Renewable Energy Systems in the Mining Industry: A Literature Review and Research Agenda

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Received: 28.02.2022 Accepted: 24.03.2022

Abstract- Renewable energy (RE) sources such as solar, wind, geothermal, hydropower, and biofuels are counted as clean energies, which their implication is becoming widespread. These sources are mostly favorable because of their environmental-friendly features compared to the conventional energy sources such as fossil fuels. Accordingly, the daily tendency to apply RE sources and hereupon RE systems in households and industries is observable. Likewise, as a leading industry in raw material production, the mining industry is trying to take advantage of these systems in its different stages, from exploration to mineral processing. Getting know the potentials, applications, and advances in the mining industry, this study presents a literature review on the scientific works performed in this area. By identifying 40 research articles, conference papers, theses, and dissertations in the literature review process, they could be divided into three main topics: 1) potential and feasibility analysis, 2) RE system selection and, 3) application and perspective of RE systems. Reviewing these studies revealed although some valuable contributions in this field were carried out in the recent decade, still more research and contributions are desirable in the future. Accordingly, the following items were proposed as research agenda: 1) multi-factor evaluations, 2) optimization methods, 3) mine and mineral processing operations and, 4) software development.

Keywords- Renewable Energy (RE) Systems, Mining Industry, Optimization, Mine Operation, Mineral Processing

1. Introduction

RE systems, which are using these days in many industries and households as the sources of clean energy, are one of the widely acceptable strategies to deal with environmental concerns, especially greenhouse gases (GHG) emission reduction [1]. It will help societies to fulfill the sustainable development strategies targeted by the Sustainable Development Goals (SDG) [2, 3] as well as the Paris Agreement 2015 [4]. As the economical point of view, the benefits of RE systems are also undeniable, mainly because of electricity production at lower prices in comparison with fossil fuels [5]. Figure 1, for instance, shows the electricity cost in the photovoltaic (PV) solar system by cumulative module production [6]. This figure clearly depicts that by increasing the electricity production capacity of the installed modules through the last three decades the price of electricity produced by renewable energy systems is decreased.

Figure 2 depicts that the decreasing trend of the RE systems' electricity cost, which are solar, storage, and grid connection, in this case, will be even continued in the future [7]. Additionally, incentivized regulations specially providing financial aids for grid planners and distributers [8] will help an easier and faster transition from the conventional electricity supply methods to the RE.

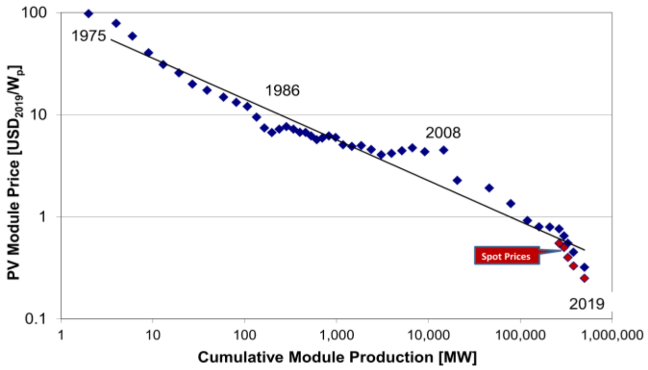

Fig. 1. Electricity cost produced by the PV system [6]

Add to the environmental and economic advantages of RE sources, the positive social effects must also be taken into account as well, such as the ability to produce electricity in remote places and communities by installing off-grid RE systems, especially wind and PV systems [9, 10, 11, 12].

Considering all these facts and figures, it can be an opportunity for industries to shift their demand for electricity from the conventional means of supply, which are mostly fossil fuels, to the RE sources.

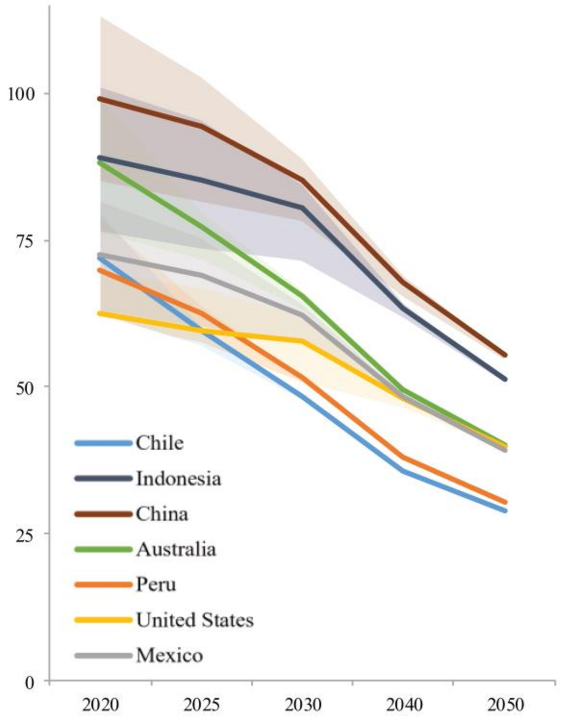

Fig. 2. The prediction of the average cost of electricity produced by solar, storage, and grid connection in some countries. The shaded areas depict the grid price scenarios [7]

