



Article Evaluation of Environmental and Economic Benefits of Land Reclamation in the Indonesian Coal Mining Industry

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Abstract: While the successful reclamation of coal post-mining land sites in Indonesia has been evaluated, no cost-benefit analysis has been carried out on the reclamation of mined land, and the impact of the reclamation work has not been determined. The results of this case study indicate that reclamation work is not an emission-free process, but that the benefits delivered from this work are considerable. It was found that the emissions involved at the coal mined reclamation in Indonesia were $25.4-26.6 \text{ t-CO}_2/\text{ha}$, with topsoil management and land preparation contributing over 98% of the total emissions (9.5 t-CO₂/ha and 16 t-CO₂/ha, respectively). The ability of the trees on the reclaimed land to absorb CO₂ emissions was calculated to be $26.4 \text{ t-CO}_2/\text{ha}$, with the amount of oxygen produced calculated to be as much as $143 \text{ t-O}_2/\text{ha}$ of oxygen. The economic value of the ecosystem services delivered by reclamation work. Improvements to reclamation work could be designed mining and reclamation plans with attention paid to reducing fuel consumption, and therefore, reducing CO₂ emissions. Furthermore, law enforcement and transparency, human resource development, and community participation are strongly required.

Keywords: mine reclamation; land rehabilitation; responsible sourcing; ecosystem services; coal mining

1. Introduction

Coal mining is typically associated with a devastating impact on the environment, due to extensive land use and consumption. If not properly managed, coal mining leads to soil erosion, land and water degradation, biodiversity loss, and climate change. As a major global coal producer, Indonesia faces a series of environmental problems, especially forest loss, due to large-scale open-pit coal mining [1]. Therefore, the Indonesian government requires mining companies to perform land reclamation and rehabilitation work to be performed along with their operations as an environmental obligation. The reclamation plans must be submitted together with the mining operation plan.

Land reclamation involves rehabilitation measures to reduce the adverse environmental impacts of mine works throughout the mining cycle. Under the Indonesian Law no. 4/2009 of the Mining Principles, reclamation is an activity carried out during the mining business phases to arrange, restore, and improve the environment and quality of the ecosystem so that the land can be appropriately utilized. The aim of reclamation is to establish a stable landscape that is aesthetically and environmentally compatible with the surrounding undisturbed area [2]. Moreover, reclamation plays an essential role in landscape planning for integrated and sustainable post-mining land use [3]. As such, land reclamation involves efforts related to landscaping, physical stabilization, surface and groundwater quality, erosion, topsoil recovery, the revegetation of appropriate plant species, and wildlife habitats. The soil structure and fertility, microbe populations, topsoil



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). development, and nutrient cycling are considered at the planning stage of reclamation efforts to ensure that the ecosystem is reverted to a condition as close as possible to its initial condition [4]. Revegetation was defined by the then Ministry of Forestry as an effort to repair or recover vegetation loss through planting and maintenance activities on land formerly forested (Regulation no. 4/2011). This concept, mostly directed at the mining industry, is the most widely accepted and effective way to lessen erosion, increase evapotranspiration, and preserve the soil from degradation. The Indonesian government takes a serious approach to the reclamation and revegetation work at mine sites, as can be seen from the many regulations issued addressing this issue. The regulations include technical guidance issued by two technical ministries related to the mining sector, the Ministry of Energy and Mineral Resources (MoEMR, Jakarta, Indonesia) and the Ministry of Environment and Forestry (MoEF, Jakarta, Indonesia). These regulations include Government Regulation of Rehabilitation and Forest Reclamation (Peraturan Pemerintah (PP) no. 76/2008), Government Regulation of Reclamation and Post-Mining (PP no. 78/2010), Technical Guideline for Land and Forest Rehabilitation (Regulation of MoEF no. P. 70/ 2008), Evaluation Guideline for Successful of Forest Reclamation (Regulation of MoEF no. P.60/2009) and Implementation for Reclamation and Post-Mining at coal and mineral mining operation (Regulation of MoEMR no. 7/2014). According to these regulations, mining companies are obliged to perform full-range reclamation management, from topsoil removal and storage to the replanting of trees and their maintenance. Therefore, using the term 'reclamation' in this study, includes the concept of revegetation.

