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Research paper

Decision-making on the integration of renewable energy in the mining industry: A case studies analysis, a cost analysis and a SWOT analysis

Kateryna Zharan*, Jan C. Bongaerts

Department of International Management of Resources and Environment, Technical University Bergakademie Freiberg, Schlossplatz 1, 09596, Freiberg, Germany

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ABSTRACT

The mining industry is showing increasing interest in using renewable energy (RE) technologies as one of the principles of sustainable mining. This is witnessed in several pilot projects in major mining countries around the world. Positive factors which favor this interest are gaining importance and negative barrier factors seem to be less relevant. For a mine operator, the switch from fossil fuel to RE technologies is the outcome of decision making processes. So far, research about such decision making on the use of RE in mining is underdeveloped. The purpose of this paper to present a practical decision rule based on a principle of indifference between RE and fossil fuel technologies and on appropriate time management. To achieve this objective, three investigations are made: (i) a case studies analysis, (ii) a comparative cost analysis, and (iii) a SWOT analysis.

1. Introduction

Sustainable mining principles, such as reducing its impact on the environment and enabling ethnical business practices and progress for local communities (Mining with principles, 2017), play a key role for mining companies and society in general. Sustainable mining comprises many issues, such as establishing transparent relationships with communities as a fundamental metric for investment decisions, engaging with communities in order to establish responsibility and accountability to enhance the industry's performance, reducing the environmental impact in all stages of the mining operation, striving for high levels of health and safety at work and maintain mutually beneficial relationships with government authorities. In this context, the impact of energy in mining on these issues has received much less attention, except in cases of conflict, as evidenced, by way of example, in the recent fight over a new electricity tariff between copper miners in Zambia and the state-owned Copperbelt Energy Corporation (Hill & Mitimingi, 2017). As an alternative way of energy procurement and in order to lower energy costs, mining companies have begun to focus on the use of renewable energy.

As a matter of fact, in recent years, mining companies around the globe have started to pay more attention to using RE technologies in their operations. There are several reasons for this. Firstly, the overall costs of RE technologies diminished significantly from 2005 (Kost et al., 2013) and the costs of RE equipment (photovoltaic (PV) modules and wind turbines, etc.) and maintenance are continually decreasing. Secondly, hybrid energy systems (HESs) have been suggested as an effective instrument to increase RE penetration (Chen & Rabiti, 2017) and represent a solution that avoids RE volatility (Kim, Chen, & Garcia, 2016). Thirdly, off-grid mines in remote areas depend on diesel as their main source of energy and, hence, adopting RE into such off-grid mining operations may improve economic perspectives (Golubova, 2016).

According to the Paris Agreement (UNFCCC, 2015), in order to limit the growth of the global average surface temperature to 1.5–2 °C, developed countries around the globe must focus on the decarbonization of their economies. In 2015, the average concentration of carbon dioxide was about 40% higher than in the mid-1800s (IEA, 2016). Therefore, replacing fossil energy used for mining operations with RE will contribute to the global requirements. Together with economic benefits, reducing carbon dioxide emissions with RE technologies may lead mining companies towards "green operations".

* Corresponding author. Johann-Sebastian-Bach-Str. 1, 09599, Freiberg, Germany.
E-mail address: eszharan@gmail.com (K. Zharan).

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Although RE has an environmental advantage, its dependence on weather conditions implies volatility and intermittency. This is an important obstacle to overcome for the integration of RE in mining operations, but HESs can represent a solution for this problem (Jung & Villaram, 2017), describe a hybrid renewable energy system as consisting of two or more RE sources used together. This mitigates the intermittent nature of RE resources, ensuring an overall balance to energy supply and the improvement of system efficiency. In addition (Choi & Song, 2017), described HESs as an effective solution to increase RE penetration (Zahraee, Assadi, & Saidur, 2016).

According to Martin (2014), RE use in the mining industry will increase from less than 0.1% to about 5%, and – tendentially – up to 8% by 2022. At present, RE technologies are sufficiently developed so as to enable complex and large implementation within the mining industry.

So far, there has been no investigation on a decision-making approach towards the integration of RE into the mining sector. To address this limitation, the purpose of this paper is to develop a practical decision rule based on a Cash Flow approach. It is derived from analysis of case studies and cost analysis. It is evaluated in a wider context in a SWOT analysis, giving a perspective on its applicability within the range of external and internal opportunities and constraints.

2. Material and methods

The purpose of this paper is to develop a decision-making approach to implementing RE into the mining industry. This paper consists of four sections, and three appendices. Section 1 includes the literature review, purpose of this paper, and relevance of this topic. Section 2 comprises the methodology that has been used to achieve the purpose of this study.

In section 3, analysis of case studies accomplished using a two-step approach is reported. Section 3.1 contains the evaluation of specific features of the case studies. Section 3.2 contains the analysis of the case studies of mines using RE technologies. Section 3.3 contains government regulatory mechanisms. Sections 3.4 to 3.6 include cost analysis of RE and fossil energy as a quick decision rule to decide on PV projects as alternatives to diesel plants. Section 3.7 contains a SWOT-analysis to analyze the benefits and barriers with respect to the integration of RE into the mining industry, i.e., the main strengths, weaknesses, opportunities, and threats in internal and external environments towards RE use in mining projects. Section 4 covers the conclusions of this study.

3. Results and discussions

In this paper we analyze the case studies of four major mining countries, i.e. (i) Australia, (ii) Canada, (iii) South Africa, and (iv) Chile were selected. The objectives of this analysis are (i) to give a structure of the specific features of the mines and (ii) to specify the characteristics of their RE projects. The analysis takes place in two steps. Step 1 contains the characteristics of the mines and Step 2 contains the RE projects in those mines.