In the last two decades, the mining industry also tried to put RE systems into the application and contribute to these aspects, particularly environmental issues. Table 1 summarizes some of the RE systems applications in mines that are historically recorded and identified. From the technical and economic point of view, by increasing the mining industry's energy demand (Figure 3) and fluctuating fossil fuel prices, it is risky to rely on conventional sources of energy merely. Additionally, new environmental rules defined for mines that need to be obeyed by miners during design and operation, e.g., CO_2 emission reduction, force them to seek alternatives for fossil fuels.

Considering all these technical, economic, and environmental challenges in mines, a supplementary energy source needs to be introduced. As a result, the RE systems' application in the mining industry is getting noticed in the last two decades. However, struggling with some barriers such as technical and economic difficulties, supplying continuous energy, high capital costs, particular need to infrastructures, etc., demotivated miners to appropriately implement and benefit from these systems [13, 14]. Accordingly, many researchers attempted to investigate various viewpoints of the RE systems in the mining industry, which can be helpful to overcome some of these obstacles and difficulties.

This paper aims at presenting a literature review on applying the RE systems in the mining industry. Additionally, by highlighting the focusing point on the previous works, which will be discussed in the following sections, this study offers a research agenda about the potential field of studies that can be investigated in the future.

2. Methodology

The literature review was performed through searching in the well-known scientific databases, especially Scopus, which encompasses a broad range of journals and proceedings. In addition, any published theses and dissertations related to the subject of this study were considered. Since this paper illustrates the scientific works on the RE system in the mining industry, any other non-scientific sources such as websites, news, interviews, etc., were neglected. Even though there are numerous scientific works on the RE systems, only the references were selected, in which their "research topic" was directly related to the contribution of the RE systems in the mining industry. As the result, 40 studies were identified, which representing the main body of this paper as the literature review. As it is shown in Figure 4, increasing trend of the studies related to the RE systems in the mining industry shows the importance and acceptability of this research field by researchers. The relatively low quantity of research in this area can also be interpreted as a relatively new research topic in mining.

Table 1. Installed RE systems worldwide (2003-2020) [15, 16, 17]

Mining corporation	Mine	Financing	Connection	Location	Size (MW)	Source	Date of the first operation
Lihir Gold limited	Newcrest	Own investment	Off-grid	Papua New Guinea	56	GT	2003
Royal Gold	El Toqui	Own investment	Off-grid	Chile	1.65	W/HE/D	2010
Barrick Gold	Punta Colorada	PPA	On-grid	Chile	20	W	2011
Rio Tinto	Diavik	Own investment	Off-grid	Canada	2.3	W/D	2012
Codelco	Gabriela Mistral	PPA	On-grid	Chile	34	PV	2012
Cronimet Mining AG	Thamazimbi	Own investment	Off-grid	South Africa	1	PV/D	2012
Galaxy Resources	Mt Cattlin	Own investment	Off-grid	Australia	3.6 / 1	W/PV/D	2012
Antofagasta Minerals	Chuquicamata	PPA	On-grid	Chile	1	PV/D	2012
Antofagasta Minerals	El Tesoro	PPA	On-grid	Chile	10.5	CPV	2012
Xstrata/Anglo American	Collahuasi	PPA	On-grid	Chile	25	PV	2012
SNIM	Nouadhibou	Own investment	On-grid	Mauritania	4.5	W	2012
Solarpack	Calama	PPA	On-grid	Chile	1.1	PV	2012
Antofagasta Minerals	El Tesoro	Own investment	Off-grid	Chile	0.06	CSP	2013
Quiborax	El Aguila	PPA	On-grid	Chile	2.3	PV	2013
Minera Dayton	Andacollo	PPA	On-grid	Chile	1.26	PV	2013
BHP Billiton	West Leinster	Own investment	On-grid	Australia	0.3	PV/D/G	2013
Pampa Elvira Solar	Gabriela Mistral	PPA	On-grid	Chile	27.5	ST	2013
Solairedirect	Andacollo	PPA	On-grid	Chile	1.26	PV	2013
Anglo American	Kriel colliery	PPA	On-grid	South Africa	0.24	PV	2013
Barrick Gold	McCarren	Own investment	Off-grid	USA	1.51	PV/G	2014
Barrick Gold	Veladero	PPA	Off-grid	Argentina	2	W/D	2014
Glencore	Raglan	Own investment	Off-grid	Canada	3	W/D	2014
Grupo CAP S.A.	Amanecer	PPA	On-grid	Chile	94	PV	2014
Imagold	Rosebel	PPA	On-grid	Suriname	5	PV	2014
Rio Tinto	Weipa Bauxite	PPA	Off-grid	Australia	6.7	PV/BS/D	2014
Shanta Gold	New Luke	Rental	Off-grid	Tanzania	1	PV/D	2014
Antofagasta Minerals	Los Pelambres	PPA	On-grid	Chile	115	W	2014
CAP Group	Copiapo	PPA	On-grid	Chile	100	PV	2014
EDL	Coober Pedy	PPA	Off-grid	Australia	6	W/PV/BS	2014
Ozkoyuncu Mining Co.	Cappadocia	Own investment	Off-grid	Turkey	2	PV	2014
Codelco	Chuquicamata	Own investment	On-grid	Chile	0.065	PV	2014
Solarpack	Pozo Almonte	PPA	On-grid	Chile	25.4	PV	2014
Mandalay Resources	Cerro Bayo	PPA	Off-grid	Chile	1.8	W/D	2015
SunEdison	Los Pelambres	PPA	On-grid	Chile	69.5	PV	2015
City of Kimberley	Sullivan Mine	PPA	On-grid	Canada	1	PV	2015
Glencore Raglan Mine	Katinniq	Own investment	Off-grid	Canada	3	W/D	2015
Sandfire resources	Degrussa	PPA	Off-grid	Australia	35.6	PV/D/BS	2016
Iamgold/Government of Burkina Faso	Essakane	PPA	Off-grid	Burkina Faso	62	PV/D	
Goldcorp	Borden	Own investment	On-grid	Canada	-	BS	2019
EIG and Abengoa	Cerro Dominador	PPA	On-grid	Chile	210	PV/CSP	2019
Antofagasta and barrick Gold	Zaldivar	PPA	On-grid	Chile	550*	W/HE/PV	2020