Despite recognizing the importance of reclamation, a significant proportion of the land opened up by the Indonesian coal mining industry has not been reclaimed. According to a 2017 report, only 40% of the total area opened for mining has benefited from reclamation work (Ministry of Energy and Mineral Resources, personal communication, 2018). Meanwhile, there is also a discrepancy between the scale of the overburden (OB) area, the disposal area, and the reclamation area in the coal mining sites. In 2017, reclamation work had been carried out on only about 33% of the OB disposal area (Mining Company, Annual Report, 2008–2017). The reasons for this are complex: Among the many problems cited are technical problems, low environmental awareness, lack of human resource capacity, improper management, and the misperception that reclamation is a burden rather than a productive activity. Currently, there is little environmental management data related to reclamation works at mine sites in Indonesia, and there have been few comprehensive evaluations of reclamation activities. According to the regulations mentioned above (MoEF no. P.60/2009 and MoEMR no. 7/2014), the evaluation of the reclamation activities at a mining site should consider the success of land preparation, revegetation, and construction work, including erosion and sedimentation control, and completion. However, the studies of reclamation works do not include observations of the full-range reclamation work, and typically are focused on assessing the extent of the revegetation.

The focus of evaluations of the revegetation efforts in coal post-mining land sites in Indonesia [5–7] has been limited to vegetation development and growth. These studies have assessed such parameters as the height of the trees and the diameter of the tree trunks over a period of time. While these studies provide some insight into the condition of the reclamation area, they do not show include sufficient information about the complete reclamation process [8]. Reclamation performance and the impact of reclamation work in terms of changes to the ecosystem have not been widely considered. In one study, the impacts of the reclamation of mined land on the ecosystem and changes to the environment were evaluated in terms of the impact on hydrology functions [9]. In other studies, the assessment of ecosystem processes and services, such as carbon sequestration [10], and the carbon stocks [11], offers valuable monitoring methods for evaluating the success of reclamation work [12]. In these studies, however, the various reclamation activities are undertaken, and the impact of these tasks was not evaluated in detail. For example, the carbon emissions from machinery and heavy equipment used in the land preparation part of the reclamation works have not been considered.

The increase in carbon dioxide (CO₂) emissions from vehicle and machinery fuel use, due to reclamation activity at Indonesian coal mining sites has yet to be determined. Likewise, the amount of energy, resources, and materials consumed during the reclamation processes has not been determined. In the context of global efforts to make radical transformations in the effort to become a low carbon society, it is important to consider the potential of reclamation work at coal mining sites to contribute to carbon sequestration. Indeed, the economic value of reclaiming mined land in Indonesia has not been considered. This may well be because most of the advantages of reclamation are in terms of ecosystem services that have no direct economic value, or the mining companies may not fully understand their responsibility to carry out extensive reclamation work. Ecosystem services refer to the benefits (valuable services and goods) provided by the ecosystem to support human wellbeing, categorized as provisioning, supporting, regulating, and cultural services [13]. The opportunities to further explore the potential of reclamation are hindered by the propensity of companies not to take their responsibility for reclamation work seriously.

The objective of this study was to evaluate the performance of the various processes in a reclamation work at an Indonesian coal mining site in terms of the energy input, materials used, and CO_2 emissions, and to assign a monetary value to the reclamation work. In so doing, the cost-effectiveness of reclamation activity for mining stakeholders in Indonesia can be assessed. The results of this study are expected to serve as quantitative evidence for decision-making regarding resource and land use, environmental conservation, and policymaking. It is also expected that the results will serve as a basis for increased public awareness of the value of reclamation activities and their benefits to the environment in Indonesia.

2. Methods and Materials

2.1. Methods

A Cost-Benefit Analysis (CBA) was employed to evaluate whether reclamation work undertaken at mine sites in Indonesia is beneficial or merely an extra cost burden for the mining companies. A CBA is typically used to assess the implications of public policies or projects by weighing the estimated benefit value against the cost of public policies or projects [14]. In the mining industry, a CBA is used to evaluate its financial profitability and economic contribution and estimate the externalities on the same basis [15]. According to these definitions, reclamation activities by mining companies could be seen as a policy product required by mining laws and regulations. In the cost analysis, the cost of reclamation was considered, including the operational cost (materials, fuels, workforce) and the costs incurred from the process or life cycle of the reclamation work. Rather than only consider the operational costs, the costs of the reclamation process in its entirety were considered, including the cost of using primary resources to yield output and the cost of emissions. A Life-Cycle Cost (LCC) analysis was employed to address the costs of all the reclamation activities from an early stage. That is, the capital costs, risks costs, and environmental costs were all considered [16]. While the capital cost encompasses the cost of all the resources and equipment used for the process, including the research and development cost, costs associated with resources and materials and the risks are generally already included in the operational cost. The research and development costs were not included in this study, due to the lack of information available to analyze cost separation for reclamation and non-reclamation. In this study, water usage is considered an issue of resource consumption, and the emissions involved in all reclamation tasks are assigned monetary values. That is, the total reclamation cost includes the actual operational cost, emission cost, and water usage cost. The data used in this study was obtained from the mining site considered in this study for the 2011–2017 period. It should be acknowledged that there was inconsistency and discontinuity in the available data. Factors, such as changes in the report format, missing or scattered data, and outdated data may have contributed to this problem. The approach to determining the value of reclamation works in terms of cost and benefit is explained in Section 2.4.

