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Utilization of solar and wind power-generation systems in the mining industry: recent trends and future prospects

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Abstract

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Keywords

Mining industry, Renewable energy, Carbon neutrality, Sustainable mining

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Abstract

In recent years, the mining industry has faced many challenges, such as rising demand, fluctuating energy prices, increasing energy consumption due to declining ore grades, and environmental concerns. According to the Paris Agreement, countries worldwide must focus on decarbonizing their economies to mitigate the global average surface temperature growth. This paper reviews how renewable energy, specifically photovoltaic and wind power systems, can be used to tackle some of these challenges. Operating mines globally, like the South Deep gold mine in South Africa and the MA'ADEN Alumina Refinery in Saudi Arabia, and abandoned mines, such as former coal mines in the USA, Poland, and Germany, repurposed with PV systems, are examples of using renewable energy in the mining sector. Wind power systems were installed in various mines like Seriti Resources mines in South Africa and the Agnew gold mine in Australia. In addition, former coal mines in Scotland, South Africa, and Serbia have changed into wind farms. Integrating renewable energy sources into the mining industry not only mitigates greenhouse gas emissions but also offers economic benefits such as long-term cost savings and energy independence for the mining industry. By using renewable energy, mining companies can prove their commitment to sustainability and adapt to the increasing global attention to a low-carbon future.

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1. Introduction

Mining is an energy-intensive industry and a crucial resource supplier for industrial sectors like production, construction, transport and haulage, and energy. The increasing need for minerals, along with the falling ore grades, is contributing to the growing energy consumption of the mining industry, which could potentially elevate its already substantial greenhouse gas emissions [1]. According to the World Energy Outlook 2018 of the International Energy Agency (IEA), renewable energy generation in global power production is projected to increase from 25% in 2017 to 40% by 2040 [2]. The worldwide energy industry is experiencing a consistent rise in electricity demand, largely driven by the rapidly expanding economy. In late 2019, the European Commission (EC) introduced the European Green Deal, detailing key regulation measures to achieve zero net greenhouse gas emissions by 2050 [3]. Moreover, the global focus on renewable energy resources is rising because of the increasing need for sustainable energy sources, the importance of energy security, and various ecological issues linked to the generation and consumption of other energy sources. Recently, numerous researchers have been developing cost-effective and ecological renewable energy advancements, which are finding extensive applications in industries [4]. A mix of different renewable energy technologies is crucial to address the energy-related challenges of the mining industry [1]. Photovoltaic (PV) systems are utilized in several active mines in Australia [5,6], South Africa [7–9], Madagascar [10], Saudi Arabia [11,12], and Chile [13]. PV systems are utilized in several abandoned mines, showing the successful

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implementation of renewable energy technology in promoting other industries on previously unused lands. Examples of such applications include the USA [14], China [15], Finland [16], Poland [17,18], North Macedonia [19], and the Inden opencast mine in Germany [20], all of which have effectively repurposed the land following mine closures. Moreover, operating mines such as Sibanye-Stillwater [21] and Seriti Resources mines in South Africa [22], the Port Gregory garnet mine in Australia [23], and the Sierra Gorda Copper Mine in Chile [24] have implemented wind power generation systems. Also, substantial wind farms have been installed at abandoned mines. Examples include the wind farms at the Drumduff opencast coal mine in Scotland [25], the Kostolac wind farm in Serbia [26], and the Breunsdorf wind farm in Germany [27].

From an environmental perspective, utilizing renewable energy can directly decrease greenhouse gas emissions [4]. Socially, renewable energy technology generates new job opportunities in these regions [28]. In addition, reducing greenhouse gases and carbon dioxide levels in mining areas due to renewable energy use improves the health of local communities [29]. Economically, mines can profit by selling excess electricity generated through this technology. Furthermore, it fosters a circular economy by promoting collaboration between mining operations and renewable energy companies [30].

