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MORALITY BEFORE KNOWLEDGE

The strategic role of renewable energy in supporting net-zero emissions targets in industrial clusters: Pathways to achieving sustainability

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ABSTRACT

Background: Indonesia's industrial sector has a high demand for electrical energy, contributing significantly to global energy consumption and greenhouse gas emissions. With 84.53% of national power generation relying on fossil fuels, concerns arise regarding energy security and environmental sustainability, particularly CO_2 emissions from coal-fired power plants. **Method:** This study examines CO_2 emission reduction through rooftop solar panel implementation in the MM2100 BEFA Industrial Area. A combination of literature review and spatial analysis was used to assess emission reduction potential and formulate sustainable industrial strategies. **Findings:** The research estimates that rooftop solar panels can reduce greenhouse gas emissions by 0.15 Mt-CO_2e/year (literature study) and 0.04 Mt-CO_2e/year (spatial analysis). Spatial studies provide more precise estimations than literature-based approaches. Achieving these reductions requires increased funding, technology transfer, human resource investment, improved social acceptance, local actor empowerment, industrial coalitions, and policy updates. **Conclusion:** Transitioning to renewable energy in industrial areas can significantly reduce CO_2 emissions. However, comprehensive strategies integrating financial, technological, and policy support are essential for effective implementation. **Novelty/Originality of this Study:** This study uniquely compares literature-based and spatial analysis approaches to assess emission reduction potential. It also provides a strategic framework for sustainable industrial transformation, emphasizing the role of local and international collaboration in implementing renewable energy solutions.

KEYWORDS: green house gases; renewable resources; reduction of CO_2 emissions; sustainable industry; spatial studies.

1. Introduction

The industrial sector plays an important role in the Indonesian economy. Based on the BPS (2023), the processing industry is ranked first in the distribution of Gross Domestic Product (GDP) according to business fields, namely 18.25% of the overall GDP contributor in Indonesia. This figure also shows positive development with a growth value of 4.88% year on year (y-on-y) in the 2023 BPS report. In addition, according to the National Labor Force Survey Report by BPS (2023), the processing industry also occupies the third largest position in terms of labor absorption per sector, namely 13.58% of the total workforce in Indonesia. The massive movement and growth of the industrial sector in Indonesia is also accompanied by the large demand for electrical energy needed to support the operational activities of these industries.

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Based on data from the International Energy Agency (2021), the industrial sector contributed to 38% of total energy use in 2020. On a local scale, currently the majority of electricity needs in Indonesia are still supplied by PLN (ESDM, 2022) and the percentage of electricity use per sectors also show similar trends. Based on data from the PLN Statistical Report (2022), 32.32% or 88,843.30 GWh of PLN electricity sold is from the industrial sector. Despite its status as the second largest customer after households, in the same report it was noted that the industrial sector only occupied 0.2% of all PLN customers. This can be an illustration that electricity use in the industrial sector tends to be energy-intensive (Napp et al., 2014). The industrial sector's electricity demand is also not stagnant and continues to increase every year. Energy sold for the industrial sector in 2022 was recorded to increase by 22.48% compared to the previous five years (PLN, 2022).

The ever-increasing energy demand affects the use of natural resources in the upstream power generation industry. Based on the Electricity Statistics Report by the Ministry of Energy and Mineral Resources (2022), currently 84.53% of the installed capacity of national power plants still depends on non-renewable resources from fossil fuels such as coal, gas and petroleum. High dependence on non-renewable resources such as fossil materials can potentially lead to an energy crisis. According to the publication of the Institute for Essential Services Reform (IESR) in 2022, the current global energy crisis is occurring due to an imbalance in demand and availability of fossil fuels which has resulted in drastic changes in social, economic, political and environmental aspects. This crisis resulted in an increase in energy prices such as coal, natural gas, petroleum and electricity by two to four times in 2022 compared to the previous three years (World Bank, 2022).

Apart from having an impact on the energy crisis, the practice of using fossil fuels, especially coal, also has a high environmental impact. Currently, 46.93% of installed electricity capacity in Indonesia still depends on coal-fired power plants (ESDM, 2022). The average CO_2 emission factor obtained from electricity generation using Indonesian coal energy sources is still relatively high, namely 99,718 kg CO_2/TJ (Damayanti & Khaerunnisa, 2018). According to the UNFCCC (2022), CO_2 emissions in Indonesia in 2019 reached 1,845 Gt with 34.49% coming from energy use. CO_2 emissions are predicted to continue to increase along with rising needs and living standards in developing countries (Napp et al., 2014). Apart from that, the latest report from the IPCC (2022) also states that the industrial sector is the sector that shows the fastest trend in releasing CO_2 emissions, as well as producing more than a third of global greenhouse gas emissions, relative to energy consumption and heat generation.