2.2. Materials

2.2.1. The Characteristics of the Site Location

The site investigated in this case study is an Indonesian coal mining site located in South Kalimantan, which is one of the three most abundant coal resource regions in Indonesia, as shown in Figure 1. The mining company is one of the first generations of the Coal Contract of Work (CCoW) agreements between a private company and the Indonesian Government. The company operates a single mine site that is comprised of a three mine-pit by surface mining methods and produces sub-bituminous coal of moderate calorific value (CV) 4000–5000 kcal/kg GAR (Gross as Received). The site is located at the eastern margin of the Barito Basin, and extends over an area of approximately 35,800 ha [17].



Figure 1. Mining site location (source: Wikipedia and d-maps.com, accessed on 21st November 2020).

According to exploration and survey activities, the site had abundant coal resources, at 5238 million tons, and 932 million tons of reserves in 2017 (mining company, annual report document, 2018). Although this guarantees that operations will be sustained over a long period of time, the first-generation contract will end in 2022, with two ten-year extension periods possible. In the last five years, the company had successfully maintained an annual coal production of over 50 million tons, except for in 2017, when production was at 47 million tons. Only 20% of total company group sales in 2017 were for domestic power generation and the domestic cement industry, while about 80% was exported to Malaysia, China, South Korea, Japan, and others (mining company, annual report document, 2017).

Data from the Ministry of Energy and Mineral Resources indicates that 75–80% of the coal produced in Indonesia is shipped out and distributed abroad, mostly to India, China, Japan, South Korea, and several neighboring countries, including Malaysia, Philippines, and Thailand [18]. This confirms the important role played by Indonesia in the economies of Asia.

2.2.2. Study Boundary

Reclamation work is continuously carried out throughout the production stages at the mining site and is intensified toward the closure of the mine and at the decommissioning stage. In Indonesia's open-pit mines, the reclamation process starts when the OB is removed to access minerals or coal. In this process, the vegetation is cleared, and the topsoil is removed and kept in a storage area in a process referred to as "topsoil management". The next phase begins after the area has been mined and already declared accomplished and reclaimed. In this phase, the land is prepared and revegetated, and involves considerable maintenance work. The full range of reclamation stages is shown in Figure 2.



Figure 2. Mining reclamation stage and associated activities.

This study established a system boundary to investigate the energy and materials used as input and the generated emissions in the reclamation process, as shown in Figure 3. The input and the generated emissions were measured and calculated, and the output for one-set of the reclamation process from topsoil management to the revegetated area was also measured and calculated. A functional unit is defined as one hectare of the reclaimed area. The average United States Dollar (USD) exchange rate in 2017 on USD1 = IDR 13,385 [19] was applied to normalize the value of all the costs and benefits in this study.



Figure 3. The system boundary of the study.

2.3. Data Collection

In this case study, one Indonesian coal mining site was investigated to provide a representative view of land reclamation work at an Indonesian mine site. To obtain technical data regarding the reclamation process, several approaches were used: A desktop study, personal communication, interviews with the mining rehabilitation expert, and a visit to the coal mining site. Henceforth, in this article, the term 'mine site' refers to the site where this study was undertaken. Several meetings were conducted with related government officers to gain and confirm the validity of the data from the Ministry of Energy and Mineral Resources and the Ministry of Environment and Forestry in Indonesia. It must be noted that several high-quality data were considered confidential, including the fuel consumption data for the heavy equipment used in reclamation work. For this reason, several assumptions were made and used in this study to cover the gaps in the data. Due to these assumptions, the fuel consumption of the heavy equipment used in the land preparation process to regrade and refine the mined land surface could be estimated.

2.3.1. Land Preparation

The assumptions made regarding the energy consumption of heavy equipment in preparing the land provided average fuel consumption. The general assumption was that the heavy equipment used in coal mining land preparation is the same as that typically found on mineral mining sites, as shown in Table S1 in Supplementary Materials. Among the many dynamic variables for the physical properties of the land and the reclamation plan, the following assumptions were made to estimate the amount of energy consumed by each unit of heavy equipment:

- Land preparation was performed on the regular area (overburden without waste rocks), and with no Potential Acid Formation (PAF),
- The target area is relatively flat,
- Annually, an area of 100 ha was prepared,
- The topsoil layer was 30 cm in thickness,
- The distance between the land clearing area to the topsoil stockpile point was 5 km, and was the same as that from the topsoil stockpile to the reclamation area,
- Since no drainage channel was constructed, and the site did not require slope formation, or the building of infrastructure, only surface regrading and the spreading of topsoil were considered in this study.

A technical calculation for the production capacity and fuel consumption was obtained based on the above assumption (details of the calculations are given in the Electronic Supplementary Materials).

