



BUSINESS PLAN DEVELOPMENT FOR THE IMPLEMENTATION OF THE BEST AVAILABLE TECHNIQUE (BAT) TO RAISE ENERGY EFFICIENCY IN THE GOLD MINING PROCESSING INDUSTRIES. CASE STUDY IN SUDAN

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Abstract: *Improving energy efficiency in gold mining is both an economic and environmental essential, especially as energy costs rise and sustainability standards tighten. This study includes a complete business plan for developing and implementing Best Available Techniques (BAT) to improve energy efficiency in gold mining production. The suggested approach includes technological, financial, and operational strategies to maximize energy usage in crushing processes. The study identifies high-impact BAT solutions, including enhanced grinding technology, energy-efficient crushing systems, and renewable energy integration. A cost-benefit analysis shows that, despite initial capital investment, these solutions provide significant long-term benefits through reduced energy usage, fewer greenhouse gas emissions, and greater operational performance. The business plan details the implementation phases, risk assessment, and finance. It also handles regulatory compliance and conformance with international sustainability standards (ISO 9001:2015, ISO 14011:2015, and ISO45001:2018), which have already been adopted by the Sudanese firm enterprise. In this study, the solar trailers are presented as an energy source covering consumption in crushing processes in gold mining processes by an enterprise in Sudan. This project gives positive economic results in reducing gas emissions, environmental savings around 145,000 EUR per year, and a payback period for the project of only one year.*

Keywords: *Environmental impact, Sustainable energy, crushing processes in mine, Green mining, solar trailer, CO₂ emission, Feasibility study of BAT*

1. Introduction

The Best Available Technique (BAT) refers to the technology used to manufacture goods, perform operations, and provide services based on current scientific and technological advancements. It is the best combination of criteria for achieving environmental protection goals within the available technical capabilities. Environmental compatibility and energy efficiency are key factors in the development of several economic sectors, such as mining. Improving energy efficiency leads to significant energy savings in several countries worldwide [1]. Chinese scholars invented sustainable development in mining processes. The world has traditionally relied on mining to maximize profit. Green mining GM was given away as an alternative to optimum economic advantage based on environmental protection theory and ecology [2]. Green and climate smart mining were proposed to study all stages of the mining life cycle. The goal is to reduce climatic impact and address environmental and sustainability issues in mining, leading to cleaner mineral exploitation [3]. Moreover, the concept of GM changed over time. Initially, it focused on greening mining regions but has since evolved to include optimal use of nonrenewable natural resources [4]. However, GM has several fundamental misunderstandings. The first is the tension between resource scarcity and waste. The second is the disagreement between economic development and environmental protection. The third is the contradiction

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between technology research and development (R&D). The development of GM technology is the main driving force for the realization of the green transformation [5]. Fuel and power are considered 20% of the operating cost. A data analysis study conducted for five gold companies presented this result. Another analysis study shows that 65% of CO₂ is emitted from fuel in gold mining. Regarding this, thinking about reducing the consumption of fuel is the main goal for BAT in the field of mining [6], [7]. Renewable energy systems (RE) are a generally recognized strategy for addressing environmental issues, particularly reducing greenhouse gas emissions (GHG). This will support societies in achieving Sustainable Development Goals (SDGs). In the past two decades, mining companies have made efforts to integrate renewable energy technologies into their operations, addressing environmental problems. RE sources can potentially supply the mining operation with energy in different forms. RE systems have potential for remote places, end consumers, and post-mining applications, which are often missed. These systems have significant promises, particularly for economic and environmental benefits, which are being explored further [8]. Gold production is thought to be the mining industry's most energy- and greenhouse gas-intensive metal per unit produced, and this trait is probably going to continue as high-grade gold reserves run out. In contrast to the manufacture of iron and steel, which heavily relies on fossil fuels for heat processing and feedstock processing, the production of gold requires a significantly larger quantity of electricity, offering more options for the integration of renewable energy [9]. For that reason, the RE system was theoretically studied in one of the mining enterprises in Sudan as a case study. The aim of this study is to consider the possibility of using these technologies to increase productivity, reduce fuel costs, and reduce environmental effects. Photovoltaic systems have been used in several operational mines worldwide. In South Africa. A significant 100 MW solar plant was installed at the Mogalakwena platinum mine in 2023. Another project in South Africa involves a 50 MW solar facility; this project reduces the mine's carbon emissions by around 110,000 tons annually. In Chile, 2019, built a pilot photovoltaic plant with 87 kW capacity in a copper mine. The system reduces 58 tons annually of emissions. A 70 MW floating solar power plant was installed in China in a coal mining area and decreased carbon dioxide emissions by 150,000 tons per year. In Poland a 70 MW solar power plant was planned to achieve a major environmental objective that was reducing emissions by 56,700 tons per year. to reduce carbon emissions in North America, constructed solar plants with 100 MW in coal mines. In Germany, a 170 MW photovoltaic facility had been built over an abandoned lignite open cast mine with a capacity of 300 MW. Saudi Arabia is building the largest solar processing heat plant in the world, with a capacity of 1500 MW. The environmental goal is to reduce emissions by over 600,000 tons per year [10]. In Sudan, this is the first time a SE system has been investigated for implementation in a gold mining operation.