GT: Geothermal
CPV: Concentrated photovoltaics system
HE: Hydropower system
PV: Photovoltaic system
BS: Battery storage
*: GWh/year
W: wind system
D: Diesel
G: Gas
ST: Solar thermal
PPA: Power purchase agreement
EDL: Energy development limited
CSP: Concentrated solar power

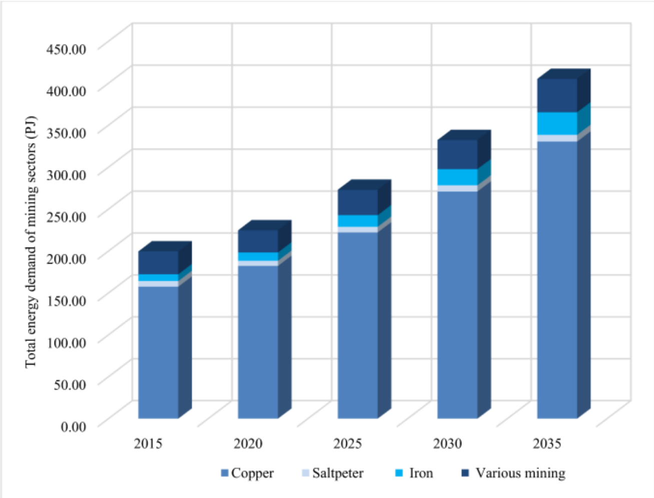

Fig. 3. Prediction of the energy demand in the mining industry [18]

3. RE systems and the mining industry

Based on the literature review, the identified studies can be generally divided into three main categories considering their subject and content: 1) potential and feasibility analysis of RE systems 2) RE system selection and, 3) application and perspective of RE systems. Each of these categories will be thoroughly described in the following subsections. They are also summarized in Table 3.

3.1. Potential and feasibility analysis of RE systems

The potential evaluation of RE systems in the mining projects, whether in a specific country [15, 19, 20] or even a continent [21], was one of the primary focusing points of research in recent years. For this, having some knowledge about the RE sources availability in the countries or regions is one of the first steps to potential analysis. For instance, Figure 5 shows the availability of solar energy per square meter in Australia [22]. The potential sources of RE can be efficiently evaluated for each type of RE in each region through these contour maps.

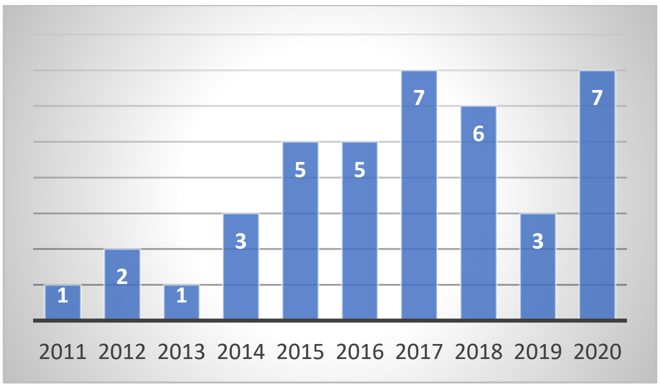

Fig. 4. The quantity of research in the field of RE system in the mining industry in the last decade (drawn by the authors)