3.1. Specific features of the case studies

This part of the paper is dedicated to the first step of the analysis of the case studies. Table 1 contains the criteria used for this first step. Literature sources on these case studies are contained in Appendix A. Table 2 lists the characteristics of the mines of the case studies.

Table 1
Criteria used for the first step of the analysis of the case studies.

Criteria	Criteria
Type of mine	Date of construction and lifespan
Location	Logistic characteristics
Total production, t/year	Fossil energy generation facilities
Climatic conditions	

Obviously, all mines are different, as they are located in different climate conditions, geographical regions, are of different sizes, lifetimes, technologies, production levels etc. As will be shown in the second step of the analysis of the case studies, all mines have implemented RE projects. As such, it can be concluded that the characteristics listed in Table 2 have no impact on these RE project and do not impose any barriers.

3.2. Case studies of mines using RE technologies

This part of the paper is dedicated to the second step of the analysis of the case studies. Table 3 contains the criteria used for the second step. Table 4 contains the outcomes of the analysis of the case studies. Literature sources on these case studies are contained in Appendix B.

According to Table 4, there are five solar-diesel and three wind-diesel projects, hence, HESs are most often used. The generation capacity varies between 1.7 MW and 40 MW. The biggest project with a capacity of 40 MW and an integrated solar-diesel microgrid system is operated by Gold Fields in South Africa. The largest RE wind-diesel microgrid system has a capacity of 9.2 MW (Diavik Diamond in Canada). Gold Fields also reports that the integration of a HES reduces diesel consumption by up to 20% of total energy consumption and that GHG emissions are reduced by 100,000 tons a year.

According to Table 5, wind technology saves the most GHG emissions per GWh of RE production in the case of the Diavik Diamond mine. The Reglan mine has been saving more diesel per MW of RE production by implementing solar PV technology. Table 5 shows the project values per GWh and MW.

3.3. Government regulatory mechanisms

Table 4 also reveals two government regulatory mechanisms for the integration of RE into mining: (i) a Power Purchase Agreement – PPA and (ii) an Independent Power Producers – IPPs mechanism. A PPA is a contract between a provider (an electricity generator) and a buyer (power purchase) for a long-term period, e.g. from 5 to 20 years. In a PPA agreement, the provider may or may not use a grid connection to serve their customer.

An IPP mechanism is a facility for a private utility (the IPP) to generate and sell electricity to a grid operator, often a government agency. Such an IPP can only operate with access to a grid (Golubova, 2016; Eberhard, Kolker, & Leigland, 2014; THEnergy ANALYSIS, 2017). Hence, a PPA requires a contract between a generator and a well-defined user whereas an IPP mechanism does not require such a use contract, but rather a feed-in agreement. Both mechanisms can be used for the integration of RE into the mining industry under different conditions of (i) off-grid and (ii) on-grid. The requirement to employ capital-intensive technology with a high up-front high investment requiring a long amortization period is common to both. Table 4 shows that PPAs are strongly correlated with off-grid locations of the mines. However, three mines operate their own RE projects. Hence, mine operators have a choice of "make or buy" in the classical sense of procurement.

Table 2
Characteristics of the mines implementing RE.

Country	**Australia**	**Canada**	**South Africa**
Name	**Rio Tinto (Weipa)**	**Diavik Diamond**	**SNIM Company**
Type of mine	Open-pit	Open-pit and underground	Open-pit
Location	Lorim Point on the Embley River	20 square kilometer island, at Lac de Gras, Northwest Territories, power lines carry 13,800 kV	Kedia d'Idjil area of northern Mauritania
Total production, t/year	26 million	up to 2 million	11–12 million
Date of construction and lifespan	1963	2003 (16–22 years)	1952
Logistic characteristics	19 km of railway to transport mined bauxite to the port area, two stockpiles and two ship loaders	One road, built out of ice and crossing frozen lakes, joins the mine with other operations and Yellowknife	Port facilities at Nouadhibou on the Atlantic coast, with power plants and linked by a 700 km railway
Energy generation facilities	Two diesel engine power stations (26 MW and 10 MW)	Two power houses: five Caterpillar 3616 and four Caterpillar 3512s diesel engines producing each 4,4 MW, end 1,25 MW, four Caterpillar 3616s and two 3612s (3.3 MW each)	n/a
Climatic conditions	Tropical savanna (Aw)	Tundra (ET)	Warm desert (BWk)
Name	**DeGrussa Mine**	**Raglan Mine**	**Gold Fields**
Type of mine	Underground	Underground	Underground
Location	WA's Bryah Basin mineral province	Nunavik, more than 1800 km from Montreal	Mpumalanga region of South Africa
Total production, per year	67,154 t 37,386 oz	2014: 37,246 t nickel-in-concentrate 10,260 t copper-in-concentrate 777 t cobalt-in-concentrate	800,000 oz
Date of construction and lifespan	2012	1997–2041	1961–2080
Logistic characteristics	700 km of road to the Pilbara port of Port Hedland or the Mid West port of Geraldton	Bay seaport facilities, the 27,000-metric t capacity ice breaker (MV Arctic), a train 150-km road	Grid connected (Eskom), 95% of electricity from coal
Infrastructure	n/a	A fresh water supply source, a water treatment plant, fuel tanks, a power plant.	Two shaft systems. Average needs load 55 MW, to peak at 75 MW.
Climatic conditions	Warm desert (BWk)	Tundra (ET)	Humid subtropical (Cwb)
Country	**Chile**	**South Africa**	**West Africa**
Name	**Codelco**	**Gold Fields**	**IAMGOLD Essakane**
Type of mine	Open-pit	Underground	Underground
Location	100 km south of Calama in the Atacama Desert	The West Rand Goldfields situated in the geologically unique and world renowned Witwatersrand Basin	North-eastern Burkina Faso
Total production, per year	1,707,000 t (2016)	2.2 million oz (2014)	813 oz (2016)
Date of construction and lifespan	1971–2067	1887–2052	2010
Logistic characteristics	located in the middle of the Atacama Desert, 1650 km north of the capital city of Santiago, and is 2870 m above sea level	n/a	n/a
Infrastructure	n/a	two shaft systems that mine various auriferous conglomerates from open ground and pillars that occur at depths between 1575 m and 3500 m below surface	n/a
Climate conditions	Cold desert (BWk)	Humid subtropical (Cwa)	Warm semi-arid (BSh)

n/a - data missing/not available.