2.3.2. Topsoil Management

In this study, the topsoil term refers to the top part of the soil near the surface, which was removed from the land clearing or stripping process in the early stages of the production phase and stored in the appointed storage area. Topsoil management is a collection activity, including loading, hauling, and transporting the topsoil from the land clearing area to the collection point (topsoil stocking pile). Since the topsoil travels the same distance when it is transported for storage and returned for reclamation work, the results of the calculations were used for both tasks.

2.3.3. Revegetation

In the Indonesian mining industry, conventional revegetation techniques (tree planting) tend to be used on mined land. That is, trees are directly planted by hand, after digging a hole and fertilizing the soil. Revegetating in this way is labor-intensive and requires a nursery to be operated in the vicinity of the mine. Light vehicles are required to transport the workers (mobilization), which consumes diesel fuel. In this study, the materials and technical data are based on the standard practice of revegetation used and applied at the site (mining company, personal communication, 2018), for instance:

- The density of trees 1100–1111 trees/ha with the range 3 m \times 3 m,
- There is no watering activity in the field (watering only in the nursery),
- Moreover, maintenance allocation for replanting failed (dead) trees is 10% of the total trees planted.

It is also possible to employ mechanical revegetation methods. This requires a tanklike machine with a blade fan-agitator inside to stir and mix the materials. It is driven either by belt-pulley, hydraulic pump, or water circulation, and either uses a centrifugal pump to suck the slurry from the tank and spread it through the boom charge gun or uses a hydraulic hose. The machine is usually mounted to a truck for ease of mobilization. This technique was applied at the site to spread and plant the ground-cover seeds (grass, shrubs, crop), due to its efficiency and resulting in homogenous, even growth. Since 2011, this technique has been used at the site to apply ground-cover plants and tree seeds to ensure tree planting covers a more extensive area than possible when planting by hand. For this study, it was assumed that revegetation involved using one unit of hydromulcher or hydro-seeder machine with a capacity of 1800 US gallons (around 7000 L) and using belt-pulley for agitator-driven (mining company, personal communication, 2018). This machine is mounted and installed on a truck with a gross weight roughly equal to 26,000 kg. Seeds, fertilizer, other organic matter, bonding agents, and materials for soil enhancement are the required materials. For daily operations, a light vehicle is used for personnel and the mobilization of materials. Details of the properties and materials involved in the revegetation technique are shown in Tables S2 and S3 in the Supplementary Materials.

2.4. Environmental Valuation

In the mining industry, the environmental valuation method is applied in environmental liabilities and project appraisals. The aim is to estimate the value and cost of environmental resource usage or damage [15]. By conducting an environmental valuation, the monetary value of the costs and benefits of the environmental goods and ecosystem services can be obtained even though they have no direct market price. This approach allows the costs to the ecosystem to be determined by considering the water used, the cost of the emissions, and the benefits of reclamation work. The use of the environmental valuation technique to provide monetary value is suitable for assessing environmental goods and services [20], and allows the cost and benefit to be measured and compared in terms of the same unit (money) and plays a key role in economic damage evaluation [21].

2.4.1. Water Usage Cost

In this study, the market price-based approach was used to estimate the water usage costs in reclamation work. The water usage includes the water used for operational and domestic consumption, with a conversion factor of 1 m³, which is equivalent to 10³ L. The charges for water consumption from the local government-owned water enterprise in 2018 and the tariffs imposed are as follows:

Group IV (class for industry):

- Up to 10 m³: USD 0.37/m³,
- Within a range of 11–20 m³: USD 0.41/m³,
- Twenty-one meters cubed and over: USD 0.45/m³,
- Fixed cost for abonnement USD 1.68/monthly.

2.4.2. The Cost of Emissions

In this study, most of the CO_2 emissions were from the diesel fuel used in daily operations. The on-site heavy equipment average fuel consumption was multiplied by the emission factor using 3EID (Embodied Energy and Emission Intensity) for Japan (based on Input-Output tables) to calculate CO_2 emissions. That is, diesel fuel was assigned a calorific value of 37.7 GJ/KL, and its CO_2 emission factor is 0.0687 t- CO_2/GJ . As mentioned above, fuel consumption was calculated based on several assumptions about the reclamation work. Technical details of the fuel consumption of the heavy equipment are shown in the Electronic Supplementary Materials. The average fuel consumption of the heavy equipment is multiplied by the emission factor, as shown in Equation (1).

$$e_r = C_F \times e_d \tag{1}$$

where e_r is the CO₂ emission, C_F is the consumption of diesel fuel, and e_d is the emission factor of diesel fuel. This equation is also used to calculate emissions from the equipment used in revegetation.