This review shows that using solar and wind power generating systems in mining has served several purposes. These systems have not only solved the energy supply problem but have also effectively reduced greenhouse gas emissions in mining. In the case of abandoned mines, these renewable energy systems have also played a crucial role in prompting replacement industries that can utilize the potential of these depleted mining sites. Considering the beneficial environmental and economic effects of solar and wind energy systems in the mining sector, their accession is anticipated to increase.

Abbreviations

EC	the European Commission
IEA	International Energy Agency
MLR	Mined Land Reclamation
PV	Photovoltaic

Units

GWh	gigawatt-hour
ha	hectare
kW	kilowatt
MW	megawatt
MWh	megawatt-hour
W	watt

2. Materials and methods

Basic principles of solar and wind power generation have been discussed in previous studies [31–35]. Available resources and land, along with geographical and climatic conditions, have a major impact on choosing the renewable energy generation method for each case [36]. Suitable for areas with high solar irradiance, typically found in regions with long, sunny days and minimal cloud cover [37]. Locations with consistent and strong wind patterns, such as coastal areas, open plains, and high-altitude regions, often provide optimal conditions for wind farms [35]. Located in remote areas and highlands with minimum obstacles and abundant land, mines are a proper location for installing renewable energy power plants.

This study considered the recent trends in the implementation of photovoltaic and wind energy-generating technologies in both active and abandoned mines and compared them with previous renewable energy implementation conditions in the mining industry. The data were collected through other scientific articles, mining news journals, and reports. Furthermore, the study period was 2018–2025, and comparing them to before 2017 status [4]. Implementing and installing solar and wind power plants are considered land reclamation methods after mine closure or co-locating them with other renewable energy systems and active mining sites [38].

2.1. Mined lands reclamation methods

Mining operations are temporary land-use activities, the duration of which depends on the deposits and economic viability of mine sites [39]. Implementing a mined land reclamation (MLR) strategy for closing a mine presents a complicated decision-making challenge, considering the need to examine the impact of both certain and uncertain factors [40]. Plans have been developed for land restoration and management of permanent changes, with sustainable reclamation being considered [41]. Some land reclamation methods are soil amendments and ecological restoration for agriculture and forestry pasture, hay land, leisure areas, wildlife habitat, bricks and blocks making, fish farms, swimming pools, and large-scale solar and wind power generation plants [38,39,42]. Utilizing mined land areas for renewable energy facilities offers a significant benefit. The incorporation of renewable technologies with mining can significantly eliminate environmental concerns and enhance the ecological status in the mining area. Along with repurposing areas for energy generation, it addresses the mined land's ecological impacts. The adoption of renewable energy in the mining industry directly or indirectly impacts the environmental, social, and economic measures of sustainability [30,33].

2.2. Literature review

Due to increased environmental threats and global disasters resulting from climate change, attention is on the shift to utilize clean energy to reduce greenhouse gas emissions. In this situation, it becomes crucial to concentrate on strategies to limit the quantity of greenhouse gas emissions and environmental damages [43]. In mining operations, a significant amount of carbon emissions is produced from the consumption of electricity and transportation. Therefore, mines must use renewable energy technologies and implement autonomous driving to reduce carbon emissions [29]. The mining industry needs to adopt sustainable practices to minimize mining operations' economic, social, and environmental impacts, not just during the operational phase but also after the mines have been closed [44]. Implementation of renewable energy systems in the mines has been divided into active and abandoned mines and assessed separately.

2.2.1. Photovoltaic systems in active mines

Photovoltaic systems have been utilized in several active mines all over the world, for instance, in Africa, Asia, Australia, and South America. A brief description of solar energy projects and installations in various countries follows:

In Africa, three planned projects were installed in South Africa. A significant 100 MW solar plant was installed at the Mogalakwena platinum mine in 2023 [8,45]. The Khanyisa project in the South Deep underground gold mine involves a 50 MW solar facility, with plans to extend it by adding a 10 MW solar plant in the second phase. This 50 MW project reduces the mine's carbon emission by around 110,000 tonnes annually [7,46]. In addition, a 30 MW photovoltaic facility was installed at the Harmony gold mine in 2023 to add an extra 137 MW in the second phase of the Harmony mine solar plant by 2025. By installing the first phase, the Harmony mine mitigates 65,000 tonnes of carbon emissions annually [9,47].

