spanning mineral extraction to product manufacturing, and adopting renewable energy sources and effective carbon capture techniques are pivotal strategies for mitigating energy consumption and greenhouse gas emissions. This collective effort ultimately leads to a reduction in environmental pollution. To achieve these objectives, harnessing the synergy of multiple renewable energy sources and addressing the complex challenges associated with their seamless integration within the

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mining sector is imperative.

Energy consumption for mineral extraction is of two types: off-grid and grid-connected. In plenty of mines, most energy is supplied by off-grid plants. Depending on the type of fossil fuels used in these mines, diesel, heavy oil, or coal is burnt to manufacture and transport minerals in the mineral extraction stage [5]. Nevertheless, grid-connected mining operations partially rely on fossil fuels. The grid provides the least costly energy source for mining operations in the mining sites where the grid is available. However, many countries with unreliable grid sources have to utilize backup energy sources generally powered by fossil fuels in mining sites, which raises production costs.

Among the foremost cost drivers within mining operations, energy expenditure reigns supreme. Typically, energy costs represent a substantial portion, ranging from 15% to 40%, of the overall operational expenses in the mining sector. A significant chunk of mining endeavors revolves around the generation and provisioning of energy, with a notable reliance on fossil fuels to meet these energy demands. Consequently, the mining industry remains highly susceptible to the ebbs and flows in fossil fuel prices, making it intricately entwined with energy market dynamics (Fig. 1). It is speculated that the energy demand for mining operations will be raised by 36% by 2035, compared to 2018 [6].

Apart from the economic dimension, the dependence of mining on fossil fuels negatively influences the well-being of local communities, infrastructure, air and water quality, and the environment. Hence, it can harm sustainable development goals (N. 2019). Sustainable development is a prerequisite for attaining human development objectives since it preserves natural resources and ecosystem services on which the economy and society depend. In general, sustainable development comprises 17 core goals, and the use of fossil fuels has direct and indirect adverse effects on these goals. Using renewable energy in mining operations can regulate the operational costs of mines and reduce destructive impacts on the pillars of sustainable development, i.e., the economy, society, and the environment [5].

The mining industry is one of the industries requiring a great amount of energy. This industry accounts for approximately 38% of the energy utilized in all industries, 15% of the global electricity consumption, and 11% of global energy use. Furthermore, the mining industry uses about 19% of coal and coal products worldwide. It accounts for 5% of global natural gas and 2% of global oil consumption (Awuah-Offei 2016; [7]. The energy use of the mining industry in 2021 in the whole world is estimated to be about 12,000 PJ (1 PJ (PJ) = 31.6 million m^3 of natural gas or 278 million kilowatt hours of electricity) ('MINING ENERGY CONSUMPTION '). In many developing countries, the mining sector has a significant share of energy consumption. For instance, the mining industry consumes around 50% of the energy used in Zambia [8]. Because of using a great deal of energy, the mining industry emits large amounts of greenhouse gases, destructively affecting water and air quality (T 2020a).

The impacts of energy consumption on climate change are undeniable. For example, previous studies have demonstrated that the global production of copper concentrates, iron, and bauxite is responsible for the emission of 30, 17, and 0.8 Mtpa CO2-eq worldwide [8]. The mining industry utilizes much energy for mining operations, negatively influencing climate change.

Beneficiaries of diminishing the use of fossil fuels are trying to develop equipment that boosts the application of renewable energy in the mining industry to lessen greenhouse gas emissions [4,9]. The integration of renewable energies into various industries entails the identification of energy-intensive processes. The mining industry includes blasting (if necessary), producing, transporting, crushing, processing, smelting, and refining minerals (Awuah-Offei 2016; [7]. It is essential to align various mining operations with renewable energy technology to obtain desirable outcomes [10,11].

Studies on using renewable energies in mines can be categorized into three major groups. Studies in the first group explore the potential of integrating renewable energies into mines located in remote areas and primarily using off-grid energy sources. These mines either consume fossil fuels or rely on electricity that is produced by diesel generators [12,13]. Studies in the second group exclusively focus on renewable energies, for instance, wind and solar systems (Klass and Mitchell 2022; [14]. Studies in the last group limit their investigations to specific areas and focus on the opportunities and challenges of using renewable energies in certain countries [6]. Few studies have thoroughly investigated the consumption of renewable energy in mines. 2020, about 5 GW of renewable energy projects were planned or cumulatively implemented in mines [5]. This energy is a small proportion of the total energy consumed in mines.

Strategic planning studies regarding integrating renewable energy

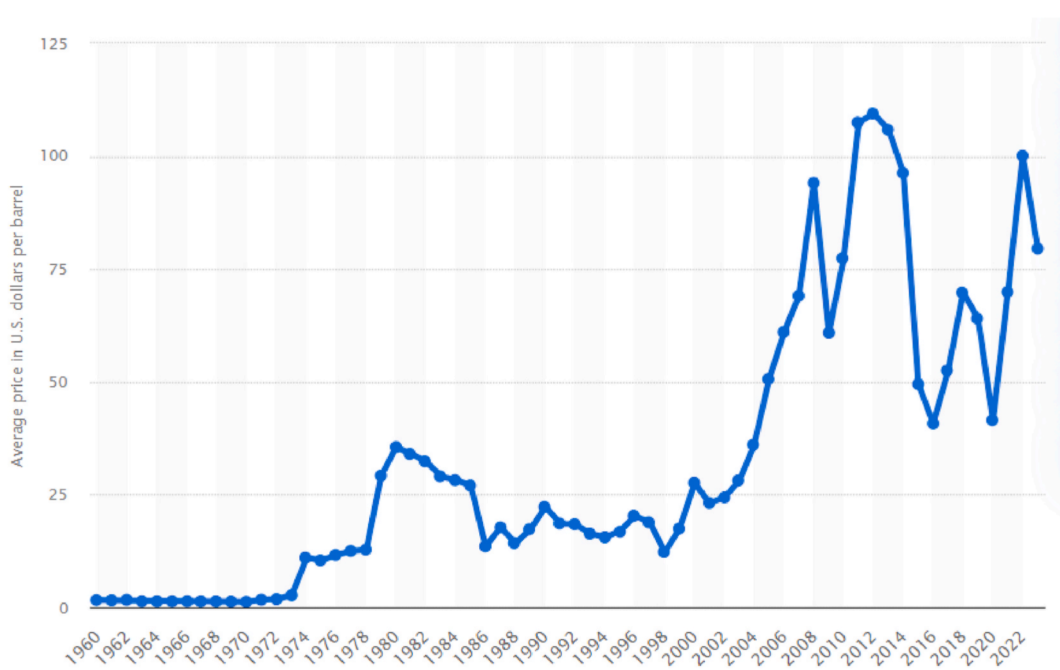

Fig. 1. Average fluctuations in diesel prices from 1960 to 2022 (USD/Gal) ('Diesel prices') ('statista.com' 2023).

sources into mining operations have revealed substantial research in this domain. However, much-existing research has primarily focused on the conceptual aspects of incorporating renewable energy within the mining context. While conceptual studies are undeniably vital in shaping industry perspectives, the absence of quantitative analyses undermines confidence in adopting these technologies. Consequently, this article comprehensively examines renewable energy's application in the mining sector, particularly emphasizing its impact on sustainable development metrics. Furthermore, SWOT strategic planning aims to furnish a lucid and quantifiable perspective on the utilization of renewable energy within the mining industry and its ramifications on diverse sustainability indicators.

As previously introduced in the initial section of this article, we laid the foundation for understanding the application of renewable energy in the mining sector. Moving forward, the second section delves into the intricate challenges that have emerged within the mining industry, particularly those about energy supply. Sections 3 and 4 comprehensively explore both the challenges and prospects associated with integrating renewable energy within mining operations. In Section 5, we employ the SWOT strategic management model to craft an optimal strategy for seamlessly integrating renewable energy into mining practices. Sections 6 and 7 are dedicated to the ensuing discussion and conclusive remarks.