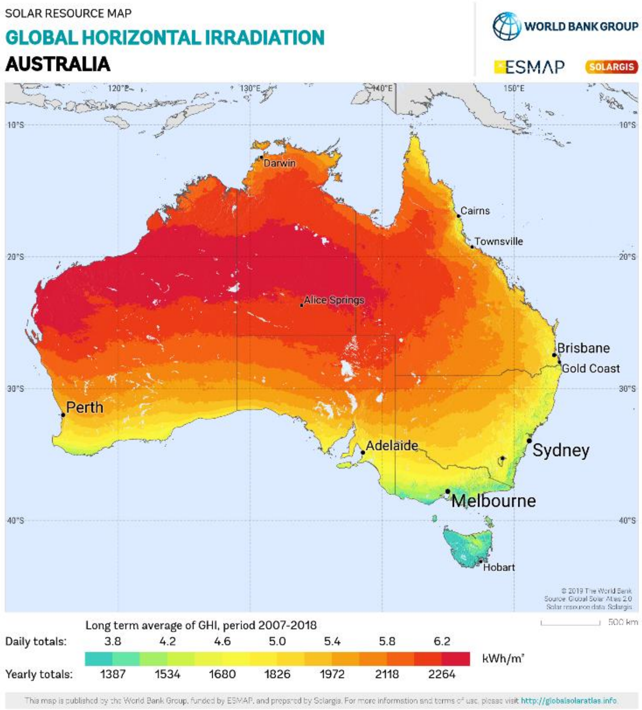

Fig. 5. Average annual solar energy in Australia [22]

RE sources can potentially supply the mining projects with their energy in different forms of electricity, heat water [23, 24], etc. These potentials and feasibilities are mostly related to the less-discussed side of the RE systems, such as their feasibility in the remote areas, end consumer of electricity, and the potential application of RE systems in the postmining stage. Nevertheless, there are still clear potentials for these systems, which are discussed more, mainly their economic and environmental advantages.

The environmental and economic benefits of RE systems are their most favorable potential in the mining industry. In a review study [25], it was discussed that the RE systems could significantly reduce emissions produced by the mining industry while supplying the energy needed for the mine operations. Based on this research, it could be up to 46% of the total industry emissions when using biofuels and charcoal instead of fossil fuels [25]. This quantity would be 28% and 2-7% using hydrogen and solar thermal, respectively [25]. In another study, a multi-stage stochastic method based on the economic factor, GHG reduction, and evaluating a social life cycle assessment was developed. This study aimed to investigate the applicability of RE systems in the zinc mines in Iran [26]. It suggests that the application and installation of wind and solar energy for the zinc mine industry in four different locations in Iran presents a sustainable and optimized solution by considering economic, environmental, and social aspects [26].

Since mines are mostly located in remote areas, supplying electricity is always one of the challenging issues for the mining projects due to having trouble accessing the electricity network as an on-grid connection. Accordingly, in some cases, constructing and installing off-grid networks is inevitable [27, 28, 29]. The potential use of RE systems for such mines was discussed in a study through analyzing mine's dependency reduction to fossil fuels and replacing it with RE systems [30]. By illustrating some case studies, RE systems' benefits were proved, in conjunction with some hints on shifting from fossil fuels to RE systems such as installation and the mine lifetime [30]. Additionally, off-grid systems will reduce or cut the transportation cost of fossil fuels to the mine sites. In one study it was shown that an off-grid system in the exploration phase can contribute to save nearly 47500 liters of diesel [29]. This will therefore help in carbon dioxide reduction by 9.7% and 50% during the exploration and extraction phases respectively [29].

Even though PV and wind power systems are the most well-known types of RE systems whose potentials are thoroughly investigated [24], geothermal energy as a specific type of RE source was another point of research. Its potential in the mining industry is unfavorably confined by some factors such as mine location, local climate condition, distance to the power distribution, pricing, the quality, and quantity of the geothermal resource in the mine area, etc. [31, 32, 33]. As an example of geothermal potentials, Figure 6 shows the heat flow map in South America as one of the primary sources of geothermal power [34].

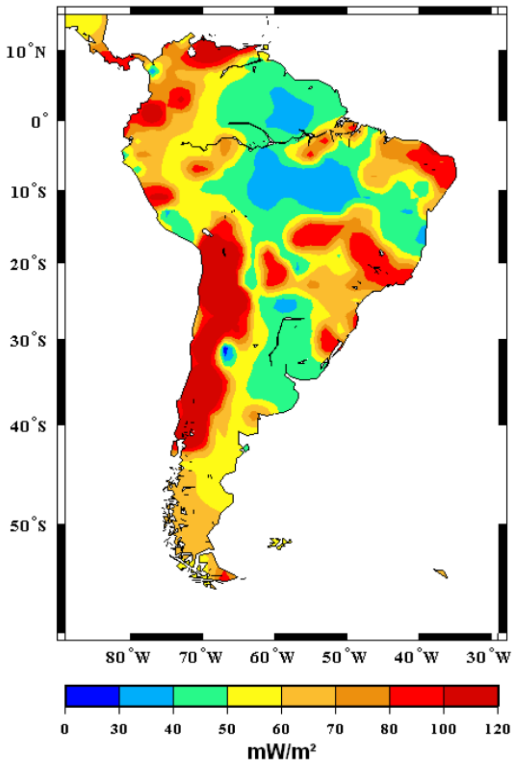

Fig. 6. Heat flow map of South America [34]