In the southeast of Madagascar, QIT Madagascar Minerals, a titanium and zircon mine, has installed an 8 MW solar photovoltaic power plant to power the mine and decrease its CO_2 emissions by 26,000 tonnes yearly. In its second phase, an 8 MW solar power system was set up, following the installation of a 12 MW capacity wind farm in 2023. These two renewable energy plants have a total capacity of 20 MW and are connected with an 8.25 MWh battery storage system [10,48].

In Asia, Saudi Arabia, the MA'ADEN's Alumina refinery is building the largest solar processing heat plant in the world with 1500 MW capacity and will reduce MA'ADEN's CO_2 emissions by more than 600,000 tonnes per year [11]. In addition, The Mansourah and Massarah gold mine installed a 44 MW solar plant in the northeast of Jeddah in Saudi Arabia [12,49].

In Chile, in South America, for the first time, Angelo American built a pilot photovoltaic plant with 87 kW capacity over the Los Bronces copper mine's tailings pond in 2019. This project reduces the mine's CO_2 emissions by 58 tonnes annually [13].

The Mount Keith nickel mines in Australia installed a total of 38.1 MW solar power generation system in two parts, including a 27.4 MW solar plant at Mount Keith, a 10.7 MW solar plant, and a 10.1 MW battery storage system at Leinster. It is estimated that the mine's CO_2 emission decreases by about 54,000 tonnes per year [6].

2.2.2. Photovoltaic systems in abandoned mines

Several documented cases of solar system installations at abandoned mines in Asia, Europe, and North America exist.

In Asian countries, in 2018 China, a 70 MW floating solar power plant was installed, which covered more than 63 ha of the Huainan subsidence coal mining area and decreased carbon dioxide emissions by 150,000 tonnes per year [15,50]. Up to this point, solar plants with a capacity exceeding 150 MW have been established in the subsidence lake at the Huainan coal mining region [51].

In the European countries, Poland, with two significant projects in Konin and Adamów coal mines, made great investments in renewable energy. The Konin project was Poland's first large-scale renewable energy plant with solar and wind power generation in 2023, with a 193 MW solar plant and a 19.2 MW wind power generation system [17]. Adamów is a former lignite mine that was transformed into a 70 MW solar power plant, which reduced CO_2 emissions by 56,700 tonnes annually [18]. In Germany, a 170 MW photovoltaic plant was built on an abandoned lignite open-cast mine in Klettwitz, part of the Lausitz energy park with

300 MW capacity. The Inden PV system was connected to a battery storage system with up to 9.6 MWh capacity [20,52]. Finland also built a 75 MW solar facility in the Hitura mine in Nivala and the Callio mine in Pyhajarvi. The project reduced CO_2 emissions by 5885 tonnes per year [16]. By 2030, North Macedonia goals to generate 38 percent of its electricity from renewable sources. To this end, a 10 MW solar power plant has been constructed in the exhausted EMS lignite coal mine. This PV system reduced 44,000 tonnes of CO_2 annually [19,53].

The Martiki coal mine, located between Kentucky and West Virginia in the US, constructed a 100 MW solar plant to reduce carbon emissions in North America [14].

2.2.3. *Overlook of photovoltaic systems utilization in mines*

The use of photovoltaic systems in both operating and abandoned mines is shown in Table 1. The MA'ADEN plant in Saudi Arabia, being the largest with a capacity of 1500 MW, underscored the significance of reducing greenhouse gas emissions in the mining sector, even in countries with abundant oil resources. The utilization of solar systems in developing countries such as Poland, North Macedonia, and Madagascar underlined the importance of environmental considerations in reducing CO_2 emissions and fuel costs. In addition, successful implementations of floating PV systems in the mining industry have been observed in locations such as the Los Bronces tailings pond and the collapsed coal mine in Hainan, China. These cases highlighted the growing interest in floating solar energy systems due to their higher efficiency [54,55]. Moreover, there was a shift towards utilizing hybrid systems that combine PV systems with wind power generation and battery storage systems. Integrating both solar and wind sources enhanced energy reliability, making the combined system more cost-effective. The strengths of one energy system could compensate for the weaknesses of the other, contributing to improved overall efficiency of the system [56].