3.4. Cost analysis of RE integration in a mining operation

The global mining industry consumes around 400 TWh of electricity a year. Moreover, the Navigant Research Report (Richard, 2014) shows that by 2020 more than 1438 MW for mining operations will be deployed by RE globally. This contribution of RE to mining can lead to reduced fossil fuel consumption by up to 0.04% worldwide which aids the decarbonization of mining operations. Moreover, mining companies have less exposure to the volatility of fossil fuel prices and, eventually, of carbon emission prices. In as much as RE technologies benefit from decreasing costs, they also benefit economically.

Taking the example of Germany up to 2030, a long-term downward tendency of LCOE is expected and, with RE technologies replacing fossil fuel technologies in electricity generation, its current share of more than 40% of Germany's total GHG emissions will decrease (Appunn, 2016). Moving to the worldwide mining industry, a similar cost analysis can be registered and it sets incentives for the integration of RE into mining. Fig. 1 shows a historical comparison of electricity generation cost from solar PV and diesel in Australia. It is interesting to see that, in 2005, the generation of 1 MWh from Solar PV had a cost of around 900 $/MWh and the same amount of electricity with diesel could be generated at 200 $/MWh excluding Capital Expenditure (CAPEX). In 2011, this

Table 3
Criteria used for the second step of the analysis of the case studies.

Criteria	Unit
Type of extracted resource	–
Location of the mine	–
Type of RE source	–
Generation capacity	MW
Output capacity	GWh/year or MWh/tn Cu
Government regulatory mechanism	–
Diesel saving	L/year
General mine's energy consumption	L/year
GHG emissions reduction	t/year
Total project value	–
Special features	–

situation changed completely, as cost differences disappeared.

For a mine operator, taking especially fossil fuel costs as a key component of overall energy costs, this development brings a PV project closer. Referring to Fig. 1, it is clear that before 2011 a mine operator investing in a PV project suffered a dead loss, as shown by the vertical lines 1, 2 and 3. As of 2011, this dead loss vanished. In as much as the long-term downward tendency of PV LCOE will continue, 2011 can be considered as a decisive “year of no return” (BREE, 2012).

3.5. Cost analysis of RE integration in a mining operation: a quick decision rule

Continuing along this development and for a given level of PV CAPEX, diesel costs must be above a certain level to consider a PV project as a viable alternative to a diesel plant. Fig. 2 shows a quick decision rule to evaluate this trade-off. The straight line DP represents the trade-off boundary of indifference between a PV project (indicated by its capital cost CAPEX per MW) and a diesel plant (indicated by the diesel price). Obviously, the higher CAPEX per MW, the higher must be the diesel price for this indifference. Hence, for any given CAPEX per MW, the space below DP covers opportunities in which diesel plants are favoured over PV projects and the space above DP covers opportunities in which PV projects are preferable to diesel plants. By way of examply, at $\overline{P_{d1}}$ and at $\overline{P_{d2}}$ there are benchmarks of a small-scale and large-scale PV project, respectively.

3.6. Cost analysis of RE integration in a mining operation: PV project and diesel plant lifetime

The quick decision rule presented in Fig. 2 is static in the sense that it applies a principle of indifference for a given constellation of

Table 4
Case studies analysis on RE projects in mining operations.

Country	**Australia**	**Canada**	**South Africa**
Name	**Rio Tinto (Weipa)**	**Diavik Diamond**	**SNIM Company**
Type of extracted resource	Bauxite	Diamonds	Iron ore
Location of the mine	Off-grid	Off-grid	On-grid
Type of RE source	Solar PV	Wind	Wind
Generation capacity	1.7 MW	9.2 MW	5 MW
Output capacity	2.6 GWh/year	20.8 GWh/year	19 GWh/year
Government support mechanism	15-year PPA	n/a	IPP
Diesel saving, L/year	up to 600,000	5.2 million (11% of total saving)	3.025 million
General mine's energy consumption, L/year[a]	n/a	42.3 million	n/a
GHG emissions reduction, t/year	1600	14,404 (7.2% of total emissions)	11,500
Total project value	$3,500,000	$31,000,000	n/a
Special features	n/a	Availability rate of the wind farm is 98% Payback 7 years	n/a
Name	**DeGrussa Mine**	**Raglan Mine**	**Katanga region**
Type of resource	Copper-Gold	Nickel-copper	Copper
Location of the mine	Off-grid	Off-grid	Off-grid
Type of source	Solar PV	Wind	Hydro
Generation capacity[a]	10.6 MW	3 MW	
Output capacity	21 GWh	n/a	2.8–4.5 MWh/tn Cu
Government regulatory mechanism	5,5-year PPA	n/a	PPA
Diesel saving, L/year	5 million (about 20% of total diesel consumption)	2.5 million (5% of total saving)	n/a
General mine's energy consumption, L/year[a]	25 million	50 million	n/a
GHG emissions reduction, t/year	by over 12,000	1000	n/a
Total project value	$40,000,000	C$3,500,000	n/a
Country	**Chile**	**South Africa**	**South Africa**
Name	**Codelco**	**Gold Fields**	**IAMGOLD Essakane**
Type of resource	Copper	Gold	Gold
Location of the mine	Off-grid	Off-grid	Off-grid
Type of source	Solar PV	Solar PV	Solar PV
Generation capacity	34 MW	40 MW	15 MWp
Output capacity	n/a	100 GWh/year	n/a
Government regulatory mechanism	No	25 years PPA	15 years PPA
Diesel saving, L/year	20 million	up to 20%	6 million
General mine's energy consumption	80% of the annual energy demand for the heating of water	500GWh	n/a
GHG emissions reduction, t/year	15,000	100,000	18,500
Total project value	n/a	n/a	USD 20 million

n/a. not available.
[a] self-calculated.