2. Specification of the enterprise

Sudan's gold mining industry produces approximately 90 tons of gold annually, ranking it as the world's tenth largest producer. They are one of the largest gold miners in Sudan. Furthermore, the enterprise is among Africa's top five mining groups. The strategic goal is to optimize and improve operations and technologies through effective sustainable development solutions. To attain optimal operational performance, the enterprise is focusing on waste management and the utilization of modern equipment. The enterprise was the first private mining company in Sudan to work in gold mining, contributing significantly to the country's economy [11].

2.1 Environmental strategy of the enterprise

The enterprise has worked diligently to reduce its negative environmental impact and provide risk-reduction solutions for operational technologies. The enterprise has already worked on high-quality productivity through management, technology, and leadership assessments, as well as new employee training programs. The enterprise vision is accomplished at a high level of health, safety, and environmental performance. In addition, the company was the first to process artisanal gold tailings in Sudan. They always strive to minimize environmental impact as much as possible in order to find solutions to reduce risk and create a safe environment for all environmental activities that aim to achieve high levels of environmental precautions in the organization. They started to develop its energy industry, which includes renewables, as the next source of power generation to support Sudan's mining sector in addition to the other industrial and agricultural sectors. GM's program began with inspiring many other mining corporations to engage in solar PV conversion to reduce carbon emissions from the mining industry while also adding value by offering alternate sources of energy to these growing industries. They have already established good relationships with numerous developers in the renewable energy sector and are rapidly becoming one of Sudan's leading privately owned power producers. Renewable energy's environmental benefits, such as lower carbon footprints and reduced air pollution, have been widely recognized for decades. Its numerous socio-economic benefits, however, have only become apparent in recent decades as the deployment of RE technologies has become more widespread.

2.2 Technical operations in the gold mining industry take into consideration environmental problems

There are numerous methods and technologies used in gold mining; one of the most common is CIL (carbon in leaching). Fig1. CIL is commonly used in high grades of ore material because it gives the best result in the gold recovery parameters, about 98%. First, the ore material must be crushed to a tiny size using a jaw crusher. These crushers emit a lot of dust into the surrounding environment. The first environmental difficulty is dust, which is also an economic problem because dust contains a high grade of gold, and emitting dust into the air is regarded as a loss of profit. Furthermore, due to the mixing of mine ore with waste ore from random miners, the ore material contains mercury. The ore material must be milled in order to be obtainable for cyanide leaching by ball milling (wet grinding). Ball milling produces dust waste; nevertheless, it is small when compared to crusher dust. Following this, in the thickener processes, the density and pH parameters might have to be increased prior to cyanide leaching. The CIL process has many tanks connected by a hot air system. After thickening, cyanide was transferred to the first tank for leaching, followed by activated carbon from tank two, even before reaching the last tank. The CIL system in the production plant consists of eight tanks. The first involves cyanide leaching from tank number two to tank number seven for carbon adsorption, followed by the feed filter in tank number eight. The filter separates water and solid waste. The leftover cyanide in the landfill leaches into groundwater sources, contaminating them. The rich carbon is processed using desorption and electrocell equipment; to recover gold from the carbon, pure carbon must be reintroduced into the process. The gold muck is fed into smelting equipment, which depends on chemicals and energy to extract pure gold. Many of the emissions into the atmosphere in CIL operations come from electrocells and furnace gold muck; also, high energy usage resulted in a significant quantity of carbon emissions [12]. Although renewable energy is becoming more common in the mining industry, technical challenges continue to hinder its capacity to meet operational needs. Mining operations require considerable, high-quality, and generally steady energy supply, often 24 hours a day, seven days a week [13]. High capacity was used in the enterprise, leading to huge different environmental problems. In general, the process approaches in mining manufacturing consist of many hazardous chemical materials, such as cyanide, which dissolves in water. The solid waste in the landfill consists of this water, which probably moves to the groundwater source. Furthermore, air pollution is due to ore crusher equipment. This BAT study is carried out to reduce CO₂ emissions in the crusher process as well, reducing consumption of fuel in this mechanical system. Crushing techniques include working in batches, which may shut down during production. Furthermore, the company has two crushers in manufacturing. Crusher processes are more productive than other processes in gold mining manufacturing; therefore, consider RE with no operational troubles.