2. energy challenges in the mining industry

Minerals produced worldwide are generally classified into four groups: industrial minerals, metal minerals, aggregates, and mineral fuels [20]. The global production of the metal mining sector was around 9945.3 million cubic meters until 2020, and its income reached 2520.6 billion dollars [19. Based on the available historical data, mineral prices are generally cyclical. In other words, mineral prices are booming in one period while in another period, they enter stagnation. The mining sector has always been under the strictest supervision due to the social benefits of mining, the great influence of mining on government policies, mining income increase during the mineral boom (as expected by the government), the importance of workers' health and safety, and the ecological effects of mining on the surrounding environment. In many developing countries, owing to the large scope of this industry, government policies and energy allocation for mining operations gain much more importance. For example, in countries where approximately 50% of energy is consumed in the mining sector [15], the government is reluctant to integrate renewable energies into this industry since some people may lose their jobs. As a result, even if the mining industry can use renewable energies in these countries, some local factors and government policies constrain their integration into mines.

Mining is typically divided into five key stages: drilling and blasting, loading, transportation, processing, and smelting and refining. Hence, it is regarded as one of the most energy-intensive industries. Predictions show that energy use will be elevated in the short and medium terms. Given this industry's rejection of renewable energy, the majority of this increased demand for energy will be met by using more fossil fuels, which augments the generation of carbon dioxide and the emission of greenhouse gases [16].

Table 1 demonstrates energy consumption and greenhouse gas emissions in the mining processes of some metals. Based on previous studies, gold extraction requires high energy, which raises greenhouse gas emissions [17]. This substantial energy use can mainly be attributed to reducing gold deposits in mines. To be more precise, a decrease in gold deposits forces miners to penetrate deep into the earth, which requires more energy to extract gold. Based on the available data, the amount of extracted gold was about 3000 metric tons (Mt) in 2021. Based on the data in Table 1, the energy consumption and greenhouse gas emissions in 2021 and 2007 were equal. Approximately 167–254 TW h (TWh) of energy were used for gold production in 2021. This indicates that gold mining emitted 52 to 81 million tons of CO2 into the world in 2021 [18].

Table 1
Greenhouse gas and energy use for selected metals.

Metal	Feed	Process or route	Greenhouse gasses (KWh/t)	Gross energy requirement ($MtCO_2$-eq/MT)
Gold	Refractory ore (3.5 g Au/t ore)	Refectory or route	85019200	26840
	Non-refractory ore (3.5 g Au/t ore)	Non-refractory or route	55829200	17560
Titanium	Ilmenite (36.0% Ti)	Becher and Kroll processes	101080	35.7
Aluminum	Bauxite ore (17.4% Al)	Bayer refining, Halle Heroult smelting	59080	22.4
Nickel	Laterite ore (1.0% Ni)	Pressure acid leaching, solvent extraction, and electrowinning	54320	16.1
	Sulfide ore (2.3% Ni)	Flash furnace smelting and Sherritt-Gordon refining	31920	11.4
Stainless steel	Multiple ores	Electric furnace and Argon Oxygen decarburization	21000	6.8
Copper	Sulfide ore (2.0% Cu)	Heap leaching, solvent extraction, and electrowinning	17920	6.2
Zinc	Sulfide ore (5.5% Pb, 86% Zn)	Electrolytic process	13440	4.6
	Sulfide ore (5.5% Pb, 86% Zn)	Imperial smelting process	10080	3.3
Copper	Sulfide ore (3.0% Cu)	Smelting, converting and electro-refining	9240	3.3
Lead	Sulfide ore (5.5% Pb, 86% Zn)	Imperial smelting process	8960	3.2
	Sulfide ore (5.5% Pb, 86% Zn)	Lead blast furnace	5600	2.1
Steel	Iron ore (64% Fe)	Integrated route (blast (oxygen) furnace)	6440	2.3

2.1. *Grade reduction in mines*

A decrease in the average mineral grade at the surface level has pushed the mining industry to penetrate deeper into the ground to reach a higher grade of minerals to fulfill the market's needs. Gaining access to higher-grade minerals in the depths of the earth entails extracting a larger volume of minerals. Thus, it is required to consume much more energy to extract, transport, load, and process minerals in mining sites.

Previous studies have shown that a decline in the average grade of ore, along with an increase in demand for minerals, brings about the extraction of more raw mineral materials from the depths of the ground, leading to higher levels of greenhouse gas emission [19]. Furthermore, the remoteness of most mines from processing factories poses challenges concerning energy supply chains. Supplying fuels, transporting minerals, accessing mining sites, and establishing and expanding necessary infrastructure in mines raise energy consumption and generate more greenhouse gases.

2.2. Instability of mineral and fuel prices

Supply and demand shocks in the mining industry affect the prices of energy and minerals, resulting in economic uncertainty about the costs and revenues of mining activities. In the worst-case scenario, there is a rise in expenses and a drop in mining income, which reduces the profit margins for mining companies and mine owners. Sharp price fluctuations sometimes lead to temporary or permanent mine closure. On average, 15–40% of operational costs in mines are related to energy and fuel consumption [6]. Fossil fuels, which supply a large proportion of energy for mines, generally have price fluctuations due to currency price variations, tariffs, supply chain logistics, and political and economic policies in countries. For instance, from 2011 to 2014, oil prices were mostly above 100 dollars. Between 2014 and 2021, the price of oil varied between 29 and 75 dollars (except for April 2020, when the oil price reached zero). When conducting this study, the oil price was 94 dollars. Fluctuations in energy prices and reductions in metal prices may endanger the life of some projects since their implementation has no economic justification, and price fluctuations create great economic uncertainty for stakeholders. Therefore, one of the biggest concerns of mine owners and mining companies is ensuring they earn profits in investment in this industry despite these price variations [11].

2.3. Growing environmental concerns in the mining industry

Mining raises ecological concerns in two ways. The first is using mechanized equipment and systems for mining operations (from the extraction of minerals to the production of final products), which produces greenhouse gases and pollutes the air at the local and global levels. The second one is associated with mining activities, such as blasting and processing, which enhances noise pollution and produces dust and chemical-containing waste. These activities negatively impact soil erosion, land use change, and soil, water, and air pollution, eventually posing serious risks to human health and living organisms [20].

2.4. Growing political and social concerns in the mining industry

Nowadays, the mining industry is under substantial political and environmental pressure from domestic and foreign shareholders and stakeholders to regulate environmental pollution, reduce the dependence of mines on fossil fuels, and replace them with renewable fuels. These stakeholders include international organizations, governments, environmental activists, local communities, and final producers (purchasers), like large producers of electric technologies and renewable energies (T 2020b). Due to the substantial role of the mining industry in the emission of greenhouse gases, host countries and environmentalists have started to enact stricter regulations to control pollution and force mines to provide legal and justifiable reports (for example, the possible effects of using fossil fuels on the environment should be estimated in environmental assessments, and legal authorities should confirm the acceptable amount of greenhouse gas emission as a prerequisite for issuing exploitation licenses) [21]. Today, some developed and developing countries that have a leading role in mineral production, such as Australia, Chile, and Canada, enact rules and policies and build infrastructure for collecting taxes on carbon production from mines, issue mine green certifications, and encourage mines to substitute renewable energy for conventional energy (fossil fuels) (T 2020a). Generally, all mining communities support using renewable energy due to its capacity to reduce air and water pollution and its sustainability after mine closure. As a result, with a rise in demand for energy in mining operations in the future, renewable energy will increasingly be incorporated into mining operations to eliminate the concerns of stakeholders.

3. Challenges of integrating renewable energies in the mining industry

The use of renewable energy in the mining industry is on the rise. Nonetheless, the present technical challenges have hindered and restricted the application of renewable technologies on a large scale. This section discusses some challenges of incorporating renewable energy in mining.

3.1. Material consumption in processing operations

In mining operations highly dependent on fossil fuels as feedstocks, it is difficult to thoroughly replace these fuels with renewable energies and stop carbon emissions. Biomass (charcoal) can be utilized as an alternative to coke in mining operations. The sustainable global production of charcoal, the costs of transporting it to processing factories, and the complicated technical issues associated with charcoal use in the steel industry have always been among the most serious challenges of using this energy in this industry (Papadis and Tsatsaronis 2020). Hydrogen is also deemed a suitable alternative raw material to fossil fuels. From an environmental perspective, water is a more promising source of renewable electricity generation than coal. However, its high price is the biggest obstacle to the constant use of hydrogen for producing renewable energies on a desired scale. Using hydrogen, which is more expensive than charcoal and fossil fuels, in mining operations has no economic justification. Therefore, it is required to undertake further investigations to identify how to reduce the production costs of hydrogen used for mineral processing operations through renewable sources [22].