Table 5
Project values per GWh and MW.

Name/Country	GHG emissions reduction per GWh of RE, t/GWh per year	Diesel savings per MW of RE, L/MW per year
Rio Tinto (Weipa)/Australia	615.38	352,941.18
DeGrussa Mine/Australia	571.43	471,698.11
Diavik Diamond/Canada	1565.65	565,217.39
Raglan Mine/Canada	333.33	833,333.33
SNIM Company/South Africa	605.26	605,000.00
Katanga region/South Africa	n/a	n/a
Gold Fields/South Africa	1000.00	n/a
IAMGOLD Essakane/South Africa	n/a	400,000.00
Codelco/Chile	348.84	588,235.29

PV CAPEX per MW and a corresponding diesel price. From a strictly economic point of view, a comparison of CAPEX of one energy technology and of fuel cost of another energy technology is not valid. From a business point of view, this makes sense if a Cash-Flow approach is used to evaluate a diesel plant and a PV project comparatively. Obviously, both technologies require CAPEX, but, in the case of a PV project, CAPEX is the dominating part of the overall costs "costs of ownership", whereas, for a diesel plant, fuel costs tend to dominate within the "costs of ownership". This dual effect is reinforced by the lifetime of projects and plants. The longer the lifetime of a diesel plant, the higher the relative share of accumulated diesel costs and the lower the share of the CAPEX in the "costs of ownership". By analogy, for a PV project, with an increase of lifetime, the relative share of CAPEX within the "costs of ownership" decreases and the relative share of operating costs increases. The fundamental difference between both technologies consists in the fact that electricity from a PV project has no fuel costs. Hence, with lifetime increasing, the required cash-flow to operate a diesel plant increases more rapidly than the cash-flow to operate a PV project. In cases where CAPEX per MW is higher for a PV project than for a diesel plant, this comparative disadvantage decreases over time. Fig. 3 illustrates the lifetime effect on the decision rule shown in Fig. 2.

It is assumed that CAPEX per MW of a PV project (CAPEXpv) is higher than CAPEX per MW for a diesel plant (CAPEXd), but, with increasing lifetime, the "costs of ownership" of each technology develops differently. Since a PV project has no fuel costs, the increase of its "costs of ownership" (Cpv) is less than the increase of the "costs of ownership" (Cd) of a diesel plant. As a result, Fig. 3 shows a break-even point at B (above referred to as the "year of no return").

In addition, the long-term downward tendency of (PV) LCOE has to be taken into account. This leads to a dynamic decision rule accounting for a timeline of "years of no return" instead of a single "year of no return".

Fig. 4 shows this dynamic decision rule in a three dimensional diagrammatic representation. The lifetimes of the PV project and the diesel project are measured along the "Lifetime" axis. Along the "Time" x axis, the long-term downward trend of PV LCOE is measured. The vertical "Costs" axis is used to measure the (increasing) "costs of ownership" of a PV project and a diesel plant. Both "costs of ownership" are represented by the curve shaped bodies Cpv and Cd. It is assumed that the "costs of ownership" of a diesel plant do not vary together with the downward trend of PV LCOE, but that assumption is not fundamental. With progressing lifetime and with decreasing PV LCOE, the timing of the break-even "costs of ownership" is "brought forward". Hence, in the three-dimensional representation, all break-even points across time are combined in a break-even pathway.

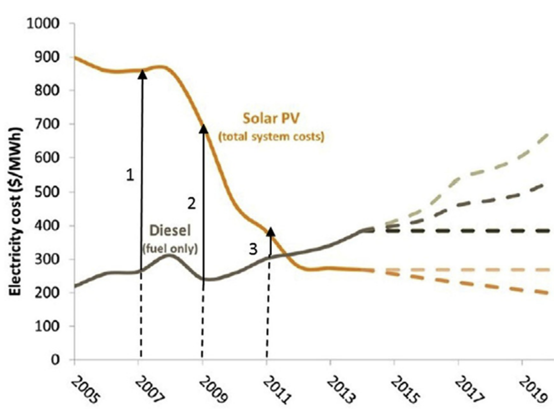

Fig. 1. Solar PV cost comparison with diesel fuel-only costs in Australia. Adapted from AECOM and ARENA (2014).

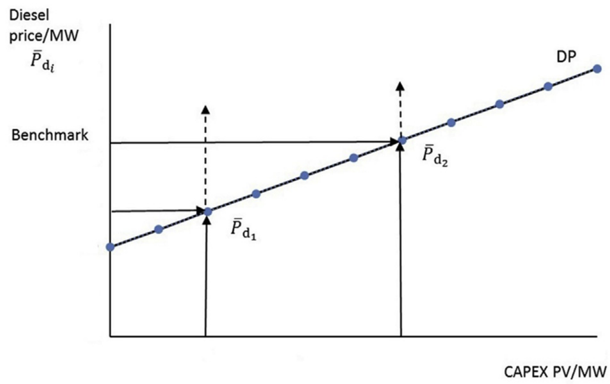

Fig. 2. Quick decision rule for the evaluation of a PV project by a mine operator.