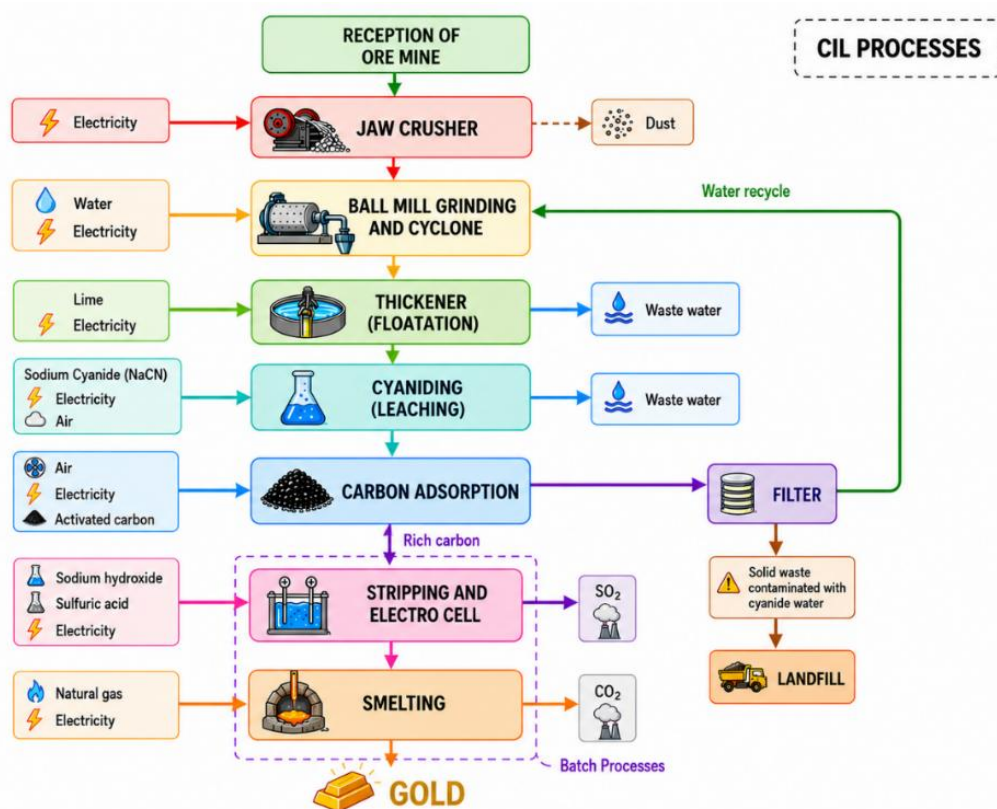


Fig. 1. CIL technology flow chart

3. Jaw crusher

A jaw crusher is a large piece of equipment that's used in mines and ore processing plants to crush rocks. Jaw crushers have seen plenty of action in the pit and quarry industries as well as in recycling processes where large materials need to be reduced. Jaw crushers use compressive force to break down large materials into smaller, more manageable pieces. The jaw crusher has two crushing jaws: one stationary and the other moving, which together produce mechanical pressure to crush the materials. The two vertical crushing jaws create a V-shaped opening called the crushing chamber, where the materials are dropped off, as shown in Fig.2.