3.2. Required heat in mineral processing operations

Heat energy is one of the most consumed in mining operations, particularly mineral processing. Mineral processing entails using a wide range of temperatures. Temperatures for this mining activity can be categorized into three major groups: low temperature (below 150 Celsius), average temperature (between 150 and 400 Celsius), and high temperature (above 400 Celsius) [22,23]. This variety of temperature demands in mineral processing highlights the need for integrating various technologies in mining sites. For example, iron ore processing requires heat between 800 and 1200 Celsius in the steel industry. The temperature needed for copper processing is 250–350 Celsius, and aluminum processing is 400–500 Celsius. Low- and medium-temperature heat is generally produced by steam, while direct heat at high temperatures is mainly generated by fossil fuels [23]. Fossil fuels provide the high-temperature heat required for mineral processing in mining. In the production of high-temperature heat, approximately 65% of coal, 20% of natural gas, and 10% of oil are consumed [22,23].

Table 2 indicates that most renewable energy technologies can supply heat at low and medium temperatures. Among different

Table 2
Current commercially available renewable energy technologies.

Category	Technology type	Temperature levels
Renewable source	Biomass, boiler	Low
	Biomass, high-temperature	Medium
	Biomass, combined-heat-and-power	High
	Biogas, anaerobic digestion	Low
	Solar PV	High
	Wind	High
	Heat pump	Low
	Geothermal direct use	Low
	Deep geothermal	Medium
Energy storage	Solar thermal	N/A
	Hydrogen	N/A
	Pump storage	N/A
	Battery storage	N/A

renewable energies, solar energy has the highest potential to be incorporated into this sector. Nevertheless, using solar energy entails a larger area of land and adequate solar resources to produce the required heat. The concentrated solar energy system can generate heat at a temperature of 550 Celsius at the industrial level [24]. Studies on solar energy have reached temperatures at 1000 Celsius using advanced laboratory facilities [25]. Researchers at the Barbara Hardy Institute could produce heat ranging from 150 to 700 Celsius using their laboratories' renewable energies and hybrid systems (comprising thermal and wind energies and thermal energy storage) [26]. These degrees of heat have great applications in processing numerous non-ferrous minerals (such as copper and aluminum) that require medium and high temperatures.

At the time of the present study, charcoal is the only economical energy resource with the potential to produce temperatures above 550 Celsius. Although charcoal can generate heat at a temperature of 1260 Celsius, finite charcoal and even wood resources place limitations on their constant use [27].

3.3. Constant energy supply in mining activities

The mining industry generally needs high-quality, constant, and round-the-clock energy. To meet this energy demand through renewable energies, merely hydroelectric and geothermal resources can be utilized. However, these resources have certain restrictions as they necessitate using mineral resources. Thus, constant energy production through renewable energy resources faces big challenges and obstacles. Technologies that combine renewable energies, like wind and solar, seem more desirable.

Nevertheless, they overproduce energy during peak production hours, which may lead to complications associated with excess energy. A certain amount of this energy can be stored in batteries or consumed in hydrogen electrolysis. The excess energy can be sold if the mine is connected to the national grid and contracts with relevant organizations to export electricity to the grid. Storing surplus energy production places some challenges because the existing technologies for electricity storage in batteries have limitations, and using larger batteries to store more energy may be economically prohibitive.

To tackle this problem, mines are more inclined to use hybrid systems to supply their excess energy with diesel generators. This solution reduces carbon dioxide emissions, but it does not stop them. Some of these hybrid systems are solar-wind-diesel generators, wind-battery-diesel generators, and solar-wind-battery-diesel generators. One of the mines in Australia has a hybrid system of 4 MW wind and 1 MW solar power plants and a battery with 1 MW of storage capacity. This system decreases about 70% of the energy produced by diesel generators. This system uses diesel generators to provide surplus energy [28]. Considering the issues mentioned above, many mines currently have the potential to generate a part of their required energy, with an average of 30–40% of the total energy consumed in mining sites, by using renewable energy resources [6].

3.4. Renovation of investment structure

Mining operations determine the amount of investment in this sector to estimate mine life. Mine life varies from 2 to more than 50 years. Estimating mine life is critical in computing the mining investment levels and the return on invested capital (ROIC) [29]. In mining projects, fundamental and major decisions are usually made in the pre-feasibility and feasibility stages. When a mining site starts operating based on predetermined plans, the facilities and technologies of the mine can be used for decades. After the necessary investment decisions are made, any alterations in the mine development plan entail the approval of many authorities and organizations and sometimes cause adverse effects on mining operational activities.

Many mining operations are based on an all-or-nothing approach. It means that as long as the operating costs of a mine are covered, the mine can produce minerals at their optimal capacity. Once the operating costs exceed the income of the mine, mining operations are ceased. To address this issue, all the operating costs required for mining operations should be measured before the mining project commences. When there is a possibility of changing investment costs in a mine (i.e., when the achieved income surpasses the estimated income), it is feasible to display more flexibility. These issues in mining raise challenges in the use of renewable energy. For example, around 70% of the steel in the world is produced in blast furnaces. This technology has built numerous plants in the last 10–20 years. Considering the long life of blast furnaces, using renewable energies in steel production before the life of these technologies ends is not economically justifiable [30]. Identifying ways to reduce CO2 or increase energy efficiency in this industry can be better than utilizing renewable energies [30]. For example, in the design and feasibility stage of two copper and nickel projects in Australia, it was predicted that the amount of CO_2 emitted by a solar-wind-battery-diesel generator (as a backup) hybrid system would be 220,000 tons less than that emitted by similar diesel-based systems [25]. The current technologies to diminish CO_2 are quite costly. Carrying out more investigations to detect effective ways of lessening costs can be a proper option for factories with blast furnaces. It may lead to the reduction of CO_2 emissions in the steel industry. Using renewable energy in the mining industry is practical and economically acceptable if the mine project is in the design phase or using renewable energy in the mine is evaluated through feasibility analysis. One of the existing obstacles to using renewable energy in mining sites is a lack of education for mining engineers. Some solutions to bridging this sector gap include holding classes on renewable energy by miners and mining companies, interacting with renewable energy supply companies, and providing mining engineers with training programs and reports.

4. Opportunities of renewable energy for the mining industry

Today, new energy production technologies, including renewable energy (like those used for generating energy through wind and solar power), are far cheaper than conventional technologies because the commonly used energies have much higher prices [31]. Using renewable energy in mining operations can also offer a good opportunity to reduce carbon emissions in mining operations. Furthermore, mine owners and companies would be less concerned about fuel price fluctuations. Renewable energy has other benefits for mining companies and governments, such as stimulating economic development, advancing technology in local communities, upgrading social permits for mining operations, and forming shared values.

4.1. Mining operations

Many mining activities are dependent on electric power. Most renewable energy sources that can provide electricity are produced by burning fossil fuels. On-grid mines have no control over the type of their electricity supply. Off-grid mining, supported by on-grid electricity supply systems, can benefit from renewable energies if necessary. Mining operations directly utilize fossil fuels for their energy supply in both on-grid and off-grid sites. Renewable energy can be used in these mining activities as an alternative to these energy sources that emit greenhouse gases (Fig. 2).

In the United States, fossil fuels are used to produce most of the metallic and non-metallic minerals in various mining operations. Compared to non-metallic minerals, the production of metals requires much more energy. In the metal sector, the iron and steel industries are the biggest energy consumers (about 70% of the energy). The alumina and aluminum industries were ranked second with 14% energy consumption [32]. For the production of non-metallic minerals, the highest energy consumption is observed in the cement industry, with 30% energy use, followed by the glass and lime industries, with 14% and 12% of energy consumption, respectively.