2.2.4. *Wind power-generation systems in active mines*

Several documented cases of wind power systems were utilized at active mines in Africa, Australia, and South America. For African countries, in Zambia, a 430 MW project was planned to be installed. It consisted of a 230 MW solar plant and a 200 MW wind facility to generate electricity for FQM's mining projects at Kansanshi copper-gold mine in Solwezi and Sentinel copper mine in Kalumbila [57,58]. In South Africa, the coal mining corporation Seriti Resources will install a 155 MW wind energy system, which is part of a 900 MW renewable energy facility. This project connected a 750 MW wind energy installation with a 150 MW solar plant [22,59]. In South Africa, another 89 MW wind power generation system will be installed in the Sibanye-Stillwater mines by 2025 [21].

In Australia, two mining companies had installed wind turbines. The Agnew underground gold mine in western Australia utilized a hybrid power system in 2021 and reduced the mine's carbon emissions by 40,000 tonnes of CO_2 per year. It comprises four main components, including a 13 MW battery energy storage system, a standalone 21 MW gas/diesel

Table 1. Photovoltaic systems utilized in the mining industry.

Site type	Mine name	Country	Capacity	Remarks
Operating mine	Mount Keith	Australia	38.1 MW	A 27.4 MW PV system at Mount Keith. A 10.7 MW PV system and a 10.1 MW battery storage at Leinster.
	South Deep	South Africa	50 MW	A 10 MW solar plant will be extended.
	Mogalakwena	South Africa	100 MW	
	Harmony	South Africa	30 MW	A 137 MW solar plant will be extended.
	QIT	Madagascar	8 MW	Extended with a 12 MW Wind farm. Connected to an 8.25 MWh battery storage system.
	Mansourah and Massarah	Saudi Arabia	44 MW	Hybrid with engine technology and solar energy.
	MA'ADEN	Saudi Arabia	1500 MW	A solar thermal plant to refine bauxite ore.
	Los Bronces	Chile	86 kW	Floating PV system.
Abandoned mine	Martiki	USA	100 MW	
	Hitura and Callio mines	Finland	75 MW	Hybrid with a 7.5 MW battery energy storage.
	Inden	Germany	170 MW	Part of a 300 MW PV system. Hybrid with a 9.6 MWh battery storage system.
	Huainan	China	150 MW	Floating PV system.
	Konin	Poland	193 MW	Hybrid with a 19.2 MW wind power system.
	Adamów	Poland	70 MW	
	EMS	North Macedonia	10 MW	

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Fig. 1. The aerial view of the Agnew gold mine's wind turbines and PV system facilities [61].

engine power plant, a 4 MW solar farm with 10,710 panels, and an 18 MW wind farm powered by five 110 m wind turbines [5,60]. The aerial view of the wind turbines and PV system facilities is shown in Figure 1.

Since 2020, the Port Gregory garnet mine located in Western Australia derived 70% of its power from a hybrid power facility, which includes a 2.5 MW wind facility (set up with reused wind turbines), a 1.1 MW PV plant, and a 2 MW battery storage system [23].

In South America, the Sierra Gorda mine in Chile had been operating 100% on electricity from renewable energy sources, including solar, wind (56 turbines with 112 MW total nominal power), hydroelectric, and battery energy in 2023. This transition signified a reduction of CO_2 emissions by one million tonnes annually [24].

2.2.5. Wind power-generation systems in abandoned mines

In Europe, Germany, Scotland, and Serbia had repurposed abandoned mines by installing wind turbines, employing them both as a reclamation method and energy generation systems.

In Germany, the Breunsdorf wind farm project was built on the inner dump of the United Schleenhain opencast mine with a capacity of 90 MW in 2024, and the electricity is used for producing 4100 tonnes of green hydrogen [27]. In Serbia, the 66 MW Kostolac site was situated on previously used coal mining land [26]. Scotland also repurposed the Drumduff coal mine into a 6 MW wind power project [25].