A deep understanding of the end consumers of electricity in mining and mineral processing operations plays a vital role in depicting a bigger map of using RE systems. In one research based on the real data acquisition extracted from various mine sites in Chile, the main characteristics of the electricity consumption were defined [35]. Accordingly, some instructive recommendations for energy management were proposed [35]. In another study, a policy analysis based on the energy consumption in the mines located in the north of Chile was carried out as along with forecasting the future demand of energy by these mines [18]. It was estimated that the energy demand would be doubled in the upcoming two decades, in which the highest portion (78.9%) goes to the copper mines [18].

The RE systems application while operation not only was the topic of research but also the use of RE systems in the post-mining phase was investigated. In one of them, the feasibility of installing a wind power system for the post-mining land use in the coal mines of West Virginia was investigated [36]. This study showed that using RE systems in the post-mining period as a closure plan would be economic and offer positive social effects such as local employment opportunities [36]. In another research, the potential use of floating PV on the mine lakes, which were constructed in the abandoned mines in Korea, was evaluated [37]. It was shown that it could result in higher economic benefits in comparison with the typical PV [37]. Furthermore, a reduction of 471.2 t carbon dioxide per year was expected [37]. By using the same method, two research were carried out to evaluate the potential installation of PV and wind power systems in the abandoned mines in Korea [38, 39].

3.2. RE system selection

Based on the literature, the RE system selection can be defined as the most challenging problem in conjunction with the RE system. Various attitudes and methods were developed by researchers to overcome this challenge. The most well-known methods for making decisions on the RE system selection can be categorized as scenario development, reliability and risk assessment, optimization, and multi-criteria methods.

Introducing a business model for the RE systems in the mining industry was an interesting and challenging research subject. Many studies tried to cover this issue to provide a decision ability for mine managers to decide among different types of RE systems. In one of these studies, four scenarios were investigated when applying RE systems in the mines [40]. It was based on comparing fossil fuels (diesel) and the hybrid RE system (combination of PV and natural gas) (Table 2). This study showed that different cost-saving outcomes could be concluded by various scenarios in different CO_2

emission prices, PV location, and degradation rate [40, 41]. By the same paradigm, another study focused on selecting an electricity power system for an off-grid mine based on a hybrid RE system [42]. This study evaluated the contribution of each means of electricity production (44% of PV, 40% of batteries, and 14% of diesel) in order to enable mines to operate normally [42].

Table 2. Scenario development for RE system selection based on the business model [40]

Scenario	Fossil fuel system	Capacity (MW)	Hybrid system	Capacity (MW)
Scenario 1	Diesel	10	PV – diesel	1 + 9
Scenario 2	Diesel (low CAPEX)	10	PV – diesel (low CAPEX)	1 + 9
Scenario 3	Conventional diesel CC	10	PV – diesel	1 + 9
Scenario 4	CGCC	10	PV – natural gas	1 + 9

Since the mine operations are mostly continuous activities, supplying electricity must not be interrupted; otherwise, the whole production and processing process could be stopped and lead to technical and economic consequences. It is undeniable that the RE systems, especially solar and wind energy, are highly dependent on the weather conditions, in which the sunshine and blowing wind are prerequisites to produce electricity. Accordingly, reliability and risk assessment of using such systems in mining projects are extremely essential. In one research, RE system selection in the mining industry was studied by turning these two factors (reliability and risk) into the economic factor of cost, [43]. This research presented a non-linear optimization function as a summation of system reliability and risk costs to find the lowest cost hybrid system suitable for three case studies in Chile, Australia, and Canada [43]. By the energy output profile from the optimization, which a schematic view is illustrated in Figure 7, it was shown that a diesel system as a backup is needed due to the discontinuous energy production by RE systems. Nevertheless, most of the electricity can be still produced by RE systems [43].