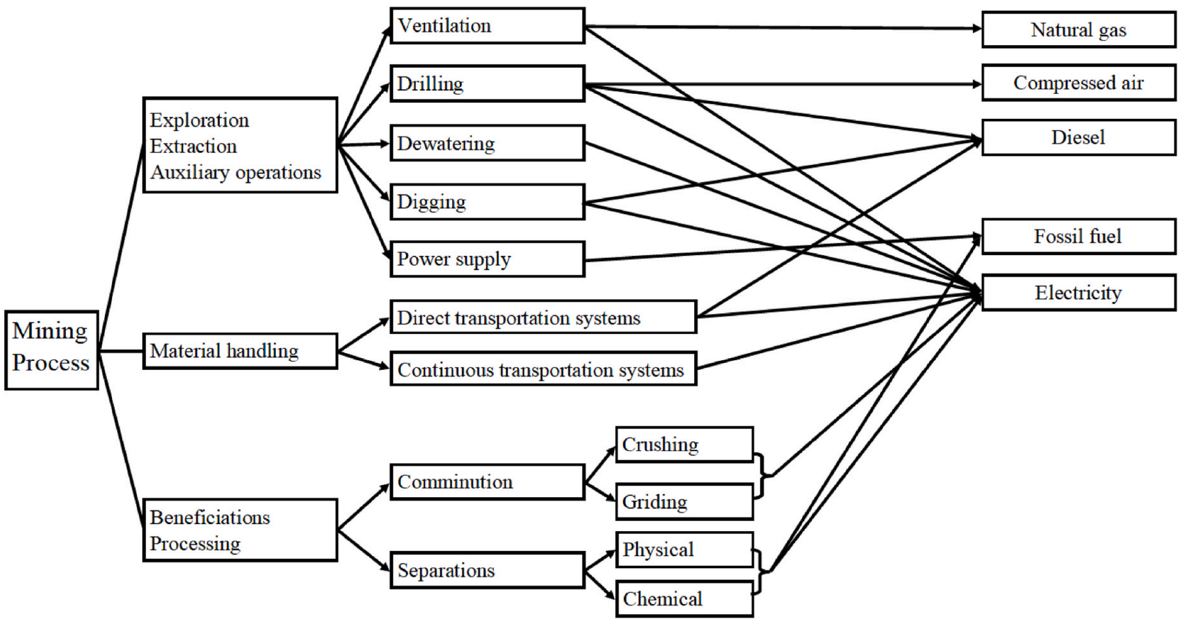

Fig. 2. Mining process and associated fuel sources.

In mining, most energy is used to provide heat in the processing and smelting stages. Fossil fuels, such as coal and natural gas, supply this energy. This indicates that making plans to reduce the dependence of this mining phase on fossil fuels and use renewable energies to provide the required heat for the processing stage can significantly decrease carbon emissions.

4.2. Response to market demand

Renewable energies are essential in altering heavy oil, diesel, and coal consumption patterns in electricity-dependent mining operations. For example, the crushing and grinding process is one of the energy-intensive activities in mining operations [29]. Studies have demonstrated that 15% of iron and 21% of gold mining energy is consumed in the crushing and grinding stages. Stone crushing and grinding is the only mining operation whose energy is exclusively supplied by electric power. Therefore, this mining activity can readily lend itself to renewable energy technology. Another part of mining whose energy is provided through electricity is the ventilation of underground mines. About 20% of the total energy needed for gold production in underground mines is consumed by mine ventilation. In general, 63% of mine electricity in the United States is supplied by off-grid sources. The energy resources used to produce this electricity are fossil fuels that can be replaced with renewable energy resources [33].

The mining industry can use off-grid electricity generated by renewable energies with on-grid electricity backup. In certain cases, companies can supply and sell their excess electricity to the grid and benefit from a good source of income. It can also make renewable energy (wind, solar, and geothermal energies) more attractive for mine owners and companies. Rio Tinto plans to build a 34 MW solar photovoltaic (PV) resource with a 12 MWh lithium-ion battery system for the Koodaideri mine (J 2020). This system provides about 65% of the electricity in mines during peak hours. Geothermal energy resources and wind power used to supply electricity to mines in New Guinea and Northern Canada, respectively, are other successful cases of renewable energy use (A 2016). Fig. 3 depicts a solar energy installation for a gold mine in Mali.

4.3. Fuel supply for equipment and transportation

Some activities, like ventilation and transportation, directly depend on fossil fuels in the mining process. Modifying the equipment in mines makes it feasible to replace fossil fuels with renewable energy for energy

Fig. 3. Solar installation at Fekola gold mine in Mali ('b2gold.com' 2023).

supply in some mining activities.

Transporting extracted stones (mineral transportation) is one of the highly energy-intensive mining activities. For instance, 10% of the energy consumed in iron and gold mining is allocated to transportation minerals [29]. If the mining industry is determined to lessen carbon emissions, it should devote special attention to this process and plan to use renewable energy resources as fuel for transportation. However, since diesel has always been a major energy source for many mining operations, including transporting minerals, integrating renewable energy resources as fuel into this process is quite challenging [34]. Some attempts have been made to use electricity, biodiesel (e.g., trucks with biodiesel engines), and hydrogen as alternatives to fossil fuels to transfer minerals. Nowadays, to follow diesel particulate emission standards, these new energies have received much more attention in underground mines than in surface mines with larger machines [35].

4.4. Substitution in mineral processing operations (alternatives to coal)

In some mining activities, fossil fuels are used as mineral processing materials. For example, coal and natural gas are currently basic raw materials in processing minerals, and substituting renewable energies for them poses big challenges. Some studies have observed that renewable energy, as an alternative to fossil fuels, can supply 20–30% of feedstocks demanded in processing operations [23]. In converting iron ore into steel, coal (coke) is the main raw material of blast furnaces, and 70% of the steel produced globally relies on coke. Manufacturing 1000 kg of raw steel entails consuming 780 kg of metallurgical coal (Iron and Works 2020). Coal and natural gas are also used for other purposes in steel production. For instance, natural gas combines water and heat to produce hydrogen and carbon monoxide required to convert iron ore to direct-reduced iron [36].

4.5. Creating opportunities for mining communities and a circular economy

The rapid growth of renewable technologies provides synergistic opportunities between the mining industry, local and national governments, and renewable technology. Most of these sectors depend on materials that are critical to productivity. In other words, some materials in some industries play a vital role in the raw material supply chain. In renewable energy technology, these materials include cobalt, lithium, nickel, and rare-earth metals. Replacing these materials with other metals is usually impossible or severely affects the efficiency of this technology [37].

The obstacle to supplying these materials for renewable energy technology is partly posed by political instability and environmental concerns for extracting these metals. Unstable countries have a significant share in producing these minerals; for example, 50% of cobalt in the world is mined by the Democratic Republic of Congo (Patterson 2018). Many mines are located in rural and agricultural communities. Sharing renewable energy with local communities can expand agricultural activities and enhance employment opportunities. Therefore, it would have a long-lasting impact on communities and raise social influences and political stability. These factors ultimately exert positive effects on sustainable development goals.

Reducing mining costs by lessening energy costs can elevate competitiveness and the economic attractiveness of mining communities and encourage mining companies to carry out mineral processing operations in host countries. It is vital and strategic for many mining countries to implement this strategy. One of the inhibiting factors for mineral processing in host countries is a lack of affordable and reliable energy. Many countries export the produced minerals to countries where energy costs are lower, and energy supplies are more reliable, making processing operations more cost-effective [38]. Hence, these countries are deprived of the added value processed materials produce.

4.6. Use of renewable energies in the mining industry and sustainable development

The concept of sustainable development is thoroughly discussed in other studies. "For more information, see Refs. [3,39–41]". Given that one of the main elements of sustainable development is to benefit from modern technologies , the bond between sustainable development and renewable energy is irrefutable. The use of renewable energy can directly or indirectly affect the environmental, social, and economic indicators of sustainable development (Fig. 4). In this section, the impacts of renewable energy on sustainable development indicators are explicated.