2.2.6. Overlook of wind power-generation systems utilization in mines

The list of wind power generation systems in active and abandoned mining regions is summarized in Table 2. According to this table, the Kansanshi and Sentinel mines in Zambia have the highest capacity among the operating mines listed, with a capacity of 200 MW. This facility operates as a hybrid system with a 230 MW solar plant. However, it is worth noting that Seriti Resources in South Africa plans to build a 900 MW renewable energy power plant. In the initial phase, Seriti Resources will build a 155 MW wind power plant in Mpumalanga. Like the photovoltaic systems mentioned above, the wind power plants were designed as hybrid systems with solar plants and battery energy storage. An energy storage-equipped power system could offer manageable and consistent power production, ensuring load dependability [62]. Therefore, in the absence of wind to rotate the turbines or no solar radiation available (for instance, during nighttime), batteries supply the electricity needed for mining operations [63].

3. Discussion

Previous research has shown various possibilities for using renewable energies in the mining

Table 2. Wind power generation systems utilized in the mining industry.

Site type	Mine name	Country	Capacity	Remark
Operating mine	Port Gregory	Australia	2.5 MW	Assembled reused wind turbines. Hybrid with a 1.1 MW solar farm and 2 MW battery storage.
	Sierra Gorda	Chile	112 MW	Hybrid with solar, hydroelectric, and battery energy storage.
	Sibanye-Stillwater	South Africa	89 MW	
	Seriti resources	South Africa	155 MW	The first phase of a 900 MW renewable energy project.
	Kansanshi and Sentinel mines	Zambia	200 MW	Hybrid with a 230 MW solar farm.
	Agnew	Australia	18 MW	Hybrid with a 4 MW solar plant and a 13 MW battery energy storage.
Abandoned mine	Drumduff	Scotland	6 MW	
	Kostolac	Serbia	66 MW	
	United Schleenhain	Germany	90 MW	

industry. Efforts to integrate renewables should be aligned with the identified energy-demanding unit operations, which include material supplying, crushing, heat processing, and refining, to ensure that the integration of renewables delivers the desired results in the mining industry. Reducing mining expenses through energy cost reduction can enhance a country's competitive edge, leading to more domestic mineral processing operations, like MA'ADEN's Alumina Refinery in Saudi Arabia [1,11].

Comparing this study with a similar report from 2017 [4], it was clear that renewable energy in mining had been mainly used in industrialized countries. There was a recent shift as developing countries in Eastern Europe, Asia, and the Middle East also use PV and wind power generation systems in their mining projects.

The data in Table 3 shows that before 2017, the implementation of solar power generating systems in the mining industry had a capacity of 1–10.6 MW for operating mines. Among the closed mines, the Meuro mine had the highest capacity for energy generation at 166 MW, while the other plants had less than 2 MW of capacity. However, after 2018, the capacity of solar plants had considerably grown due to carbon neutrality regulations and significant technological advances. This growth could be seen in solar power plants, which now range in capacity from 8 MW in Madagascar to 1500 MW in Saudi Arabia. The situation was similar for abandoned mines, where the capacity of PV systems ranged from 10 MW to 193 MW. Also, it was noteworthy that several photovoltaic plants had become hybrid, integrating with other renewable energy sources such as wind farms or battery storage systems. Examples include the Kansanshi and Sentinel mines in Zambia, the Agnew gold mine in Australia, and the QIT mine in Madagascar. As the mining industry increasingly recognizes the benefits of floating PV systems, they are expected to utilize renewable energy. In addition, floating PV systems will be prompted as a more sustainable energy landscape for mining operations, such as Huainan in China [15] and the Los Bronces copper mine in Chile [13].