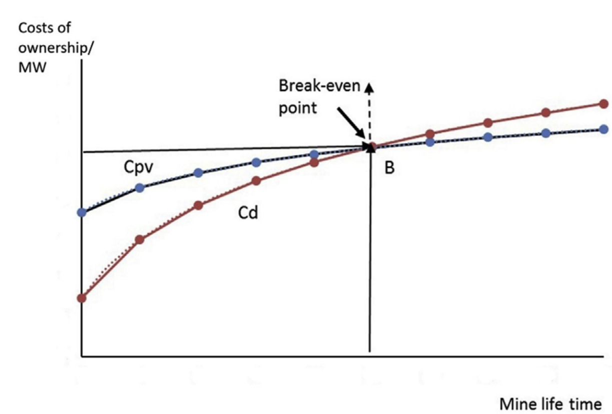

Fig. 3. Diesel and PV costs of ownership per MW considering a mine's life time effect.

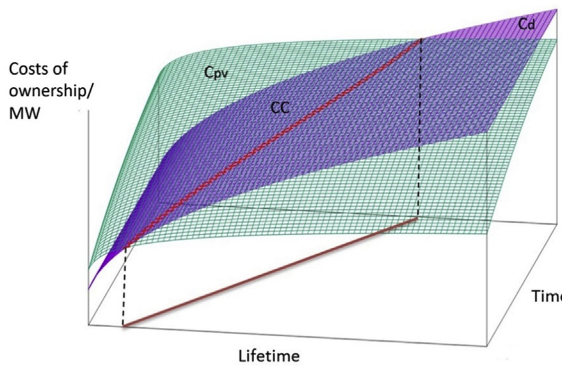

Fig. 4. Dynamic decision rule in a three dimensional diagrammatic representation.

The green body represents the PV LCOE ("costs of ownership") as they accumulate with the lifetime of the PV project ("Lifetime axis") and as they decline with the long-term downward tendency ("Time" axis). It is assumed that, at lifetime 0, the PV LCOE ("cost of ownership") is higher than the "costs of ownership" of the diesel plant – (the green body is "above" the pink body). Since, with increasing lifetime, the increase of the "costs of ownership" of the diesel plant is higher than the increase of the PV "costs of ownership", the green body "cuts through" the pink body from below after some lapse of time, then the pink body "is below" the green body. For each initial level of PV LCOE, this "cutting" time lapse is different and the time lapses shorten with the long-term downward tendency. The "cutting" curve (CC) represents the timeline of the "years of no return". Fig. 5 shows the dynamic decision rule in a three dimensional diagrammatic representation in four (a, b, c, d) views.

3.7. SWOT analysis

Based on the analysis of the case studies, the comparative cost analysis and the static and dynamic decision rules, a summary of the attractiveness of RE projects in mining, from the point of view of a mine operator, can be presented in a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis. As is well known, the objective of any SWOT analysis is to identify key internal and external factors which are important for achieving a given objective (Paschalidou, Tsatiris, & Kitikidou, 2016; Phadermroda, Crowder, & Wills, 2017; Polat, Alkan, & Sürmeneli, 2017; Shi, 2016). The outcome of the SWOT analysis of RE projects in mine operations is shown in Table 6. It should be noticed that such a SWOT analysis may comprise many more elements which are not considered in this paper. However, the elements of Table 6 are all relevant for preferential decision-making by a mine operator towards RE technologies.

4. Conclusions

This paper has reached the following conclusions.

The analysis of the case studies has three main results: (i) in principle, the technological characteristics of mines have no impact