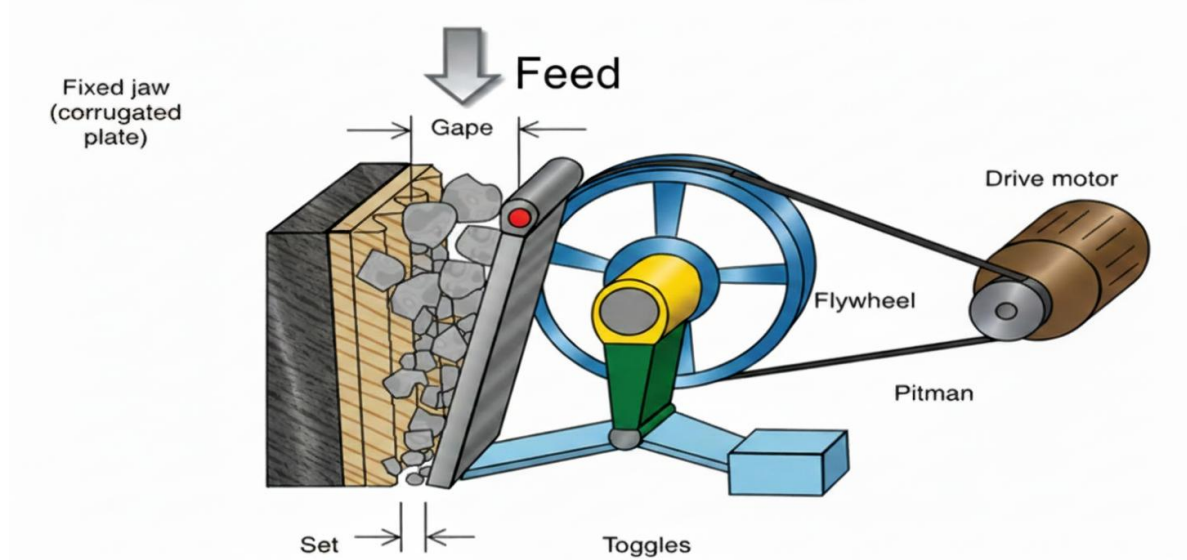


Fig. 2. Jaw crusher equipment's

3.1 Sources of waste generation and other types of negative impact on the environment

Following a study of the production processes, it is required to identify the exact stage of primary or auxiliary production where the cause of the environmental problem is located. It is essential to quantify the problem using an ecological, material, or energy balance and demonstrate its significance in contrast to others. Ecological balance is shown in Fig.3.

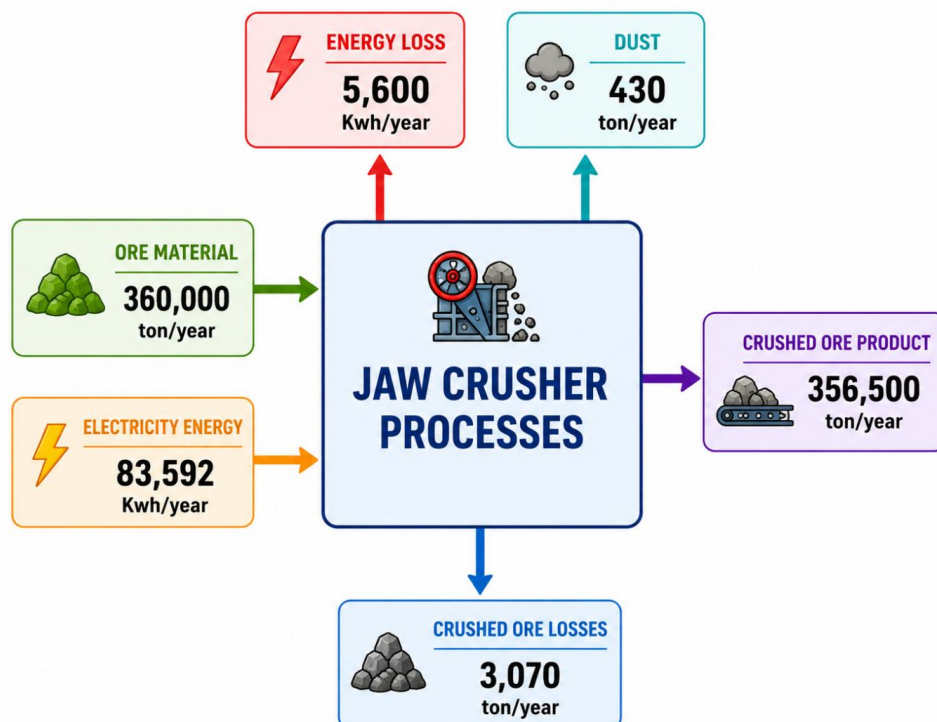


Fig. 3. Ecological balance of jaw crusher production

A few facts and assumptions about the enterprise 's crusher operations as demonstrated:

- CIL capacity in the manufacture 1000 ton/day = 360,000 ton/year.
- Average grade was used in this mining area by enterprise 2.5gGold/ton Ore.
- The capacity of manufacturing 1000 ton. Ore/day (360,000 ton/year) to produce approximately 855 kg. Gold/year when recovery of processes is about 95%.
- The global market is used to determine cost of materials and for electrical sources used in Sudan.
- Duration of operation of equipment - 24 h a day.
- Amount of diesel fuel in the current situation: $20 \text{ l/hr} \cdot 24 \text{ hr} \cdot 360 = 172,800 \text{ l/year} = 145 \text{ ton/year}$
- Price of 1 ton diesel fuel [14] = $0.92(0.86)(\text{EUR/l}) \cdot 1000(\text{kg/ton}) \cdot 0.838(\text{Kg/l}) = 1032 \text{ EUR/ton}$

3.2 Emissions of pollutants into the atmosphere

Depending on the geochemical composition of the ore being processed, dust emissions may comprise both crystalline silica and trace metal-bearing particles. The consumption of diesel fuel in crusher operation emits combustion air pollutants such as NO_x, CO, SO₂, and CO₂, which have a negative impact on the environment. Overall, these emissions represent serious occupational and environmental health risks, including worker respiratory morbidity and metal-rich particle deposition in ecosystems. The quantitative and cost indicators that describe the problem of atmospheric air pollution induced by stationary source emissions are generally depicted in Figures 4 and 5 and quantified in Tables.1 and Table.2.

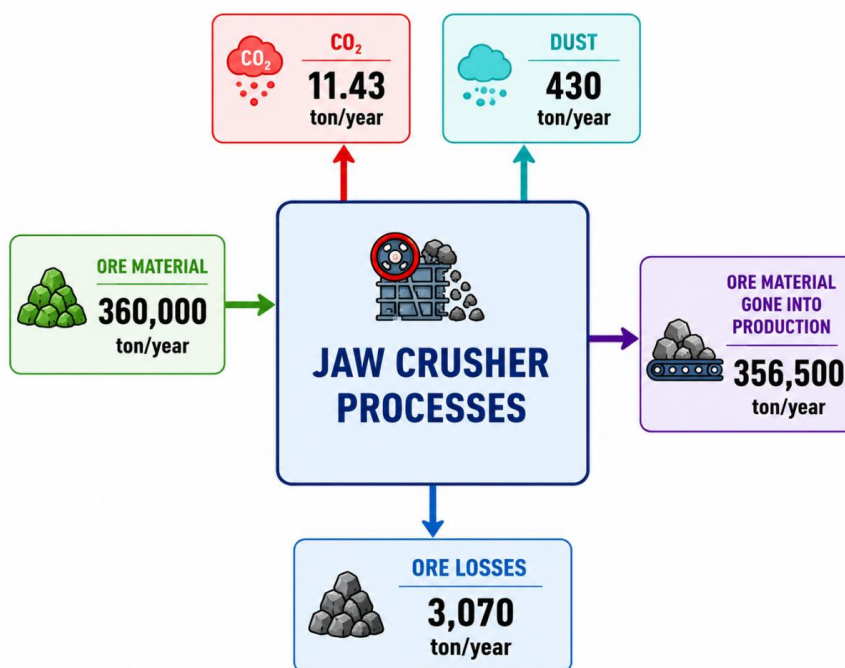


Fig. 4. Material balance of atmospheric emissions



Fig. 5. Economic losses

Table 1. Economic losses related to process of crashing

Name of losses in product	Amount, t/year	Average grade of gold, g in 1 t	Price per unit EUR/g	Missing profit, EUR/year
Crushed ore losses	3070	2.5	26.29	0.2 M
Dust	430	2.5	26.29	0,028M