In this study, the emission cost refers to the cost attributed to the activity that generates emissions. The estimate uses the same market price-based approach as that used for the carbon price. Since Indonesia has not adopted a carbon tax or a carbon trade scheme, the price of carbon trade in the REDD+ (Reducing Emissions from Deforestation and Forest Degradation plus) partnership scheme was applied, at roughly USD 5/t-CO₂ [22]. The

REDD+ scheme is the Indonesian stewardship program to reduce emissions by protecting the tropical forest from deforestation and land degradation.

Besides emissions from diesel fuel, this study also considers emissions from the consumption of the electricity used to support such tasks, such as administration, the warehouse, and nursery operation. It should be noted that only the electricity usage for seed storage for mechanical revegetation was well recorded and made available. The source of electricity derives from the on-grid network, since the seeds were stored in a facility in a nearby town. The CO₂ emissions from the electricity consumed were obtained by multiplying the average electricity used and the average on-grid emission factor in Indonesia in 2017, at approximately 0.934 kg CO₂/kWh [23], as shown in Equation (2).

$$e_e = (m_e \div P_R) \times e_o \tag{2}$$

where e_e is emissions from the consumption of electricity, m_e is the average electricity consumed each month, P_R is the reclamation productivity, and e_o is the average on-grid emission factor. The reclamation productivity is calculated from the monthly average reclamation work achievement.

2.4.3. The Cost of the Reclamation

In this study, the total reclamation cost is a term that encompasses the actual operational cost, the emission treatment cost, and water usage cost. The data for the operational cost for the reclamation work for the period 2011–2017 was used when calculating the total cost from Equation (3).

$$TC_R = C_e + C_w + C_o \tag{3}$$

where TC_R refers to the total reclamation cost, C_e is the CO₂ emission treatment cost, C_w is the water usage cost, and C_o refers to the operational cost. The cost of the CO₂ emissions was obtained by multiplying the emissions released (e_r) by the estimated cost of emissions (e_c) obtained by the environmental valuation approach, shown in Equation (4). The cost of water usage was obtained by multiplying the water usage (w_u) by the water price (w_p) for industry, as shown in Equation (5).

$$C_e = e_r \times e_c \tag{4}$$

$$C_w = w_u \times w_p \tag{5}$$

2.4.4. The Benefits of the Reclamation Area

In principle, reclamation landscape of the mined area resembles a forest, and one of the essential forest services is climate regulation. Therefore, in this study, among the many benefits to the ecosystem from reclamation work is the expansion of state-owned forest land, and the associated benefits of CO_2 absorption and oxygen production. These three were selected because tropical forest loss and global warming are strongly associated with changes in land-use and land cover [24], which is a global concern. Even though oxygen production looks insignificant given the nature of oxygen composition in the atmosphere [25], the photosynthesis process, where the trees absorb CO_2 and release oxygen, is categorized as a supporting service of the ecosystem [13]. The expanded forest land, due to the reforestation efforts of reclamation work, can be considered a secondary forest. It can be retrieved when the mining contract is over without the need for any extra spending. For this reason, the replacement cost approach was applied to represent the price of the forest land in increments. The price was determined based on the regulation of the Director General of Watershed Management Control and Protected Forest No. P8/PDASHL/SET/KUM.1/8/2017 for estimating the cost of reforesting.

In addition, the market price-based approach was used to estimate the production value of oxygen, since there is an industrial oxygen price in the Indonesian market. At the time this study was conducted in April 2019, the cost of industrial oxygen was roughly

technique

USD 0.15–0.22/kg (the cost of production, storage, and distribution are excluded). The value of oxygen production from the reclamation area is gained by multiplying the oxygen production with the industrial oxygen price. Since it has been estimated that, on average, one tree produces 260 pounds of oxygen or approximately 130 kg each year [26], it is possible to calculate the amount of oxygen produced per hectare simply by multiplying the number of trees per hectare by this value. This amount of oxygen is assumed as the net oxygen produced by the tree after oxygen uptake in the respiration process.

However, the ability of trees and other plants to absorb CO_2 varies significantly depending on the number of factors. The species, the age, the silviculture management implied, and the density of trees in the area are all known factors influencing the extent to which carbon can be stored by trees and forests [10]. While there have been several studies proposing different methods to estimate the ability of trees and forests to absorb CO_2 , in this study, we adopted the rate of 48 pounds or approximately 24 kg CO_2 being absorbed by a single tree each year [26]. This amount is the assumed net CO_2 absorption after CO_2 is released into the air in the respiration process. Again, since Indonesia has no fixed price for carbon trading schemes, the only data available is based on the REDD+ partnership scheme for reducing emissions from deforestation and land degradation. Therefore, this data was used to estimate the price of CO_2 absorption by the revegetated area.