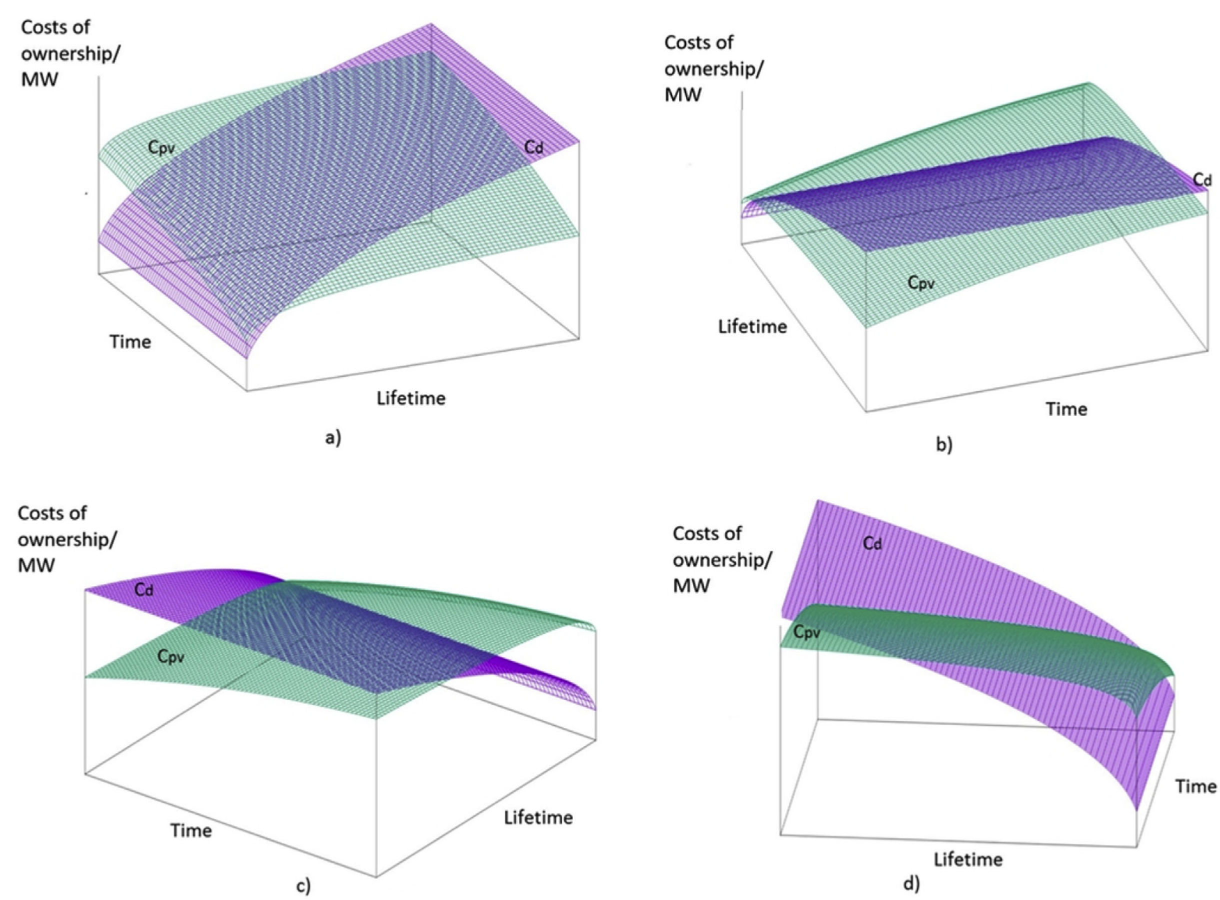

Fig. 5. Dynamic decision rule in a three dimensional diagrammatic representation in four (a, b, c, d) views.

Table 6
SWOT analysis of RE projects in mining operations.

Environment	POSITIVE	NEGATIVE
	Strengths	**Weaknesses**
INTERNAL	RE projects are applicable to a large variety of mining operations, independently of their characteristics (Table 2). Grid connections allow for a IPP arrangement as a "buy" option instead of a "make option" (Section 3.3). Off-grid locations allow for a PPA arrangement as a "buy" option instead of a "make option" (Section 3.3). CAPEX of RE projects may be higher than CAPEX of fossil fuel projects but RE projects bear no risk of future fuel costs developments (Fig. 1). CAPEX of RE projects may be higher than CAPEX of fossil fuel projects but RE projects have no fuel costs and, hence, become more attractive with project lifetime (Fig. 3). Combinations of RE projects and fossil fuel plants (HESs) increase security of energy supply (Tables 2 and 4). RE projects imply reduced GHG emissions benefits – giving mine operators an opportunity to contribute to Climate protection policies of their host countries (Table 4).	Focus on off-grid locations may distract mine operators from RE projects in the presence of grid connections (Table 2). Especially with grid connections, electricity procurement arrangements may demotivate mine operators to develop a preference for RE. The "buy option" may detract mine operators from a preferential use of RE in favor of a fossil fuel plant for reasons of secure energy supply. RE projects may require higher CAPEX than fossil fuel plants (Section 3.6). Mine operators may take a wait-and-see attitude towards the long-term downward tendency of RE CAPEX and postpone decisions about RE projects (Fig. 4).
	Opportunities	**Threats**
EXTERNAL	The LCOE of RE technologies, especially PV and wind power are declining over time (Fig. 1). Competent RE technology partners may enhance preferences for RE projects of mine operators. Harsh logistics conditions for fossil fuel transport increase preferences for RE projects (Table 2).	Climatic and geographical conditions may limit the choice of specific PV technologies (Table 2). Absence of competent RE partners may demotivate a mine operator to consider an RE project. Absence of government regulatory mechanisms may lower incentives to invest in RE projects (Section 3.3). High CAPEX for RE project may demotivate providers of finance.

on their RE projects and do not impose any barriers. In addition, the use of RE in a mining operation becomes more attractive, the longer the mine life which, in itself, depends on a mine's mineral deposit characteristics. (ii) There are five solar-diesel and three wind-diesel projects with a generation capacity between 1.7 MW and 40 MW. The biggest project (40 MW) is operated by Gold Fields in South Africa. The largest RE wind-diesel system has a capacity of 9.2 MW (Diavik Diamond in Canada). (iii) Wind technology saves more GHG emissions per GWh than PV technology and substantial savings of diesel are achieved.

There are two government regulatory mechanisms (PPA and IPP) for the integration of RE into mining. PPAs appear to be strongly connected with off-grid locations of the mines. However, three mines operate their own RE projects. Hence, mine operators have the choice to "make or buy" in the classical sense of procurement.

For a mine operator, taking especially fossil fuel costs as a key component of overall energy costs, the long-term downward tendency of PV LCOE brings a PV project closer. In the case of Australia, in as much as this tendency of PV LCOE will continue, 2011 can be considered as a decisive "year of no return".

A quick decision rule for the integration of RE projects into mining operations has been developed, first as a static concept for given PV CAPEX and given diesel costs at a given moment in time, and, second, as a dynamic concept, taking the long-term downward tendency of (PV) LCOE into account. This leads to a dynamic decision rule accounting for a timeline of "years of no return" instead of a single "year of no return".

A SWOT analysis has been made as an overall summary to highlight the attractiveness and challenges of RE projects in mining from the point of view of a mine operator.

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Appendix A. Literature sources for the specific features of the case studies

Table A.7
Literature sources for the specific features of the case studies.

Name	Source
Rio Tinto Mine – Weipa	(Rio Tinto Weipa operations 2015 sustainable development report, 2015)
DeGrussa Mine	(Opportunity redefined: 2015 Annual report, 2015)
Diavik Diamond Mine	(Liezl, 2013)
Raglan Mine	(Reglan Mine, 2016)
SNIM Company	(SNIM, Mauritania, 2016)
IAMGOLD Essakane	(Slavin, 2017)
Katanga Mine	(Henin, 2016; Boussougouth, 2013)
Gold Fields	(Hamilton, 2016; Mineral Resources and Mineral Reserves Overview, 2009)
Codelco Mine	(LAMGOLD Corporation, 2017; Zuniga, 2015; Choi & Song, 2017)
World climate zones	(CLEAR confortable low energy architecture)

Appendix B. Literature sources for the case studies

Table B.8
Literature sources for the case studies.