As a response to the greenhouse gas problem, in 2015, Indonesia and 196 other countries agreed to an international treaty related to climate resilience which is also called the Paris Agreement. This agreement states that participating countries agree to maintain a maximum increase in global average temperature of 2.0 degrees Celsius compared to pre-industrial times and as far as possible keep the temperature increase to no more than 1.5 degrees Celsius (UNFCCC, 2015). Commitments to the agreement were reduced in terms of several targets. The targets of this agreement emphasize increasing the ability to adapt to the impacts of climate change, increasing climate resilience, and implementing development that is low in greenhouse gas emissions (UNFCCC, 2015). This target must also be supported by an allocation of financial needs that can support low-emission and climate-resilient development.

As a country that has ratified the Paris Agreement, Indonesia through its Nationally Determined Contribution (NDC) is committed to reducing emissions produced in 2020–2030 by 29% (non-conditional) to 40% (conditional) compared to the Business as Usual (BaU) scenario (UNFCCC, 2022). The Indonesian government has also issued several local regulations to support this target. Republic of Indonesia Government Regulation no. 79 of 2014 concerning National Energy Policy states that the use of coal and petroleum is targeted to decrease by 30% and 25% respectively in 2025, and 25% and 20% in 2050. The decrease in the use of fossil fuels is replaced by an increase target the use of renewable energy will be at least 23% in 2025 and increase to 31% in 2050. This energy transition target is reaffirmed in Presidential Regulation number 22 of 2017 concerning the General National

Energy Plan, which states that apart from achieving 23% renewable energy by 2025, energy intensity must also be reduced by 1% per year. The increase in the use of clean energy as targeted is expected to make a positive contribution to reducing CO_2 emissions as well as being a concrete step to achieve the targets in the Paris Agreement. This brings us back to the fact that the industrial sector significantly influences energy consumption and should be a primary focus when considering measures to enhance environmental sustainability.

In the industrial sector, resources including energy are harvested and processed for various purposes that provide added value, including asset development and public and private consumption (Roberts, 2004). The concept of industrial ecology grew by applying principles where manufacturing production and consumption could be designed to mimic natural systems (Hawken et al., 1999). In a system like this, organisms and other natural elements that have a negative impact on life are able to coexist and support each other in the ecosystem in which they exist or exist (Roberts, 2004).

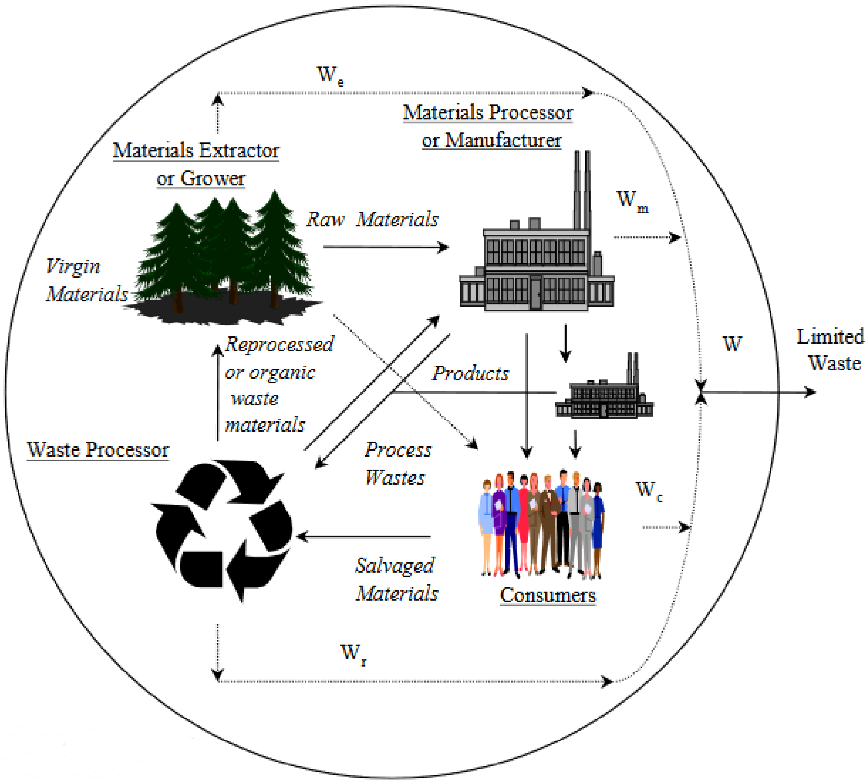

Fig.1. Basic concept of industrial ecology
(Graedel, 1996)

In relation to ecology, humans often take more from nature than they give back. These exploitation activities can have a negative impact both directly and indirectly on the environment. Applying the concept of industrial ecology in strategy development can provide a more holistic picture for handling industrial area issues from an economic, social and environmental perspective (Figure 1).