The benefits to the ecosystem can be calculated by Equation (6). In this study, TB_R refers to the total benefit of reclamation work, B_f is the benefit from increments of reforested land, B_a is the benefit from CO₂ absorption, and B_p is the benefit from oxygen production. The values for B_a and B_p were obtained by multiplying the market value, due to environmental valuation by the number of trees planted in the reclamation work (per ha).

$$TB_R = B_f + B_a + B_p \tag{6}$$

3. Results

3.1. Energy Consumption and Emissions

The calculated fuel consumption for each section of the reclamation work, electricity and water use, and operational cost are presented in Table 1. Furthermore, the energy consumed in reclamation work at the mine site is shown in Figure 4 with the associated emissions. The diesel used for fueling the heavy equipment used in topsoil management, surface grading, topsoil spreading, and revegetation accounts for the greatest portion of the energy consumed. Among those activities, the most energy-intensive are the spreading of topsoil and managing that topsoil, which emitted 12.5 t- CO_2 /ha and 9.5 t- CO_2 /ha, respectively. Both tasks involve dump trucks, which must load the material (soil) at a different point and transport it a certain distance. Details of the average fuel consumption of these heavy vehicles are shown in Table S4 in Supplementary Materials.

Section	Fuel Consumption (ℓ/ha)	Electricity Consumption (KWh/ha)	Water Consumption (ℓ/ha)	Operational Cost (USD/ha)	
Topsoil management	3680	N a	N a	3751	
Surface regrading	1380–1610	N a	N a	2010	
Topsoil spreading	4670-4835	N a	N a	- 3040	
Planting: Conventional technique	50–60	N a	2500-4000	1646–2056	
Planting: Mechanical	143	23	22,000	2626	

Table 1. Calculation results for fuel, electricity and water consumption, and operational cost.

Note: N a = not applicable.



Figure 4. Energy consumption and associated emissions in reclamation work at this site.

Revegetation involved both conventional and mechanical techniques, with diesel required to operate light vehicles to transport both workers and materials. The trucks and the operation of the hydro-machine, which is used in the mechanical approach to revegetation, are associated with higher emissions than the conventional technique, due to the high consumption of diesel. As can be seen in Figure 4, the energy consumption involved in the conventional approach to revegetation is almost half that of the mechanical approach. That is, the conventional approach to revegetation, therefore, results in lower emissions. The two different revegetation techniques are compared in terms of the consumption of resources and materials in Table 2. Note that the consumption of both water and seeds was five times greater in the mechanical approach.

Resources and Materials	Unit	Conventional Technique	Mechanical Technique	Changes in Value
Fuel	ℓ/ha	9983	10,071	1%
Water	ℓ/ha	3250	22,000	577%
Electricity	kWh/ha	-	23	-
Materials	t/ha	3.3	7.67	132%
Seeds of land cover crop and trees	kg/ha	33	200	506%
Seedlings	trees/ha	1222	-	-

Table 2. Resource use in revegetation work at the mining site.

Organic materials are also consumed in revegetation tasks, with the mechanical approach requiring an average of 1.3 times the average quantity of organic materials used in the conventional approach. Due to the higher material consumption, the cost of the mechanical technique was also higher. Since no electricity is consumed in the conventional technique, there is no data to compare. Another point where the differences were such that no comparison could be made was the material requirement for seedlings: The mechanical technique involves only the spreading of seeds. Details of the type and quantity of resources required in each method are provided in Table S3 in Supplementary Materials.

While there were emissions associated with revegetation, there are many advantages of this work which can be seen by considering the reclaimed area as an output, with regard to the ecosystem. Based on the calculated values, the trees on the reclaimed land can absorb CO_2 roughly 26.4 t- CO_2 /ha and produce approximately 143 t- O_2 /ha/year of oxygen. Since the vegetation expands the amount of forest land, the advantages are considered in the cost and benefit calculation in Section 3.2.

3.2. The Cost and the Benefit of Reclamation

The total cost of the reclamation work is shown in Figure 5 for both types of revegetation approaches. As can be seen in the figure, the costs of each component are largely the same except for the planting, with the total cost at between USD 8642 to USD 9417/ha depending on the revegetation approach. The highest costs were for topsoil management and land preparation activities with a combined cost of almost USD 7000/ha, or 75–80% of the total cost of the reclamation work. The total cost includes the cost of the operation, water usage, and the costs of emissions. The benefits of reclamation come from the expansion of forest land, CO₂ absorption, and oxygen production, as shown in Figure 6. The total benefit is valued at over USD 27,750/ha, with the highest contribution from photosynthesis, since the trees absorb CO₂ and produce oxygen. It is clear from Figure 6 that the total benefit of reclamation surpasses the cost of the reclamation work by a large margin.



Figure 5. The total cost of the reclamation work at the mining site.



Figure 6. The total benefit of the reclamation work at the site.