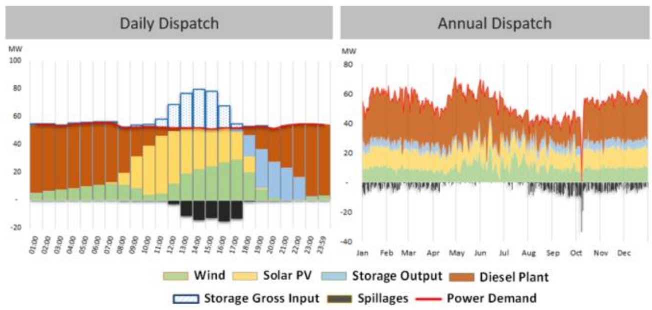

Fig. 7. an example of energy supply profile in a hybrid system [43]

The RE system selection in an optimization context was another point of attention. In one of the studies in this area, an optimization model was presented based on the technical and economic factors of using RE systems in the mining areas of Antofagasta region located in the north of Chile [44]. This study resulted in PV and wind systems that can supply at least 10% of the total electricity demand in this region [44]. In another study, an optimization method named LEELO (long-term energy expansion linear optimization) was implemented to evaluate the electricity demand for copper mining [7]. This model was based on the annual demand for electricity, electricity prices on the contracts, the application cost of each RE system, and the solar irradiation rate [7]. It illustrated that until 2030, the total electricity in the sunny regions could be supplied by the PV system, while in other regions, it will be achieved by 2040 [7]. A hybrid system, which was a combination of PV and battery storage (BS) systems, was designed based on a linear stochastic optimization method [45]. This model considered the mine scheduling for the grinding mill operation. It aimed to minimize the cost of grinding mill in the PV-BS scenario according to the stochastic behavior of the system [45]. It was proved that 27% cost reduction could be reached by using RE systems in the grinding mill process [45]. In another study, a hybrid system, including PV and BS systems, evaluated running a grinding mill [46]. This study proposed a mixed-integer linear programming and the results showed that using PV and battery storage systems could reduce the mill's costs [46].

The multi-criteria method, which is known as one of the decision-making methods mainly through evaluating different criteria, was another field of work in a few studies. In one of them, the multi-criteria decision analysis (MCDA) was performed to evaluate the RE systems viability in the mining projects based on the technical, economic, environmental, and social aspects [47]. These aspects were categorized as the “first hierarchy criteria” and other sub-items related to each aspect named as “second hierarchy criteria” e.g. investment cost, operational and maintenance cost (economic criterion), efficiency, safety (technical criterion), job creation, corporate image. (Social criterion) [47]. In another study and by the same method as well as considering the uncertain weights through the Integrated Constrained Fuzzy Shannon Entropy (IC-FSE) method, the proper RE system was determined [48]. Three alternatives of onshore wind, PV, and concentrated PV systems were evaluated based on the technical, economic, environmental, and social factors [48]. In another research, the multi-attribute value theory (MAVT) was examined for integrating RE systems in the mining projects [49]. The results showed that a combination of RE systems and diesel generators as a hybrid system is preferable rather than the system working only with diesel fuels [49]. In another research, the SWOT analysis was conducted by listing the strengths, weaknesses, opportunities, and threats of integrating RE systems into mining projects [50]. Additionally, a cost evaluation for deciding to apply the RE systems in the mines was discussed [50]. Making decision on using RE systems based on the sustainability factor was another investigate points. In one of these studies, the selection procedure was proposed by considering the values for the economic, environmental, and social aspects of RE systems for the mining projects [51]. It showed that these factors along with the qualitative description could make a better judgment for selecting a proper RE system [51].

3.3. Application and perspective of RE systems

The remaining works in the literature focused on the application of RE systems in the mining industry. In a review study, RE systems application in both operating mines and abandoned mines were studied [52]. This study showed that PV systems are widely used throughout the world, such as the USA, Chile, Australia, and South Africa. In a few countries and in non-operating mines, these systems are also applying such as Germany, Canada, and Korea to supply the electricity for surroundings. This trend was observed for the wind power system for both operating and non-operating mines in some countries such as Argentina, Canada, and Chile [52]. In another study, the application of solar systems in the mining industry for supplying power and thermal energies were discussed through some case studies in South Africa and Chile [53]. This study represented how the solar system can be beneficial in mine operations as well as mineral processing in terms of economic and environmental aspects. Nevertheless, it still made some recommendations about the feasibility of solar systems through considering three key factors of mine operations, energy management and environmental considerations [53].

Copper production as a critical material in the industry was another specific interesting point for researchers. In one of these studies, the current application and development of RE systems in copper production was discussed [54]. This study not only showed the beneficial use of RE systems through lowering the cost and emissions in copper mines but also suggested six recommendations for further research in this area, including a) developing more complex and comprehensives models; b) considering the flexibility of the system; c) water management in modeling; d) flexibility in existing copper plants; e) linking between the future design of the mine and current available RE systems; and f) life cycle assessment and its effect on the optimization models [54]. In addition to the economic and environmental benefits that RE systems offer in the mining projects, the social aspect also can be achieved, specifically improvement in the local and remote areas [55].

Several qualitative studies were carried to evaluate the perspective of the RE systems in the mining industry. The opinions' experts, in one of these studies, were collected to evaluate the future of RE systems energy adoption in the mining industry in Chile [14]. It discussed the obstacles and incentives that the mining industry faces in this country while applying RE systems [14]. Based on the same paradigm along with a survey, another study focused on the favorable and unfavorable factors to shift to RE systems in mining [56].