As for the environmental indicator of sustainable development, using renewable energy can directly reduce greenhouse gas emissions. Due to the high energy consumption in various mining operational stages, using this technology in each mineral extraction, transportation, processing, smelting, and refining process brings about significant improvements in the environmental conditions of mines. Integrating this technology into the mining industry can profoundly eliminate the concerns of environmentalists and promote the environmental conditions in the mining area. Moreover, this technology has great potential to prevent the emission of greenhouse gases. Therefore, it can hinder the increase of the Earth's global average temperature and halt climate change [42].

Concerning the social indicator, this technology raises local people's awareness in mining areas because it requires training. Through renewable energy technology, new jobs are also created in these areas. Moreover, reducing greenhouse gases and carbon dioxide in the mining areas due to renewable energy use boosts local people's health. Nonetheless, social acceptance is a significant barrier to implementing renewable energy. In other words, a huge challenge in this indicator is to make mining communities and local people accept the integration of this new technology into mining processes. Another challenge is establishing the necessary infrastructure at the local and academic levels to train people and familiarize them with this technology and its benefits. In effect, culture building at the community level is required to improve the acceptance by local people, mining companies, and mine owners. Another influential factor in renewable energy use is the political will of countries to provide essential resources, support this technology, and create necessary regulations to encourage companies and mine owners to incorporate this technology into the mining industry. The enactment of well-defined regulations by governments on purchasing the excess electricity of mines can be among other contributing factors to elevating the economic attractiveness of this technology for users.

Regarding the economic indicator, mines can earn money by selling surplus electricity generated by this technology. This technology can also create circular business by enhancing collaboration between mines and renewal technology companies. To be more precise, mines and

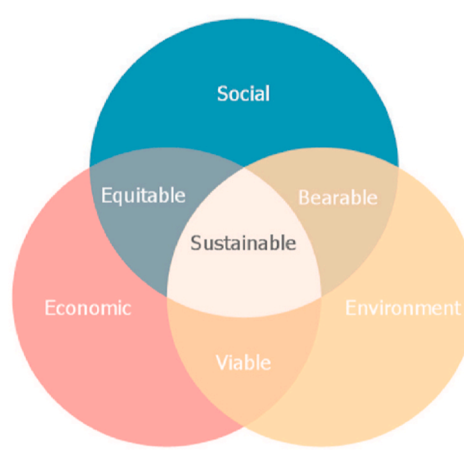

Fig. 4. Indicators of sustainable development [20].

factories supply necessary raw materials to these companies, and these companies install and operate this technology in mines. In addition, fuel price fluctuations substantially affect the cut-off grades of mines. The use of this technology can considerably regulate economic uncertainty in mining projects. On the negative side, one of the major barriers to employing this technology in the economic indicator is the high costs of establishing the infrastructure of renewable technologies. Mines planning to change their diesel equipment to electric equipment must accept all the costs of this diesel fuel-to-electric energy conversion. Furthermore, the maintenance costs of electric equipment are high. All renewable energy integration costs in mines should be predicted in the early feasibility stages. In this analysis, by considering the amounts of reserves, the value of minerals, and mine life, the capacity of current equipment and the best option for installing new equipment should be determined so that mining projects do not fail.

5. Determining appropriate strategies for renewable energy use in the mining industry

In this section, a strategic approach is presented to identify an appropriate strategy for the use of renewable energy in mining. To this end, the SWOT analysis was adopted to detect internal strategic factors (strengths and weaknesses) and external strategic factors (opportunities and threats). Four questions were constructed to identify internal and external strategic factors. Based on the responses to these questions, the SWOT matrix was formed. The Internal Factor Evaluation (IFE) and External Factor Evaluation (EFE) methods evaluated all the specified strategic factors in the next step. The strategic position for renewable energy use was then located in the Internal-External (IE) matrix. Eventually, the most appropriate strategies for using this new mining technology were introduced by considering the identified position. The SWOT framework employed to examine renewable energy use in mining is illustrated in Fig. 5.

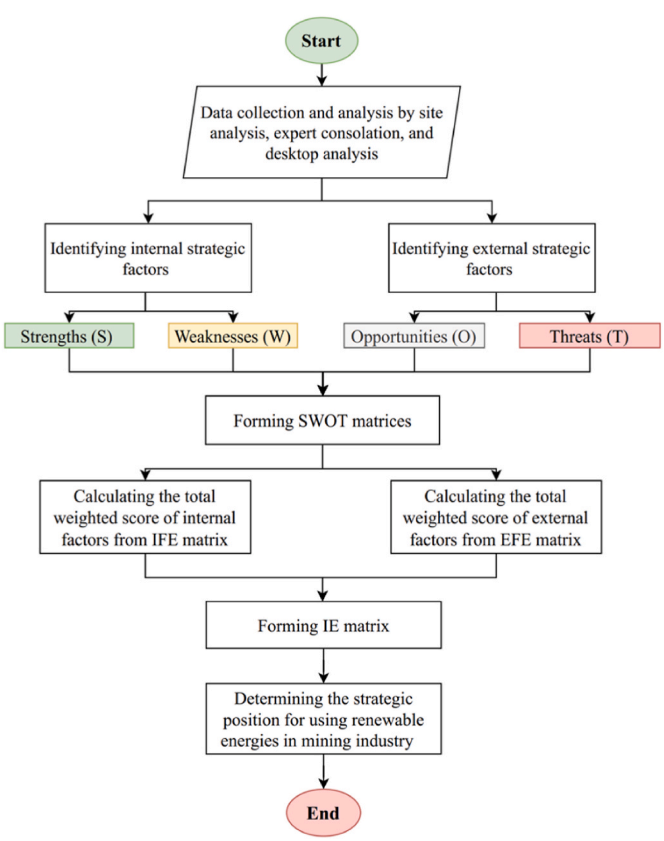

Fig. 5. SWOT framework for renewable energy use in mining.

As shown in Fig. 5, the SWOT analysis is at the core of selecting the right mining strategy for applying renewable energy technology. In general, desktop analysis, expert opinion, and site analysis are the most frequently used methods for identifying strategic factors [43]. The present study employed all three methods to identify influential internal and external strategic factors [44,45]. Site analysis was performed to determine external strategic factors that need to be evaluated on a case-by-case basis. Due to the very high volume of data, site analysis is very time-consuming. To reduce the required time, experts in this field were consulted. Considering the opinions of qualified experts with high experience and expertise would significantly impact the results. It should also be noted that the selected expert team in this study were direct and indirect stakeholders. The following questions were asked to detect influential strategic factors in the use of renewable energy in mining.

- Question 1: What are the strengths and advantages of using renewable energy in mining?

In SWOT analysis, this question helps identify the strengths of internal strategic factors whose implementation may benefit mining stakeholders. These strong points would positively contribute to implementing renewable energy use plans in mining.

- Question 2: What are the weaknesses of using renewable energy in mining?

This question helps identify internal strategic factors' weaknesses, whose implementation may benefit mining stakeholders in SWOT analysis. These weak points may pose obstacles to using renewable energy in mining.

- Question 3: What opportunities will be provided by using renewable energy in mining?

This question helps detect the opportunities of external strategic factors, which stakeholders may face by implementing the project in SWOT analysis.

- Question 4: What threats will be made by using renewable energy in mining?

This question helps identify the threats of external strategic factors stakeholders may face by performing the project in SWOT analysis.

The SWOT matrix was developed once the internal and external strategic factors were identified. This matrix was comprised of four parts: two parts for internal factors and two parts for external factors. As seen in Table 3, four major strategies were found based on the results obtained from this matrix. In the subsequent stages, these strategies can be used to incorporate renewable energy in mining and attain the

Table 3
Classification of strategies obtained from SWOT analysis [47].

ID	Strategy type	Strategy name	Definition
SO	Strength-opportunity strategy	Aggressive	maximum use of strengths to take advantage of opportunities
ST	Strength-threats strategy	Competitive	Maximum use of strengths to avoid potential threats and minimize them.
WO	Weakness-opportunity strategy	Conservative	Reducing weaknesses by exploiting the created opportunities
WT	Weakness-threats strategy	Defensive	avoiding damage caused by weaknesses against threats and external factors

following goals [46].