According to the sensitivity analysis performed, the reclamation area will still deliver benefits at the rate of 10% and 20% annually, increasing and decreasing the average total cost and average total benefit for 20 years. The result of the calculation is presented in Tables S5–S8 in Supplementary Materials. In this case, it is assumed that the mining company will be granted extensions of 20 years after the expiration of the first contract, in accordance with Indonesian mining regulations. Therefore, the reclamation area after the first period will provide long term benefits along with the benefits of the next phase of the mining operation.

4. Discussion

The assumptions of some of the data used in this study affected the outcome of this study, particularly regarding the land preparation work to estimate fuel consumption of the heavy equipment used in the reclamation process, which allows the generated CO₂ emissions to be calculated. It must be stressed that access to actual company data, such as data for land preparation activities, would result in different outcomes. It should also be acknowledged that the coal mining company which oversees the mine in this case study has a record of strong environmental management achievements and sufficient resources to perform adequate reclamation. The use of data from this company would lead to different outcomes than using data from another company with a different company culture. In addition, since the calculations in this study were done using averaged data or a median data range, different results would be expected from adopting the minimum or maximum values in the calculations. Despite this acknowledged uncertainty in the results, this study shows the reclamation process information and value of reclamation relative to the costs involved, from a cost-benefit approach. This study offers a new monitoring approach to the success of mined reclamation.

4.1. Energy Consumption and Emissions

The results show that the highest energy-consuming activities, that is, those associated with the largest emissions, are the spreading of topsoil and topsoil management. Both use dump trucks for the loading and transporting of the topsoil to and from the place of storage. Moreover, the amount of fuel consumed depends on the thickness of the topsoil layer, since that determines the quantity of materials that must be removed. Any changes in the distance, material volume, or additional earthworks in the land preparation task, such as the need for drainage channels or the construction of access roads, would clearly add significantly to the cost of reclamation work, since extra fuel consumption would result in much higher emissions.

The consumption of materials and fuel using the mechanical approach to revegetation was much higher than the conventional approach. The diesel, water, and fertilizer consumption were considerably higher in the mechanical approach, leading to higher emissions. The consumption of water is another matter which should be considered in the future, since water is an essential resource and the changes in climate with global warming may impact places with abundant water resources today. Reclamation costs depend entirely on the quantity of materials and the cost of the resources required. In this case study, the conclusion is that there are strengths and weaknesses to every option in the reclamation process. The details provided in Table S2 in Supplementary Materials show this clearly.

While reclamation work is hailed as an opportunity to provide CO_2 absorption capability in the Business as Usual (BAU) scheme [27], the potential for the trees on the reforested land to absorb enough CO_2 to offset the massive CO_2 emissions of coal mining is limited, as shown by the results of this case study. Even so, the CO_2 absorption capacity of the trees in the reclaimed mined land is sufficient to offset the emissions involved in the reclamation work itself. The results from using other absorption values may differ, since the ability of trees to absorb CO_2 varies according to several factors. However, it is expected that the ability of reclamation trees to absorb carbon will increase as they grow over time and help improve the microclimate.

According to the law and mining regulations in Indonesia, the reclamation of mined land necessarily involves human intervention rather than leaving the land to be reclaimed naturally [28]. This allows the ecosystem to be relieved from the burden of the damage caused by mining activities in the shortest possible time and provides consistent results. Our moral responsibility to restore the land may also be a primary consideration behind the requirement for active land reclamation work. Mining companies are obliged to perform good mining practices, including the reclamation of the mine site and the closure of the mine for the sustainable utilization of mined land [3]. The production rate of the mine is a key factor in determining the reclamation methods. In open-pit or surface mining, the production rate determines the amount of OB generated, determining the requirement for rock waste removal. This is the main solid-waste issue in Indonesian coal mining. Most OB is reused as backfill material in the reclamation process: As yet, it is not used in other applications, such as in the building industry or in the manufacturing of secondary products [29,30]. Therefore, removing the rock waste requires extensive storage areas or a dumping area until it can be used in the reclamation process. Dynamic, more complicated mining operations understandably would require split storage and different plans to adjust to the environmental changes. The local weather, land availability, and changes in mining plans are among the several factors that affect not only the reclamation achievement, but also the success of the whole operation. The weather is a significant contributor in reclamation work and in mining operations: Heavy rain and a high rainfall rate are limiting factors from the perspective of safety. On the other hand, reclamation work may be delayed or slowed down in the dry season to avoid planting failure. Other considerations, such as the economic situation, infrastructure availability, emergency needs, and other social considerations, may also delay the reclamation process. The mining site in this case study experienced several of the conditions above. During 2013–2017, the mining company changed the way it utilized the land at the mine site, for access construction, optimizing the disposal capacity, traffic management, and optimizing coal production (mining company, environmental management performance report, 2017). These changes are recognized and permitted by the regulations.