Table 3 shows a summary of the literature explained above. This table categorized different items for each research, e.g., the factors considered, type of RE system, applied method, offering an optimization solution, type of operations (mining and/or mineral processing operations), and the location of the case study. This categorization helps to define the research agenda for future works, which will be discussed in the next section.

4. Research agenda

As it is clear from the literature review, there are plenty of works on applying RE systems in the mining industry. Each of them investigated this issue based on any specific point of view, which are mainly technical (feasibility of RE systems), economic (cost-effective aspects of RE systems), and environmental issues (GHG reduction). These studies aimed at resolving the challenges of RE systems application in the mining industry, which hinder miners from using them properly. Despite these works, still, some crucial points need to be deeper investigated. Some of these research agendas are presented:

4.1. Multi-factor evaluation

In the application of RE systems in the mining industry, as it was shown in the previous sections, many single-factor studies were merely focused on one aspect, e.g., technical challenges like technical review studies [30, 54] and data analysis [18, 35]. Some others only concentrated on the economic part of the RE systems, such as economic reviews, feasibility, potential, scenario analysis [7, 21, 33, 36] and mathematical models [7, 41, 43, 50]. However, there is some research that involves the combination of the technical and economic aspects such as review and feasibility studies [14, 32, 37, 42, 52, 53, 56] and mathematical optimization models

[44, 45]. Adding environmental and social factors to these two factors will make the problem more complex, in which very limited studies developed this issue such as reviews [55], data analysis [25], and quantitative and qualitative models [26, 47, 48, 49].

Table 3. Literature review on the RE systems in the mining industry (based on the chronological order in the text)

Reference	Considered factors	RE type	Method	Optimized solution	Type of Operation	Location
			Potential and feasibility analysis of RE systems			
[15]	T / Ec	PV / W	Review	No	NA	South Africa
[18]	T	BM/NG	DA	No	NA	Chile
[19]	T / Ec / En	PV	PA	No	NS	Uzbekistan
[20]	T / Ec / En	ST	Simulation	No	RP	Chile
[21]	Ec	-	PA	No	NS	South America
[23]	T / En	ST	Review	No	M / P	Australia
[24]	T	ST	DA	No	NS	Chile
[25]	T / Ec / Ec	PV/BF/HE	DA	No	NA	Worldwide
[26]	Ec / En / So	PV / W	MSSP	No	NS	Iran
[27]	T	HY (PV+W+DG)	DA	No	NS	Mauritania
[28]	T / Ec / En	PV	Review	No	NA	Australia
[29]	Ec / En	PV / W / ST	DA	No	NS	Canada
[30]	T	PV / W	Review	No	NA	-
[31]	T / Ec	GT	PA	No	NA	-
[32]	T /En	GT	Review	No	NA	Worldwide
[33]	Ec	GT	Review	No	NA	-
[35]	T	-	DA	No	M / P	Chile
[36]	Ec	W	FA	No	NOM	USA
[37]	T / Ec	Floating PV	FA	No	NOM	South Korea
[38]	T / Ec	PV	FA	No	NOM	South Korea
[39]	T / Ec	W	FA	No	NOM	South Korea
			RE system selection			
[7]	Ec	PV / BS	LP	Yes	NS	Worldwide
[40]	Ec	HY (DG+PV+NG)	SA	No	NS	-
[41]	Ec	HY(PV+DG+CGCC)	MM	No	NS	Canada/Chile
[42]	T / Ec	HY (DG+PV+BS)	SA	No	NS	Ghana
[43]	Ec	HY	LP	Yes	NS	Canada/Chile/ Australia
[44]	T / Ec	PV / W	MINLP	Yes	NS	Chile
[45]	T / Ec	PV / BS	LSO	Yes	SAG	-
[46]	Ec	PV / BS	MILP	Yes	SAG	Chile
[47]	T/Ec/En/So	HY (DG+PV+W)	MCDA/Interview	No	NS	South Africa
[48]	T/Ec/En/So	W / PV / CS	MCDA	No	NS	-
[49]	T/Ec/En/So	HY (DG+PV+W)	MAVT	No	NS	South Africa
[50]	Ec	HY (DG+PV+W)	SWOT	No	NS	Worldwide
[51]	T / Ec / En	-	TBL	No	NS	USA
			Application and perspective of RE systems			
[14]	T / Ec	PV	Review	No	NA	Chile
[52]	T / Ec	PV / W	Review	No	NA	Worldwide
[53]	T / En	PV	Review	No	NA	Worldwide
[54]	T	-	Review	No	NA	Chile
[55]	Ec /So	-	Review	No	NA	South Africa
[56]	T / Ec	-	Interview/Review	No	NA	-