Like solar power plants, wind farms have been used significantly in operating and abandoned mines. The capacity of these plants had also increased considerably, particularly in operating mines. This trend indicated that the industry recognized wind energy as a viable and scalable solution and was committed to expanding renewable energy capacity and reducing the environmental impact of the mining sector. Before 2017, most abandoned mines transmitted into wind farms were in the US [4]. However, recent studies

Table 3. Comparing the capacity of facilities before and after 2017.

Facility type	Before 2017		2018–2025	
	Mine name and location	Capacity	Mine name and location	Capacity
PV-operating mine	Goldstrike – USA	1 MW	Mount Keith – Australia	38.1 MW
	Chuquicamata – Chile	1 MW	South Deep – South Africa	50 MW
	Weipa – Australia	6.7 MW	Mogalakwene – South Africa	100 MW
	DeGrussa – Australia	10.6 MW	Harmony – South Africa	30 MW
	Thaba – South Africa	1 MW	QIT – Madagascar	8 MW
	Rosebel – Suriname	5 MW	Mansourah & Massarah – Saudi Arabia	44 MW
			Ma'aden – Saudi Arabia	1500 MW
			Kansanshi and Sentinel mines – Zambia	230 MW
			Los Bronce – Chile	86 kW
PV-abandoned mine	Chevron Questa – USA	1 MW	Martiki – USA	100 MW
	Meuro – Germany	166 MW	Hitura and Callio Mines – Finland	75 MW
	Sullivan – Canada	2 MW	Inden – Germany	170 MW
	Sinseong – Korea	1 MW	Huainan – China	70 MW
	Hambaek – Korea	85 kW	Konin – Poland	193 MW
	Hamtae – Korea	80 kW	Adamów – Poland	70 MW
			EMS – North Macedonia	10 MW
Wind-operating mine	Veladero – Argentina	2 MW	Port Gregory – Australia	2.5 MW
	Diavik – Canada	2.3 MW	Sierra Godra – Chile	112 MW
	Raglan – Canada	3 MW	Sibany – Stillwater – South Africa	89 MW
	Los Pelambres – Chile	115 MW	Seriti Resources – South Africa	155 MW
			Agnew – Australia	18 MW
			Kansanshi and Sentinel mines – Zambia	200 MW
Wind-abandoned mine	Dave Johnson – USA	237 MW	Drumduff – Scotland	6 MW
	Somerset – USA	34.5 MW	Kostolac – Serbia	66 MW
	Buffalo Mountain – USA	29 MW	United Schleenhain – Germany	90 MW

suggested that other countries, such as Germany, Scotland, and South Africa, also used abandoned mine sites to build wind farms.

Before 2017, using renewable energy systems in the mining sector was primarily about reducing the cost of remote mines and reclaiming abandoned sites. However, with the signing of the Paris Agreement in late 2016, the focus shifted beyond cost considerations. The main reason for adopting renewable energy systems was to reduce greenhouse gas emissions associated with mining. As a result, the capacity of PV and wind power installations in the mining industry has increased significantly, leading to global interest in using these sustainable energy solutions. Utilizing renewable energy in the mining industry has shown significant benefits, as evidenced by the studied cases. CO_2 emissions have been reduced by millions of tonnes annually. In addition, installing wind and solar power generation systems in abandoned mines has prevented environmental issues such as acid mine drainage [64]. Economically, the adoption of renewable energy has a positive impact on the mines and surrounding communities. Although jobs created in renewable energy manufacturing, construction, and installation are often temporary and conclude with the completion of specific projects, the majority of positions in the operation and maintenance of wind and solar power systems remain active for the duration of the projects [65]. This ongoing employment supports local economies and contributes to sustainable community development.

Figure 2 indicates an overview of the use of PV and wind power installations in the global mining industry in two periods: before 2017, and between 2018 and 2025. According to Figure 2A, wind power installations were mainly used in North America and Chile, while most solar installations are found in industrialized countries. However, Figure 2B shows a clear shift towards developing and underdeveloped countries in Eastern Europe, Africa, and the Middle East, while these systems were also present in industrialized countries.