Table 2. Environmental costs - payment for the Negative Environmental Impact

Name of impact	Amount, t/year	Price per unit,	%	Missing profit, EUR/year
Waste of 5 class - crushed ore losses	3070	0.48	45	839.13
Dust	430	1.32	80	571.99

4. Feasibility study of BAT

4.1 Technical assessment solution by RE

A mine possesses intrinsically elevated energy consumption owing to the substantial machinery, illumination, and necessary safety and ventilation systems. To improve their on-site electricity usage, mines frequently rely on noisy, emissions-producing diesel generators, which have high fuel and maintenance expenses. Replacing diesel generators and complementing unreliable grid power with local renewable energy sources has the potential to significantly decrease greenhouse gas emissions and costs by decreasing or eliminating production delays due to load shedding and power outages. Providing energy via environmental energy sources presents difficulties in obtaining sufficient electricity. The solar trailers (Fig.6) are completely self-sufficient with solar charging for battery power. Mobile light trailer towers with high-efficiency LED spotlights are used for on-site illumination in mining operations, powered by solar-recharged batteries (battery banks). This type of solar panel system operates automatically and does not require an operator to turn it on at night or off in the morning. A fully automated tower can operate for 28 hours without the presence of sunlight, equivalent to one day of autonomy. They are outstanding for mining. Characteristics for solar caravan systems selected in this study are shown in Table 3 [15].

Table 3. Characteristics of the solar trailer

Characteristics	Unit	Value/ description
Energy generation	kWh/day	7.6
Energy storage	kWh	15.84
Weight	kg	1050
Voltage	V	230
Battery martials		Lithium/Lead-acid
Company		SBP electrical
Contrary		Australia



Fig. 6. Solar trailer system in mine

Investment costs of the BAT project

The investment costs of a BAT solar trailer project in gold mining depend on a number of technical and operational factors, including the solar generation capacity, battery size, mobility requirements of the trailer, and the energy demand of the mining operation. Other cost drivers include transportation to remote mine sites, installation, control systems, and maintenance infrastructure. The structure of investments (I_0) is determined and is entered for the project in Table.4.

Table 4. The structure of the investment costs for BAT project

The name of the item	Cost, EUR	Note
Purchase of equipment	83,193.71	Three pieces of solar trailer
Project development	24,958.11	30 % from №.1
Installation and commissioning	9,983.25	12 % from №.1
Shipping and handling costs	4,159.69	5 % from №.1
Training	3,327.75	4 % from №.1
Other expenses	2,079.84	2.5 % from №.1
TOTAL: I_0	127,702.35	127,71ths EUR

Operating costs of the BAT project

Solar trailer plants often have lower running costs than conventional diesel generator systems since solar power eliminates the majority of fuel prices and reduces generator operation hours. The main operational costs are system maintenance, battery monitoring, solar panel cleaning, and battery replacement on a regular basis. The overall payout includes the time and effort: \$400 per month for each worker. Labor cost per year for the BAT project is calculated by equation (1). In Sudan, the social tax is 30.2% of salaries.

$$\text{Labor costs (LC)} = 4 \text{ people} \times 400 \text{ USD} \times 0.86 \times 12 \quad (1)$$

$$\text{Total LC} = \text{LC} + \text{Social tax} \quad (2)$$

By these equations, operating cost for one year was calculated in Table.5.

Table 5. Operating costs per one year for project

Name of the cost items	Unit Quantity	Quantity	Price per unit, EUR	Cost, EUR
Maintenance and repair	Ths.EUR		7% of equipment cost	5.82
Labor costs	Ths.EUR	4		18.05
TOTAL: C_0				23.87

4.2 Environmental savings

Mainly linked to decreases in diesel fuel consumption, greenhouse gas emissions, air pollutants, noise pollution, and environmental risks from fuel consumption. Solar trailers plant could assist to reduce their negative environmental effect by replacing diesel fuel generators. Reducing the negative environmental impact (Table.6) as a result of project implementation and environmental savings are presented in Table. 7 and 8 respectively.