4.2. The Cost and the Benefit of Reclamation

The cost-benefit analysis of the reclamation of the mine in this case study was challenging in that most reclamation benefits can be categorized as benefits to the ecosystem, which have indirect financial value. Nevertheless, the reclaimed land has potential as a productive commercial forest that delivers an economic advantage to the communities which utilize this reclaimed land [31] or benefits through carbon sequestration payments under the carbon market scheme [32]. Even though the cost and benefit value of reclamation in this study was derived from the valuation approach using market prices, the results in the paper are an estimate of the true cost. Indonesian mining laws and regulations require the reclamation cost and guarantee to be included in the mining operation budget. As such, reclamation costs are not an extra or additional cost for mining operations. Based on the cost-benefit analysis in this case study, the monetary value of the ecosystem in the reclaimed area is higher than the cost of the reclamation work. This confirms that mined land reclamation is a good investment in ecosystem restoration and rehabilitation [33].

In future work, the capacity and benefits of reclamation work to the other ecosystem services to reduce erosion risk and sedimentation [21], water management, and biodiversity recovery in the ecosystem should be included and calculated. Moreover, the cost of CO_2 emissions needs to be carefully considered in reclamation studies. Since there was no carbon trading or similar mechanism in Indonesia at the time of this research, only data from the REDD+ mechanism was available for use as a reference. Therefore, the values may be lower may not significantly influence the total cost of reclamation. On the other hand, the absence of a carbon trade mechanism also contributes to a lower value of CO_2 absorption as one of the ecosystem services provided by the reclaimed land because it uses the same reference value. In the future, it is expected that Indonesia will have an emission trading system, or a similar scheme to support climate change mitigation action, particularly in the energy sector.

While reclamation is a beneficial activity, improvement is required to reduce the gap between the opened area for mining and the rehabilitated area and reduce the CO_2 emission involved in reclamation work. A suggestion is an integrated regional, and spatial management plan that includes the most appropriate post-mining land use. Such a plan would necessarily involve all the stakeholders of the mining industry. Since most of the CO_2 emissions were from the material (soil) mobilization in the land recovery efforts, the

operation plan for mining should be designed to reduce such emissions after making calculations. A reduction in fuel consumption will reduce CO_2 emissions. A proper and well-designed plan also should optimize the land utilization and prevent further changes to the reclaimed area wherever possible. Implementing fuel mixing (biofuel or biodiesel) gradually in mining operations may also reduce emissions from reclamation work. Reclaimed land can support diversity through revegetation, including the planting of bioenergy species.

Changes to mining budgets, public sentiment, unpredictable weather, and low awareness of environmental problems are issues that need attention to ensure that the achievement of land reclamation work is maximized at mining sites. It is essential that the government strictly enforces its laws and regulations and maintain transparency. All efforts must be made to maximize the capacity of human resources and improve supervision efforts, while increasing community participation in land reclamation endeavors, particularly for determining the final land use.

5. Conclusions

Reclamation work at mining sites in Indonesia requires extensive human intervention. Allowing the land to be naturally reclaimed by nature over time is not an option, and reclamation works are mandated by law in Indonesia. Reclamation work intends to improve the mined land environment by utilizing it and making it more productive. Reclamation is, however, an energy-intensive activity, mostly due to the diesel cost. The results of this study show that over 98% of CO₂ emissions from reclamation work are due to fuel consumption in the earth-moving work section. While the ability of trees to absorb carbon may be relatively small at first, this will improve with time. The results of this case study of reclamation work at a mine site in Indonesia demonstrate that the benefits of reclaiming mined land are greater than the cost of the reclamation work itself, in terms of the ecosystem services provided by expanded forest-covered land, carbon dioxide absorption, and the production of oxygen. To reduce CO₂ emissions from land reclamation work, a well-calculated and designed mining plan, as well as the implementation of a mixed fuel approach using biodiesel, is recommended. To improve the quality and success of land reclamation work at mining sites, the law must strictly be enforced, government agencies must maintain transparency, and human resources must be wisely utilized to carry out and supervise the work. Increased community participation is also recommended, particularly when determining how the land will finally be used.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10 .3390/resources10060060/s1, Table S1: General heavy equipment for land preparation task, Table S2: Properties of each revegetation technique, Table S3: Primary resource and materials used in revegetation task, Table S4: Fuel consumption of heavy equipment for reclamation work, Table S5: Sensitivity analysis on an annual increasing rate of 10% for 20 years, Table S6: Sensitivity analysis on an annual increasing rate of 20% for 20 years, Table S7: Sensitivity analysis on an annual decreasing rate of 10% for 20 years, Table S8: Sensitivity analysis on an annual decreasing rate of 20% for 20 years.

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