Name	Source
Rio Tinto Mine - Weipa	(Rio Tinto - ARENA's new solar plant for Weipa mine starts operation, 2015)
DeGrussa Mine	(Lucas, 2016)
Diavik Diamond Mine	(Diavik Diamond Mine: Socio Economic monitoring Agreement Report, 2014; Liezl, 2013; Case study: Replacing diesel power with wind energy, 2014), (CANWEA)
Raglan Mine	(Escalante Soberanis, Alnaggar, & Merrda, 2015)
SNIM Company	(SNIM, Mauritania, 2016)
IAMGOLD Essakane	(Slavin, 2017)
Katanga Mine	(Henin, 2016; Boussougouth, 2013)
Gold Fields	(Stevens & Kortenhorst, 2016; Gold Fields – Enel Green Power South Deep Solar EIA, 2017; Integrated Annual Report, 2016)
Codelco Mine	(Dyrelung; Acron-Sunmark)

Appendix C. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jsm.2017.11.004.

References

Acron-Sunmark. Large-scale showcase project. http://arcon-sunmark.com/cases/codelco-minera-gaby-chile/(Accessed 10 July 2017).

AECOM, & ARENA. (2014). *Australia's Off-Grid Clean Energy Market. Research Paper*. Sydney: AECOM Australia Pty Ltd / Canberra: Australia Renewable Energy Agency.

Appunn, K. (2016). *Germany's greenhouse gas emissions and climate targets*. Clean Energy Wire. https://www.cleanenergywire.org/factsheets/climate-action-plan-2050-negotiating-path-decarbonisation. (Accessed 20 July 2017).

BREE. (2012). *Resources and Energy Statistics. Annual 2012*. Canberra: Australian Goverment - Bureau of Resources and Energy Economics.

Boussougouth, J. (2013). *Mining, the key to unlocking Africa's independent power producer markets* (Vol. 18). Private sector & development.

CANWEA. Case Study: Diavik Wind Farm: Wind energy helps reduce carbon footprint. Canadian Wind Energy Association. https://canwea.ca/wp-content/uploads/2013/12/canwea-casestudy-DiavikMine-e-web2.pdf (Accessed 10 October 2017).

Case study: Replacing diesel power with wind energy. (2014). Clencore. http://www.glencore.com/sustainability/case-studies/p/replacing-diesel-power-with-wind-energy/(Accessed 06 July 2017).

Chen, J., & Rabiti, C. (2017). Synthetic wind speed scenarios generation for probabilistic analysis of hybrid energy systems. *Energy, 120*, 507–517.

Choi, Y., & Song, J. (2017). Review of photovoltaic and wind power systems utilized in the mining industry. *Renewable and Sustainable Energy Reviews, 75*, 1386–1392.

CLEAR confortable low energy architecture. Climatic Zones of the World. https://www.new-learn.info/packages/clear/thermal/climate/diversity/world.html/ (Accessed 18 August 2017).

Diavik Diamond Mine: Socio Economic monitoring Agreement Report. (2014). Diavik Diamond Mines Inc., 1–18. http://www.riotinto.com/documents/Diavik_2014%20mid_year_socio_economic_monitoring_agreement_report%20July%202014.pdf/(Accessed 07 July 2017).

Dyrelung, A. Large-scale solar heating in Chile. State of Green. https://stateofgreen.com/en/profiles/ramboll/solutions/large-scale-solar-heating-in-chile/(Accessed 20 July 2017).

Eberhard, A., Kolker, A., & Leigland, J. (2014). *South Africa's renewable energy IPP procurement program: Success factors and lessons* (Vol. 56). Public-private infrastructure advisory facility (PPIAF).

Escalante Soberanis, M., Alnaggar, A., & Merrda, W. (2015). *The economic feasibility of renewable energy for off-grid mining deployment* (pp. 509–518). The Extractive industries and society. http://energyandmines.com/2017/03/new-renewable-energy-for-mine-project-iamgold-essakane-to-benefit-from-largest-hybrid-plant-in-africa/. (Accessed 20 July 2017).

Gold Fields – Enel Green Power South Deep Solar EIA. (2017). *Background information document* (pp. 25–28). http://www.erm.com/contentassets/37fff9ae359c4147abb41432a23f245e/south-deep-solar-draft-bid_may2017.pdf/. (Accessed 2 August 2017).

Golubova, A. (2016). The biggest opportunities for renewable are off-grid mines - Redavia's CEO. *Energy and Mines*. http://energyandmines.com/2016/09/the-biggest-opportunities-for-renewables-are-off-grid-mines-redavias-ceo/. (Accessed 15 August 2017).

Hamilton, T. (2016). *Mining industry starts to dig renewables*. The Magazine for Cleaner Kapitalism Corporate Knights. http://www.corporateknights.com/channels/mining/mining-industry-starts-to-dig-renewables-14648472/. (Accessed 25 August 2017).

Henin, A. (2016). *Microgrid energy storage systems (ESS) – Katanga mining case study*.

Hill, M., & Mitimingi, T. C. (2017). *Africa's biggest copper mine hit by Zambian power restrictions*. Bloomberg. https://www.bloomberg.com/news/articles/2017-08-15/africa-s-biggest-copper-mine-hit-by-zambian-power-restrictions/. (Accessed 10 May 2017).

IEA. (2016). *CO2 emissions from fuel combustion highlights* (Vol. 166). International Energy Agency. https://www.iea.org/publications/freepublications/publication/CO2EmissionsfromFuelCombustion_Highlights_2016.pdf. (Accessed 24 August 2017).