For burning 1 kg of fuel, it requires 15 kg of air[16].

$$M_{\text{air}} = 1.5M_0 = 1.5 (15) = 22.5 \text{ Kg diesel/ Kg air.}$$

Density of air is requirement to calculate amount by ton.

$$\rho_{\text{air}} = 1.28 \text{ Kg/m}^3$$

$$V_{\text{air}} = 22.5/1.28 = 17.58 \text{ m}^3/\text{Kg fuel}$$

$$145\text{-ton fuel/ year. } (17.58) \text{ m}^3/\text{Kg fuel. } 1000 \text{ kg fuel/ton fuel} = 25491000 \text{ m}^3/\text{year}$$

$$M_{\text{co}} = 247. \cdot 10^{-6} \text{ kg/m}^3. 25491000 \text{ m}^3/\text{year} = 6.3 \text{ ton/year}$$

$$M_{\text{NO}} = 0.288 \text{ ton/year}$$

$$M_{\text{SO}_2} = 4.282 \text{ ton/year}$$

Table 6. Content of flue gases after burning diesel fuel

Gas emission mg/m ³	Amount mg/m ³
CO	247
NO	11.3
SO ₂	168

Table 7. Environmental assessment by BAT project

Project name	Environmental influence	Exposure profile		
		CO	NO	SO ₂
		t / year		
Solar panels station	Reduction Air pollution which produces in previous situation	6.3	0.288	4.282

Table 8. Environmental savings by BAT project

Environmental influence	Exposure profile		Price by EUR/ton	Savings, Ths.EUR/year
	Amount	%		
Decrease of using diesel fuel	145	100	1172.64	149,64
Decrease of payment for NEI, total				0.0035
including:				
CO t/year	6.3	100	0.019	0.00016
NO t/year	0.288	100	1.13	0,00041
SO ₂ t/year	4.282	100	0.55	0,0029
TOTAL:				149.65

4.3 Economic appraisal of BAT project

Economic savings due to reduction of air pollution and fuel energy in the crusher are shown in Table.9.

Table 9. Economic assessment of BAT project

Name of savings /costs	Current situation		After the project implementation		Economic savings	
	Amount	Sum, Ths.EUR	Amount	Sum, Ths.EUR	Amount	Sum, Ths.EUR
Reduction of pollution to the environment						0.0035
Reduction of fuel energy						149.64
Operating cost	-	-	-	23.87		-23.87
Total: net annual savings: (FV) B =						Σ 125.76

Payback period PB, years

Is the time required for an investment to get back its initial cost from the cash inflows it generates. It is calculated by equation (3).

$$PB = I_0 / B \quad (3)$$

where I_0 - investment costs, Ths.EUR; B - net annual savings, Ths.EUR/ year.

$$PB = 127,71 / 125.76 = 1.02 \text{ year.}$$

Net present value NPV

A financial metric that assesses the profitability of an investment by evaluating the present value of cash inflows and outflows over time. The NPV is calculated by the equation (4). If the NPV is positive, the project provides revenue. The calculation of the NPV of the BAT project of equipment operation is shown in Table.10. The project will yield a profit of up to 527,255.07 EUR within a period of 10 years.

Table 10. NPV calculation of BAT project

Year (y)	$(1+0.2)^y$	FV (B) Ths.EUR	PV Ths.EUR
0	1	-127.71	-127.71
1	1,2	125.76	104.80
2	1,44	125.76	87.33
3	1,728	125.76	72.78
4	2,074	125.76	60.63
5	2,488	125.76	50.55
6	2,986	125.76	42.12
7	3,583	125.76	35.09
8	4,299	125.76	29.25
9	5,159	125.76	24.38
10	6,191	125.76	20.32
		FV=1,129.89	NPV=527.26

The profitability index *PI*

It is an economic indicator that is used in capital budgeting to assess the viability of an investment or project. It calculates the ratio between the present value of future cash inflows (NPV) and the investment costs (I_0), as shown in equation (4). The BAT project scores PI about 4.1. A PI bigger than one means the project has remarkable economic results.

$$PI = \frac{NPV}{I_0} \quad (4)$$

The internal rate of return *IRR*

Is the nominal interest rate (rate of return) at which the NPV value is zero, i.e. the amount of discounted cash revenues is equal to the amount of discounted cash expenses. In fact, *IRR* is interpreted as the marginal level of return on investment. The internal rate of return was determined by the method of iterative selection of the discount rate r . As shown in Fig.7, the project remarked IRR around 32%.