- Maximizing the use of strengths
- Hindering, eliminating, or minimizing the weaknesses
- Making the most of the opportunities created by the implementation of the project
- Avoiding possible threats caused by the execution of the project

5.1. Construction of IFE matrix

The IFE matrix is a strategy tool utilized to quantitatively evaluate internal strategic factors in the SWOT method. First, the relative weight of each internal strategic factor is calculated using IFE analysis. To do this, the importance of each internal factor is initially determined on a scale of 1–5 (1 = low importance and 5 = high importance) using experts' opinions. After that, the obtained value for each factor is normalized using Eq 1 [48]. The average score of each internal factor is then calculated as the relative weight of that factor.

$$W_{IF_i} = \frac{MVIF_i}{\sum_{i=1}^{n}(MVIF_i)} \quad (1)$$

where $MVIF_i$ is the average value of the importance of internal strategic factor i, and W_{IF_i} represents the relative weight of internal factor i. The weight of each factor reflects the importance of that factor relative to other internal factors, and the sum of these weight values is equal to 1. Based on Table 4, the experts assign 1 or 2 to each weak factor and 3 or 4 to each strong factor. The weight score of each factor is computed using Eq (2). Afterward, the overall weight of the internal factors is measured through Eq (3).

$$WS_{IF_i} = W_{IF_i} \times S_{IF_i} \quad (2)$$

$$TWS_{IF} = \sum_{i=1}^{n}(W_{IF_i} \times S_{IF_i}) \quad (3)$$

where WS_{IF_i}, S_{IF_i}, TWS_{IF} are the weight score of internal factor i, the score of internal factor i, and the weight score of all the internal factors. As the TWS_{IF} the value ranges from 1 to 4, and the average value is 2.5. When the TWS_{IF} value is less than 2.5; weaknesses outweigh strengths. Conversely, the TWS_{IF} value above 2.5 indicates the superiority of strengths over weaknesses [46].

5.2. 5-2- Construction of EFE matrix

The EFE matrix analyzes external strategic factors quantitatively. The calculation of EFE is similar to that of IFE. The only difference is that in EFE, external factors (e.g., opportunities and threats) are considered in the analysis. The relative weights of external factors are calculated using Eq (4).

$$W_{EF_j} = \frac{MVEF_j}{\sum_{j=1}^{n}(MVEF_j)} \quad (4)$$

where $MVEF_j$ is the average value of the importance of external strategic factor j, and W_{EF_j} represents the weight of external factor j. The weight of each factor shows the relative importance of that factor concerning other external factors. The sum of these weight values equals 1. Based on Table 4, experts give values 1 or 2 to each threat factor and 3 or 4 to each opportunity factor. The weight score of each factor is calculated via Eq (5). Then, Eq (6) is used to compute the overall weight of the internal factors.

$$WS_{EF_j} = W_{EF_j} \times S_{EF_j} \quad (5)$$

$$TWS_{EF} = \sum_{j=1}^{n}(W_{EF_j} \times S_{EF_j}) \quad (6)$$

where WS_{EF_j}, TWS_{EF}, and TWS_{EF} denote the weight score of external factor j, the score of external factor j, and the weight score of all the external factors, respectively. The TWS_{EF} value is in the range of 1–4. Thus, the average TWS_{EF} value is 2.5. The TWS_{EF} value less than 2.5 reveals that threats outweigh opportunities, whereas the TWS_{EF} value above 2.5 signifies the superiority of opportunities over threats.

Table 4
Description of scores for internal and external strategic factors (David and David 2016).

Score	Definition of internal factors	Definition of external factors
1	Major weakness	Major Threat
2	Minor weakness	Minor Threat
3	Minor strength	Minor opportunity
4	Major strength	Major opportunity

5.3. Construction of IE matrix

The IE matrix determines a suitable strategic position for renewable energy use in mines (Fig. 6). The IE matrix simultaneously assesses external and internal strategic factors. TWS_{IF} and TWS_{EF} are the horizontal and vertical axes of the IE matrix, respectively. As depicted in Fig. 6, the IE matrix is divided into four sections (blocks), each representing a strategic position. The characteristics of each section in Fig. 6 are described in Table 5.

5.4. Determination of appropriate strategy

The most significant external and internal factors were first detected to identify the proper strategy for integrating renewable energy in mines. Then, survey forms were designed and sent to 20 qualified experts. Among them, eight experts, whose characteristics are provided in Table 6, completed the forms. The experts' responses were analyzed using the SWOT method, and the influential strategic factors were identified. These factors are provided in Table 7.

After data collection from the experts, the SWOT matrix was constructed and the TWS_{IF} and TWS_{EF} values were calculated through Eqs (1)–(6). The results of the IEF and EFE matrices are reported in Table 8. Values in Table 8 were rounded to 3 decimal places.

As seen in Table 8, the integration of renewable energy in mining is located in Part II, i.e., the aggressive strategy. Therefore, all the strengths of this technology should be considered to take advantage of the opportunities created in the mining industry (Fig. 7).

Given the position of the strategy obtained from the SWOT analysis

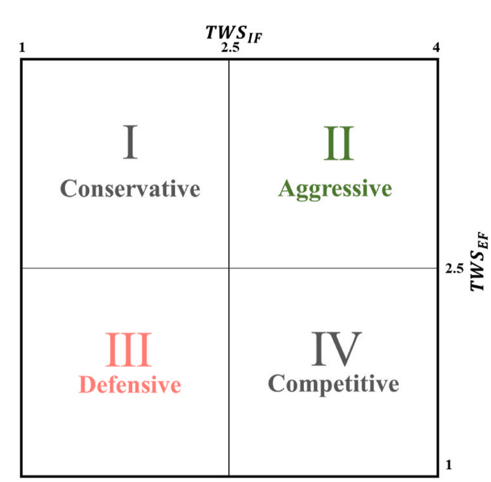

Fig. 6. IE matrix.

Table 5
Characteristics of strategic positions in IE matrix.

Block number	Strategic position	Description	Suitable strategy approach
I	Conservative	$TWS_{IF} < 2.5$ & $TWS_{EF} \geq 2.5$	Conservative strategies (WO)
II	Aggressive	$TWS_{IF} \geq 2.5$ & $TWS_{EF} \geq 2.5$	Aggressive strategies (SO)
III	Defensive	$TWS_{IF} < 2.5$ & $TWS_{EF} < 2.5$	Defensive strategies (WT)
IV	Competitive	$TWS_{IF} \geq 2.5$ & $TWS_{EF} < 2.5$	Competitive staratgies (ST)

Table 6
Characteristics of an expert team.

Skill	Education	Number of persons
Academic member	Ph.D	4
Private stakeholder	Ph.D	1
Academic students	Ph.D	1
	MS.c	2

for the inclusion of renewable energy in mining, the appropriate strategies for using this technology in the mining industry are presented in Table 9.

6. Discussion

Although there is great potential for using renewable energy in mines, the ratio of renewable energy consumption to the total energy consumption in the mining industry is still very low. This issue will be thoroughly explained in this section. By discussing the opportunities and obstacles of integrating renewable energy in mining sites with mining experts and stakeholders, effective and practical solutions for eliminating the challenges of this sector can be identified.

Integrating renewable energy into mining operations initiates a significant transformation in the energy consumption landscape within mines, transitioning away from fossil fuel reliance towards sustainable renewable sources. This pivotal shift has profound implications, generating noteworthy political and social changes at both local and international levels. For instance, adopting renewable energies displaces traditional job roles while simultaneously fostering new employment opportunities and skill sets associated with renewable energy technology. This transition is particularly evident in nations with robust mining sectors that exhibit substantial energy consumption. In these economies heavily reliant on mining activities, the recalibration of energy consumption patterns effectively reallocates substantial resources from the traditional fossil fuel supply chain to the burgeoning renewable energy supply chain. The economic feasibility of the domestic fossil fuel supply chain versus the import-dependent renewable energy supply chain varies from one country to another. In specific cases, it becomes evident that the domestic fossil fuel infrastructure may no longer be economically justifiable compared to the renewable energy alternative. In such scenarios, the determination of national governments and policymakers plays a pivotal role in driving the transition from fossil fuel dependency to the adoption of renewable energy, along with the essential development of the necessary infrastructure for these innovative technologies.