Integrated Annual Report. (2016). *Gold Fields* (pp. 1–132). https://www.goldfields.co.za/pdf/sustainbility/sustainability-reports/integrated-annual-review-2016.pdf/. (Accessed 5 August 2017).

Jung, J., & Villaram, M. (2017). Optimal planning and design of hybrid renewable energy system for microgrids. *Renewable and Sustainable Energy Reviews, 75*, 180–191.

Kim, J., Chen, J., & Garcia, H. (2016). Modeling, control, and dynamic performance analysis of a reverse osmosis desalination plant integrated within hybrid energy systems. *Energy, 112*, 52–66.

Kost, C., Mayer, J. N., Thomsen, J., Hartmann, N., Senkpiel, C., Philipps, S., et al. (2013). *Levelized cost of electricity renewable energy technologies* (Vol. 50). Fraunhofer institute for solar energy system ISE.

LAMGOLD Corporation. (2017). *Essakane Gold mine*. Burkina Faso http://www.iamgold.com/English/operations/operating-mines/essakane-gold-mine-burkina-faso/default.aspx/. (Accessed 10 August 2017).

Liezl, W. (2013). *Diavik wind farm project*. Diavik diamond mines inc. http://energyandmines.com/wp-content/uploads/2014/08/liezlvanwyk.pdf. (Accessed 15 July 2017).

Lucas, J. (2016). *DeGrussa solar power station begins operating*. The West Australian. https://thewest.com.au/news/wa/degrussa-solar-power-station-begins-operating-ng-ya-299400. (Accessed 15 September 2017).

Martin, R. (2014). *Renewable energy will supply at least 5 percent of power demand for the mining industry by 2022*. Navigant Research-Press Release. https://www.navigantresearch.com/newsroom/renewable-energy-will-supply-at-least-5-percent-of-power-demand-for-the-mining-industry-by-2022. (Accessed 21 August 2017).

Mineral Resources and Mineral Reserves Overview. (2009). *South deep Gold Mine: Technical short form report*. Gold Fields. https://www.goldfields.co.za/reports/rr_2009/tech_south.php/. (Accessed 10 August 2017).

Mining with principles. (2017). International Council on Mining & Metals. http://miningwithprinciples.com/(Accessed 05 October 2017).

Opportunity redefined. (2015). *2015 Annual report* (Vol. 128). Sandfire resource NL. http://www.sandfire.com.au/images/files/reports/SFR_-_2015_Annual_Report_-_20_Oct_15.pdf/. (Accessed 10 August 2017).

Paschalidou, A., Tsatiris, M., & Kitikidou, K. (2016). Energy crops for biofuel production or for food? - SWOT analysis (case study: Greece). *Renewable Energy, 93*, 636–640.

Phadermroda, B., Crowder, R., & Wills, G. (2017). Importance-performance analysis based on SWOT analysis. *International Journal of Information Management, 10*.

Polat, Z., Alkan, M., & Sürmeneli, H. (2017). Determining strategies for the cadastre 2034 vision using an AHP-based SWOT analysis: A case study for the Turkish cadastral and land administration system. *Land Use Policy, 67*, 151–166.

Reglan Mine. (2016). Glencore. http://www.mineraglan.ca/EN/Pages/default.aspx/ (Accessed 05 July 2017).

Richard, M. (2014). *Renewable energy will supply at least 5 percent of power demand for the mining industry by 2022*. Navigant Research-Press Release. https://www.navigantresearch.com/newsroom/renewable-energy-will-supply-at-least-5-percent-of-power-demand-for-the-mining-industry-by-2022. (Accessed 10 July 2017).

Rio Tinto - ARENA's new solar plant for Weipa mine starts operation. (2015). *World of wining - surface & underground* (Vol. 67, p. 295).

Shi, X. (2016). The future of ASEAN energy mix: A SWOT analysis. *Renewable and*

Sustainable Energy Review, 53, 672–680.

Slavin, A. (2017). New renewable energy for mine project – IAMGOLD Essakane to benefit from largest hybrid plant in Africa. *Energy and Mines*. http://energyandmines.com/2017/03/new-renewable-energy-for-mine-project-iamgold-essakane-to-benefit-from-largest-hybrid-plant-in-africa/. (Accessed 26 August 2017).

SNIM Mauritania. (2016). *Mining technology.com*. http://www.mining-technology.com/projects/snim/. (Accessed 2 August 2017).

Stevens, D., & Kortenhorst, J. (2016). Integrating solar power into Gold Fields' South deep mine. *Energy and Mines*, 1–21. http://energyandmines.com/wp-content/uploads/2016/08/Duncan-Stevens-CWR.pdf/. (Accessed 20 July 2017).

THEnergy ANALYSIS. (2017). Solar-diesel and Wind-diesel Microgrids for Off-grid Mines Gain Momentum e New Projects Expected. *THEnergy sustainable consulting*. https://www.th-energy.net/2017/05/15/thenergy-analysis-solardiesel-and-wind-diesel-microgrids-for-off-grid-mines-gain-momentum-newprojects-expected/. (Accessed 25 July 2017).

UNFCCC. (2015). *Adoption of the Paris agreement, proposal by the President, draft decision -/CP.21*. United Nations Framework Convention on Climate Change (UNFCCC). FCCC/CP/2015/L.9/Rev.1 https://unfccc.int/resource/docs/2015/cop21/eng/l09.pdf/. (Accessed 3 August 2017).

Zahraee, S., Assadi, M., & Saidur, R. (2016). Application of artificial intelligence methods for hybrid energy system optimization. *Renewable and Sustainable Energy Reviews, 66*, 617–630.

Zuniga, R. (2015). *Modeling of supply chain processes of the mineral raw materials industry from the perspective of EM*. Bremen: SCOR and DCOR models. https://elib.suub.uni-bremen.de/edocs/00104724-1.pdf. (Accessed 15 September 2017).