T: Technical factor
En: Environmental factor
FA: Feasibility analysis
DA: Data analysis
MM: Mathematical model
NA: Not applicable
BF: Biofuels
NS: Not specified
PM: Post mining
ST: Solar thermal
NG: Natural gas
BS: Battery storage
Ec: Economic factor
So: Social factors
PA: Potential analysis
SA: Scenario analysis
BM: Biomass
NOM: Not operating mine
HE: Hydro energy
GT: Geothermal
SAG: Semi-autogenous grinding
RP: Refinery process
M: Mining
MINLP: Mixed-integer non-linear programming
MILP: Mixed-integer linear programming
CGCC: Conventional natural gas combined cycle plant
LSO: linear stochastic optimization
MSSP: Multi-stage stochastic programming
LP: Linear programming
TBL: Triple bottom line accounting method
HY: Hybrid system
DG: Diesel generator
CS: Concentrated solar power
P: Processing

Although many studies focused on each technical, economic, and environmental aspects of the RE systems in the mining industry or a combination of two, there are a few studies that addressed the technical, economic, and environmental concerns simultaneously. This point is crucial mainly because a proper decision and evaluation can be reached when all the involved factors are considered. Otherwise, the result would not be desired and cannot be considered as a precise solution. Additionally, trusting only on the qualitative methods such as interviews might be restricted to a few experts' viewpoints, which could not be counted as a widely accepted solution. Accordingly, not only considering all these factors should be more investigated in conjunction with each other but also developing quantitative models in this frame is critical.

4.2. Optimized solution of considering different factors

Optimization is a field of research that is nowadays vastly utilizing in almost all branches of engineering. The mining industry also applied optimization techniques in any part of its operation, from extraction to mineral processing [57, 58]. The major benefit of optimization techniques is presenting a problem, in which the designer seeks to minimize or maximize an objective. Minimizing costs, whether capital or operating costs, are one of the most common objective functions in mine design as well as maximizing profit or Net Present Value (NPV). Although many other fields of studies implemented optimization techniques in the application of RE systems [59, 60], these implementations were investigated in a limited number of studies regarding the RE systems in mining [7, 43, 44, 45]. Additionally, there is no work to define an optimization problem in minimizing the environmental impact, especially the reduction of GHG emissions. In the same way, maximizing production while using RE systems is also one of the missing points. Accordingly, it is still highly in demand that these two gaps be more deeply investigated.

4.3. Simultaneous consideration of mine and mineral processing operations

In most works in the literature, the energy demand of the mining projects was considered as a whole without explanation about the specific demand for each operation [7, 19, 21, 37, 41, 42, 43, 44]. For instance, a few studies were performed specifically for the demand for mineral processing and refinery operations [20, 45]. However, some mine operations still need electricity, e.g., electric shovels, ventilation system for underground mines, watering and dewatering systems, conveyor belts, etc. All these operations are highly connected to each other, in which an interruption in one of them could have consequences to the whole production streamline. Additionally, for production fulfillment based on the mine's designed schedule, both mine and mineral processing operations must work in equilibrium. Therefore, it is essential to consider both above-mentioned operations simultaneously while designing and evaluating RE systems' applications in any mining project.

4.4. Software development

Dealing with any kind of model, especially when the models get complicated, is one of the challenging points for users. Sometimes, it is cumbersome for users to follow the model's logic and background while trying to solve the problem. Accordingly, the software will help them to handle their works with little concern. Despite many software available in the mining industry in different fields of design, e.g., production scheduling, transportation system selection [61], the lack of software related to the application of RE systems in the mining industry is still evident. This software should be able to cover the aforementioned aspects related to the RE systems, which are technical, economic, and environmental issues. It will not only give designers the ability to apply it as a part of their daily designs but also will make them more delighted to consider RE systems in design. Accordingly, the development of such software is crucial.

5. Conclusion

The RE sources, which are counted as the clean energy sources, get more attentions than before. It is mostly because of the economic and environmental challenges that societies and industries are currently confronting with them. The mining industry, as one of the pivotal industries responsible for supplying raw materials for the daily booming industries, is not an exception for these challenges. Accordingly, the tendency of using the RE systems in this industry is increasing particularly in the recent decade. In this field of research, some valuable works tried to deal with leastways one part of these challenges and present a solution. The wide spectrum of these studies, which was identified through this study, includes the potential and feasibility study of the RE systems in the mining, selecting the proper RE system for mining projects, and the current application and the perspective of these systems. Although the noteworthy contribution of these works, there is yet a necessity for more investigations on the defined gaps in this paper. These gaps can be fulfilled by working on these subjects: 1) multi-factor evaluation of RE systems in the mining industry, in which the technical, economic, and environmental aspects are simultaneously considered; 2) finding the optimized solution in a multi-factor space, which will lead to a more precise solution; 3) considering mine operations in conjunction with mineral processing operations because of the fulfillment of mine as a system as well as equilibrium in these operations and, 4) software development, in which the calculations of RE systems can be integrated into the mining projects.

Acknowledgement

The authors would like to express their appreciation to the reviewers, whom their constructive comments and remarks helped to improve this research.

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