The primary obstacle hindering the widespread adoption of renewable energy lies in the misalignment between the commercial and income incentives of the mining industry and those of the renewable energy supply sector. When a mine's reserves are depleted, or mineral prices decrease, it signals the end of its productive life, often leading to closure. In stark contrast, investments in renewable energy and power purchase agreements typically operate on long-term horizons. Compounding this misalignment, there is a lack of synchronization between the lifespan of a mining operation and that of renewable energy equipment. A mining operation's profitability typically commences in the second year and can extend to five decades or more. Conversely, the profitability associated with renewable energy technology tends to have a much shorter horizon, often limited to around eight years. This discrepancy in the lifespans of mining assets and renewable energy equipment and the differing profit timelines between mining and renewable energy technology present formidable challenges when negotiating agreements between mining and renewable energy enterprises.

Companies, mine owners, and governments generally do not consider renewable energy use in the planning process of a mine. Research has shown that mining engineers responsible for designing a mine lack the skills and expertise to integrate renewable energy into mine designs. Due to a lack of knowledge about renewable energy and its combination with other energies, governments in many countries where mining accounts for a large portion of GDP usually limit the accessibility of mines to renewable energy and pose obstacles to its application in mines.

Table 7
Strategic factors identified for renewable energy use in mining.

Factor	Number	Definition
Strengths (S)	S1	Possibility of supplying energy and interacting with other technologies
	S2	High production capacity
	S3	Cost-effectiveness of renewable energy use
	S4	Minimization of economic uncertainty caused by fluctuations in fossil fuel prices
	S5	Elimination of greenhouse gas emission
	S6	Possibility of using and supporting the national electricity grid in case of a lack of energy supply
	S7	Alignment with sustainable development indicators
Weaknesses (W)	W1	Lack of management and support systems, including proper infrastructure, training programs, etc.
	W2	Lack of orientation programs for mine owners
	W3	Need for a large space.
	W4	High maintenance costs
	W5	Inability to reach a temperature of 550°
	W6	No guarantee of providing constant energy
Opportunities (O)	O1	Use of government-granted facilities for investment
	O2	High capacity of the mining industry for renewable energy use
	O3	Possibility of selling surplus production to the national electricity grid
	O4	Creation of new jobs in the mining industry
	O5	Possibility of using renewable energy in all stages of mining
	O6	Reduction of cut-off grade in mines by removing fossil fuel energy and using renewable energy
	O7	Possibility of creating a two-way economy between the mining and renewable energy industries
	O8	Pressure from the international community to reduce greenhouse gases
	O9	Transfer of new science and technologies to local communities
Threats (T)	T1	Lack of high-quality equipment due to sanctions and a lack of effective global interaction
	T2	Weakness of existing rules in renewable energy use
	T3	Obstacles posed by the local community and some relevant executive organizations
	T4	high initial investment costs
	T5	high bank facility interest rates
	T6	An imbalance between granted facilities and required investment
	T7	Dependence on the technology of foreign countries
	T8	limited after-sales services
	T9	Use of Hydrogen energy as an alternative to wind and solar energy
	T10	Challenges of changing machinery infrastructure for the replacement of diesel fuels with clean energy fuels
	T11	Rejection by miners due to high investment costs and traditional management attitudes
	T12	Lack of experts in the field of renewable energy

Table 8
Results of IFE and EFE matrices for renewable energy use in mining.

IFE Matrices					EFE Matrices				
Internal FC	W_{IF_i}	S_{IF_i}	WS_{IF_i}	TWS_{IF}	External FC	W_{EF_i}	S_{EF_i}	WS_{EF_i}	TWS_{EF}
S1	0.047	3	0.14	2.953	O1	0.028	3	0.083	2.681
S2	0.07	4	0.279		O2	0.056	4	0.222	
S3	0.116	4	0.465		O3	0.014	3	0.042	
S4	0.047	3	0.14		O4	0.042	4	0.167	
S5	0.093	4	0.372		O5	0.042	4	0.167	
S6	0.093	4	0.372		O6	0.069	4	0.278	
S7	0.14	4	0.558		O7	0.056	4	0.222	
W1	0.047	1	0.047		O8	0.069	4	0.278	
W2	0.07	2	0.14		O9	0.042	3	0.125	
W3	0.023	1	0.023		T1	0.042	2	0.083	
W4	0.093	1	0.093		T2	0.056	2	0.111	
W5	0.07	2	0.14		T3	0.056	2	0.111	
W6	0.093	2	0.186		T4	0.042	2	0.083	
					T5	0.069	2	0.139	
					T6	0.028	1	0.028	
					T7	0.069	2	0.139	
					T8	0.069	2	0.139	
					T9	0.028	2	0.056	
					T10	0.042	1	0.042	
					T11	0.042	2	0.083	
					T12	0.042	2	0.083	

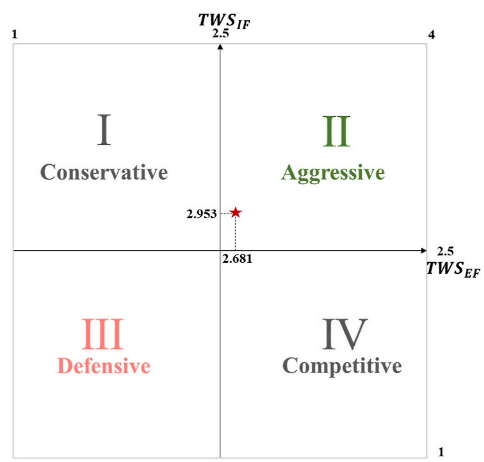

Fig. 7. Results of strategic evaluation of renewable energy use in mining via SWOT method.

It is possible to mount this equipment in mining areas; however, it presents challenges to using this technology. Another barrier to using this technology in mines is the availability of land to install renewable energy equipment. Furthermore, mining engineers have no or little knowledge about suitable land cover types and proper locations for installing solar PV and wind turbines in mining sites.

Many mining companies enter into electricity supply and purchase contracts without giving due consideration to the misalignment of incentives related to renewable energy adoption. Conversely, smaller and medium-sized mining enterprises tend to approach investments in this realm with caution due to concerns about the inflexibility of renewable energy solutions. Implementing supportive structures for surplus electricity purchase, grounded in a well-defined framework, represents an effective policy avenue for incentivizing companies to embrace renewable energy technology. Facilitating robust interactions between the energy and mineral sectors to facilitate these contractual agreements, along with host governments actively engaging in purchasing excess electricity, presents a compelling opportunity to invigorate local economies, bolster tax revenues, reduce greenhouse gas emissions, and ultimately foster the widespread adoption of renewable energy technology within the mining industry.

To enhance renewable energy use in mines, especially in small and medium-scale mines, it is essential to integrate this technology into the mining industry, access the existing tools, and provide training in the feasibility stage. Renewable energy development companies, skilled engineers, research institutes, and independent individuals can provide these capacities and facilities. Universities also play a significant role in transferring this knowledge.

Addressing the multifaceted challenges and barriers associated with integrating renewable energy within the mining sector necessitates further exploration and concerted efforts. The mining industry, in particular, seeks cost-effective solutions that can seamlessly incorporate renewable energy sources with varying capacities into mining operations. Furthermore, there is a growing demand for renewable energy technologies capable of producing high-temperature heat, offering more economical energy storage options, and providing extended storage capabilities. Research and development initiatives are indispensable in this context to facilitate the transition from diesel-powered machinery to electric equipment within mines and enhance the energy efficiency of material transportation processes. It is worth noting that advancements in renewable energy research and development can extend their benefits beyond mining, positively impacting other sectors such as food processing and the chemical industry. One prominent challenge is securing the necessary resources and capital for the widespread implementation and expansion of renewable energy solutions in mining operations. Many mines are situated close to local communities, offering a unique opportunity for collaboration. Joint energy systems that serve the mining site and the neighboring community could be a promising avenue, particularly for small- and medium-scale mining enterprises. Such partnerships can provide the community with an additional and reliable energy source, provided that logistical costs, such as wiring, are minimized. Effective policies and regulations play a pivotal role in fostering symbiotic relationships between mining enterprises and the communities in which they operate. Establishing robust interactions between the mining industry and host governments is essential for developing more efficient regulations, ultimately promoting the successful integration of renewable energy technologies within mining operations.