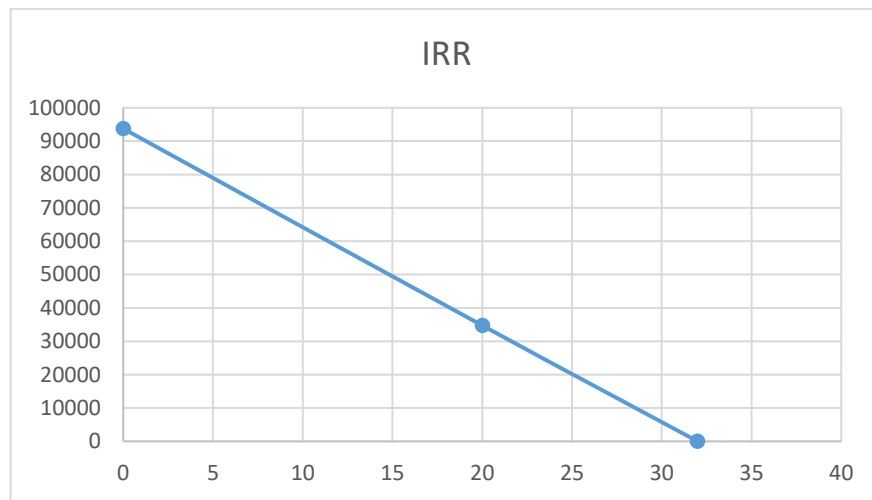


Fig. 7. IRR determination of BAT project

5. SWOT analysis

● Strength

Fuel cost in the gold mining operation has been decreased by the solar trailer system because this system is able to work temporarily without the need for a diesel generator. Using SE in mining helps enterprise achieve environmental stability by reducing the negative environmental impact caused by excessive energy consumption in the crushing process. When compared to a fuel generator system, a solar trailer system is more portable and requires less maintenance. Solar trailer systems contribute to reducing the noise pollution that gasoline generator systems produce. Moreover, this aligns with the company's social responsibility. The project is fully acceptable among stakeholders.

● Weaknesses

The system is predicted to have a high initial capital cost compared with that of a diesel generator. Less availability of sunlight during wind or rain affects energy generation. Continuous operation in crusher processes led to decreased battery efficiency due to the regular cost of replacing batteries.

● Opportunities

according to environmental stability. The enterprise will be a leader and a recognized brand in achieving sustainable development goals. Improve the system, strengthen its reliability, and formalize the training of the staff. It may reach into an important department within the structure of the enterprise that carries out regular research and development. The ability to integrate a system with wind energy is an effective opportunity for a stable power energy supply. Furthermore, stability and an increase of power supply may be able to widely cover energy consumption besides crusher processes.

● Threats

Dust and storms on the operation site can cause damage to solar trailer systems and reduce their performance. One major obstacle to the project's successful completion is the difficulty of delivering supplies to the manufacturing site [17].

6. Conclusions

A mine has inherently high energy consumption due to the heavy equipment, lighting, and safety and ventilation required. Add to that the fact that mines are usually in very remote locations and pose safety concerns with either no or unreliable grid access. Often mines have to rely on noisy, emissions-producing diesel generators with their significant fuel and maintenance costs to supplement their on-site electrical consumption. Controlling greenhouse gas emissions is critically important for the current and future status of mining activities. The mining industry is one of the largest contributors to greenhouse gases. Replacing diesel generators and augmenting unreliable grid power with local renewable energy sources has the potential to greatly reduce greenhouse gas emissions from mining operations as well as costs by reducing or eliminating production delays due to load shedding and power outages. The application of BAT in gold mining is being investigated in a Sudanese enterprise, with an emphasis on technical, environmental, and economic analyses for solar panel stations. The solar trailer system was selected in this BAT study as an example for solar energy because it is completely self-sufficient with solar charging and can operate for 28 hours without sunlight, making it suitable for use in gold mining operations. This BAT project is carried out to decrease the high energy consumption due to the heavy mechanical equipment in the crusher and reduce the diesel fuel. The BAT project demonstrated positive environmental results in reducing GHG as well as remarkable positive economic results as shown in Table.11.

Table 11. Profitability indicators of the BAT project

Indicator	Unit	Amount
General Investment (I_0)	Ths.EUR	127.71
Net Savings (B)	Ths.EUR	125.76
Payback Period (PB)	year	1.02
Net Present Value (NPV)	Ths.EUR	524.22
Profitability Index (PI)	-	4.13
Internal Rate of Return (IRR)	%	32

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