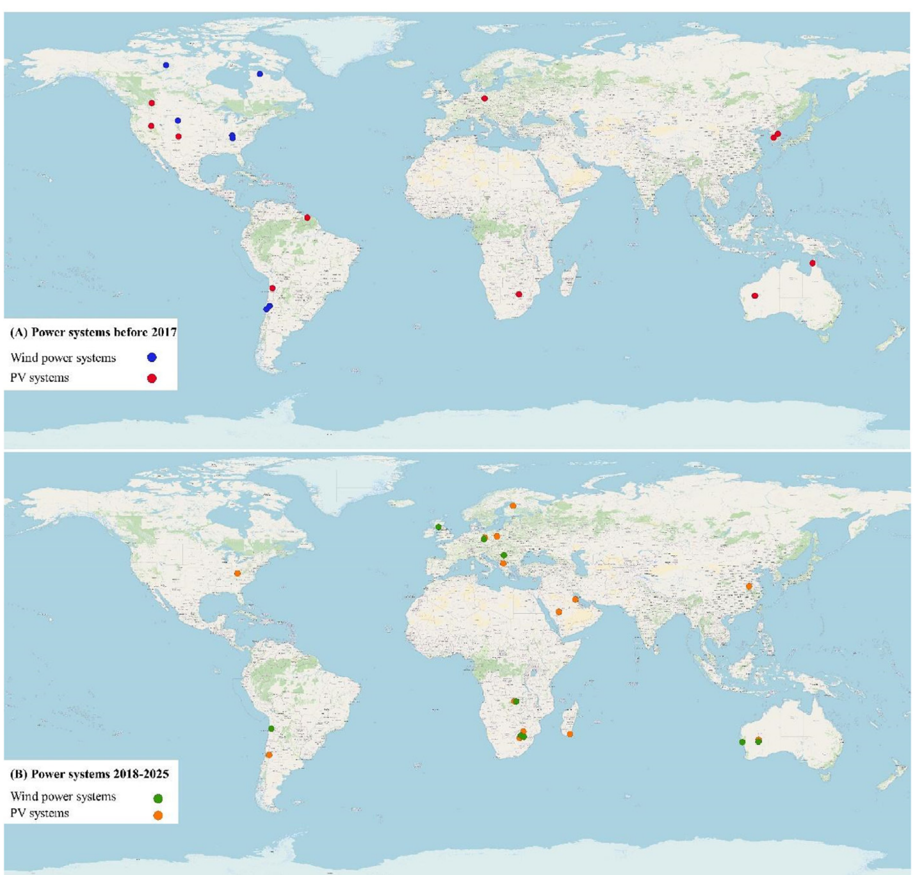

Fig. 2. Distribution map of the PV and wind power generation systems in the mining industry (A) before 2017 and (B) between 2018 and 2025 (generated with QGIS software).

4. Conclusions

This study examined the current utilization of renewable energy systems, like wind power and photovoltaic, in the mining industry (Tables 1 and 2). Photovoltaic systems have been successfully used in operating mines in several countries to meet energy needs in remote areas. Wind power systems are also installed in active and abandoned mines, with a recent trend towards larger wind farms for operational purposes.

The documented cases indicated that the integration of renewable energy technologies has a positive influence on both the environment and the economy. Reducing fossil fuel consumption led to a notable reduction in greenhouse gas emissions, and integrating battery storage systems set the way for sustainable mining operations. From an economic perspective, replacing fossil fuels with renewable energy sources improved financial viability, especially during high oil prices in remote areas. Renewable energy technology also generated new employment opportunities in these areas, contributing to local economic development [30].

In the future, the study emphasizes the importance of considering policy frameworks and regulations that influence the transition to renewable energy in mining. With the progression of technology, it is crucial to stay ahead of trends and innovations in renewable energy. Global cooperation and adopting renewable energy can guide the mining industry towards sustainability.

The continued adoption of renewable energy in the mining industry promises a lower carbon footprint, economic growth, job creation, and the development of innovative business models. The future energy landscape in mining holds the potential for both environmental and economic benefits.

Ethical statement

The authors state that the research was conducted according to ethical standards.

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Conflicts of interest

The authors declare no conflict of interest.

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