Like mine-community interactions, government policies and regulations are fundamental in many approaches to renewable energy use in mines. These interactions are increasing globally to augment cooperation and the use of these resources. Nonetheless, these efforts can be hindered locally, especially in countries rich in mineral resources. In most of these countries, regulations for using renewable energy have not been established. Some of these countries have recently reviewed and

Table 9
Suitable strategies for using renewable energy in mining using results of SWOT analysis.

Strength (S)	Opportunities (O)	Strategies based on (SO) approach
• S1: Possibility of supplying energy and interacting with other technologies • S7: Alignment with sustainable development indicators	• O4: Creation of new jobs in the mining industry • O7: Possibility of creating a two-way economy between the mining and renewable energy industries • O9: Transfer of new science and technologies to local communities	• SO1: Creating the necessary platform for training specialists and updating the educational system of universities to enhance knowledge on the benefits of renewable energy use
• S5: Elimination of greenhouse gas emission • S7: Alignment with sustainable development indicators	• O1: Use of government-granted facilities for investment • O8: Pressure from the international community to reduce greenhouse gases	• SO2: Modifying management plans and setting effective policies; Granting long-term facilities with low-interest rates and providing tax exemptions for the use of this technology
• S3: Cost-effectiveness of renewable energy use • S4: Minimization of economic uncertainty caused by fluctuations in fossil fuel prices • S6: Possibility of using and supporting the national electricity grid in case of a lack of energy supply	• O3: Possibility of selling surplus production to the national electricity grid • O6: Reduction of cut-off grade in mines by removing fossil fuel energy and using renewable energy	• SO3: Developing new regulations on the purchase of surplus energy by the government to support renewable energy producers; making necessary modifications in the mining laws and regulations of countries.
• S2: High production capacity • S6: Possibility of using and supporting the national electricity grid in case of a lack of energy supply	• O2: High capacity of the mining industry for renewable energy use • O5: Possibility of using renewable energy in all stages of mining	• SO4: Using all available capacities in mines to construct inclusive mining sites (operating all mining processes from extraction to processing) to make maximum use of this technology and meet the demands of consumers in case of a lack of energy.
• S2: High production capacity • S4: Minimization of economic uncertainty caused by fluctuations in fossil fuel prices • S5: Elimination of greenhouse gas emission • S7: Alignment with sustainable development indicators	• O2: High capacity of the mining industry for renewable energy use • O4: Creation of new jobs in the mining industry • O5: Possibility of using renewable energy in all stages of mining • O6: Reduction of cut-off grade in mines by removing fossil fuel energy and using renewable energy • O9: Transfer of new science and technologies to local communities	• SO5: Changing attitudes in macro-policy of mining in countries and creating new regulations to replace fossil energy with renewable energy in mining. • SO6: Developing essential regulations to make renewable energy use obligatory for miners in the medium term

revised the regulations on integrating this technology into mining operations.

Renewable energy can support production by reducing energy consumption and costs. In many developing countries, government policies force companies to supply a certain percentage of intermediate goods from domestic sources. Countries can also benefit from the opportunities provided by renewable energy technology for the production of goods. Joint efforts between the mining industry, the energy industry, international organizations, and host governments are necessary to create efficient policies and regulations on applying this technology.

Governments can take several measures to facilitate using renewable energy for mines, including tax exemptions, the provision of loans with low-interest rates, and the construction of required infrastructure for the guaranteed purchase of surplus electricity. These measures provide desirable conditions for companies and mine owners and encourage them to use renewable energies.

A strategic examination of the utilization of renewable energy within the mining sector reveals a dual potential for both internal and external benefits. Leveraging the inherent strengths of renewable energy technology in mining operations presents external opportunities that hold significant promise.

Recognizing these strengths, mining stakeholders can proactively harness the potential opportunities renewable energy adoption offers. To maximize these strengths and fully exploit the associated opportunities, the following strategic recommendations are proposed.

1. **Establishing a Knowledge Platform:** Create a robust educational foundation by establishing platforms for training specialists and updating university curricula to disseminate knowledge about the advantages of renewable energy utilization within the mining sector.
2. **Adapt Management and Policy:** Modify existing management plans and formulate appropriate policies that incentivize and facilitate the integration of renewable energy technology in mining operations.
3. **Financial Support:** Provide long-term financial facilities with favorable interest rates and offer tax exemptions to encourage the seamless incorporation of renewable energy solutions into mining activities.
4. **Government Energy Procurement Regulations:** Institute new regulations governing governments' purchase of surplus energy, thereby providing crucial support to renewable energy producers and fostering a conducive environment for their growth.
5. **Integrated Mining Sites:** Harness the full potential of mining sites by optimizing their capacity and transitioning toward inclusive mining sites that encompass all mining activities from extraction to processing. This approach ensures maximum utilization of renewable energy technology and helps meet consumer energy needs, especially in energy scarcity.
6. **Revise Macroeconomic Policies:** Initiate a shift in the macro-policy landscape of mining within countries by implementing new regulations to replace fossil fuel-based energy with renewable energy in mining operations. Consider making using renewable energy in mines a mandatory requirement in the medium term.

By strategically implementing these recommendations, the mining industry can tap into the inherent strengths of renewable energy technology, capitalize on external opportunities, and contribute to a more sustainable and environmentally conscious future.

7. Conclusion

Renewable energy is a paramount challenge and opportunity in the contemporary energy landscape. The convergence of escalating global population growth and industrialization across numerous nations has amplified the demand for essential raw materials, notably minerals. It is worth noting that mining operations are among the primary contributors to greenhouse gas emissions, particularly in underdeveloped and developing regions, primarily driven by the extensive use of fossil fuels. Consequently, renewable energy emerges as a pivotal alternative to curb fossil fuel dependence within mining practices. This article embarks on a comprehensive exploration of diverse facets related to integrating renewable energy solutions in mining operations. Using renewable energy brings forth multifaceted advantages that elevate the sustainability quotient within the mining sector.

Using renewable energy sources within mining operations offers a spectrum of compelling advantages. These encompass a notable reduction in environmental pollution, the enhancement of mining-related knowledge, the generation of new employment opportunities, the promotion of circular economic models, the mitigation of greenhouse gas emissions, the dissemination of novel scientific and technological advancements to local communities, and the prospect of surplus energy production being channeled into the national power grid. However, the integration of renewable energy in mining confronts a host of formidable challenges. These encompass a lack of awareness among mine owners regarding the advantages of renewable energy adoption, resistance from traditional management practices entrenched in the mining industry, substantial initial investment costs, ambiguous legal frameworks governing renewable energy application in mining, uncertainties surrounding energy supply guarantees for mining operations, a scarcity of specialized labor, elevated maintenance expenses, infrastructure adaptation requirements, substantial bank charges, and the imperative need for expansive spatial considerations. These challenges collectively shape the landscape of renewable energy integration within mining and necessitate strategic planning and innovative solutions to surmount them.

In the subsequent analysis, the SWOT framework, a widely employed strategic management tool, was employed to discern the inherent weaknesses, strengths, opportunities, and threats associated with adopting renewable energy within mining operations. Subsequently, expert insights were leveraged using the SWOT framework to derive a strategic perspective on integrating renewable energy within the mining sector. The outcomes of this SWOT analysis underscore the imperative for mining enterprises to leverage their capabilities and embrace renewable energy solutions to capitalize on the opportunities that arise from their implementation fully. Consequently, it is becoming increasingly evident that mining-dependent nations will need to embrace this transformative technology within their mining operations shortly. Furthermore, the utilization of renewable energy within mining operations aligns harmoniously with sustainable development objectives and is poised to play a pivotal role in ensuring the long-term sustainability of mining practices.

Credit author statement

Mahdi Pouresmaieli: Conceptualization, Methodology, Formal analysis, Writing – original draft Mohammad Ataei.: Methodology, Writing – original draft, Writing – review & editing, Supervision, Ali Nouri Qarahasanlou., Formal analysis, Writing – original draft, Writing – review & editing, Abbas Barabady, Writing - Review & Editin, Supervision.

Declaration of competing interest

The authors declare that they have no known competing conflict of interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Further reading

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