Rogers et al. (2008) use the term "Sustainability" to bridge the gap between human development and the environment. Sustainable life is defined as life that can be supported by the earth's natural capabilities without degrading the natural resources provided (Miller & Spoolman, 2012). This principle of sustainability can be applied in various aspects of human life, one of which is related to industrial development through sustainable industrial areas.

Sustainable industrial areas are developed using a symbiotic approach in industrial systems (Butturi et al., 2019). This industrial area consists of companies located in a geographic area together, linked by collaborative (Bellantuono et al., 2017) and competitive relationships (Sellitto & Luchese, 2018). Sustainable industrial areas rely on building synergy between companies in the area to develop a closed system by utilizing the exchange of resources such as raw materials, by-products, water and energy, so as to reduce pollution and exploitation of natural resources (Butturi et al., 2019). The model used by sustainable industrial areas is to utilize manufacturing and service business networks to share and use natural and economic resources efficiently, improve the economic performance of the companies within them, as well as reduce the overall environmental impact and create benefits for local communities (Côté & Cohen-Rosenthal, 1998).

Research related to sustainable industry to reduce environmental impacts has been developed, one of which focuses on clean energy. From 2011 to 2020, the United States and China have worked together to manage the “Clean Energy Research Center” which acts as a joint research center for the development of energy efficiency, carbon capture, and nuclear energy (Sovacool et al., 2023a). From an energy perspective, an industrial area can also be developed into an independent energy producer capable of meeting internal energy needs (Karner et al., 2016) thereby minimizing the environmental impact of electricity production required by industry (Dong et al., 2019).

The industrial sector, as one of the largest emitters of CO_2, also plays a role in realizing the targets of the Paris Agreement. Currently, the net zero emissions target is considered to be a common target and has the potential to be more organized in achieving it if managed under one management. The growth of the industrial sector itself has triggered the development of exclusive economic areas such as industrial areas, industrial zones and industrial areas. According to Butturi et al. (2019), industrial development in a special area has the potential to utilize synergies between companies in the same location to develop a closed system with the aim of exchanging resources such as raw materials, by-products, water and energy, so as to reduce pollution and resource exploitation. natural. This pattern is then utilized by world organizations as a new opportunity to achieve climate resilience targets.

At the 26th Conference of Parties forum in 2021, the World Economic Forum (WEF) launched its program with the theme "Industrial Cluster Transition Towards Net Zero Emissions Initiative". The launch of this program was followed voluntarily by four industrial areas who committed to become pilots to reduce their CO_2 emissions until they reach net zero emissions by 2050. In less than two years since the release of this program, there have been 13 industrial areas recorded throughout the world which also shows its initiative in achieving net zero emissions, with one of its regions being in Indonesia (WEF, 2023). The main principles of this net zero emissions transition program are centered on four focuses: cooperation; policy; funding; and technology. Among the technologies implemented and the funding budgeted, there are steps to reduce emissions through a program to convert fossil energy to renewable energy (WEF, 2023).

In Indonesia itself, quoted from the Bekasi Regency Government website, currently there are 10 industrial areas, making Bekasi Regency the largest industrial area in Southeast Asia. Among the 10 areas, one of the largest is the area under the management of PT Bekasi Fajar Industrial Estate (BEFA), namely the MM2100 BEFA Industrial Area with a land area of around 1700 Ha. The MM2100 BEFA Industrial Area is an integrated industrial area which is contracted by more than 100 companies and has its own supporting facilities such as water treatment installations and private power plants, gas networks, hospitals, commercial areas, government offices and other supporting facilities. The high diversity of activities in the area means that managers have their own challenges in determining emission reduction measures, including in terms of the energy transition.

Several studies related to the application of renewable energy have been developed previously, such as research by Butturi et al. (2019) which discusses the general application of renewable energy in industrial areas, and there is also more specific renewable energy research such as research on the application of rooftop solar panels on an industrial area scale (Raksakulkarn et al., 2022; Siahaan, 2018). Solar Power Plants are power plants that convert radiation from sunlight into electrical energy using solar panels or what is usually called Photovoltaic (PV) (Goswami, 2015). Solar power generation can also be applied on a smaller scale in the form of rooftop solar panels. Several studies have discussed the role of rooftop solar panels as renewable energy in reducing CO_2 emissions on an industrial area scale. Research by Raksakulkarn et al. (2022) discussed the potential for greenhouse gas emission mitigation from the development of renewable energy in Thailand's industrial areas, where a generation potential of 1,421.05 MW was obtained, equivalent to 0.95 $MtCO_2e$ of GHG reduction potential each year. Other research by Siahaan (2018) discusses technical and financial analysis regarding the potential of the rooftop solar panel business in the Pulogadung industrial area with a potential electricity generation of 186.92 GWh per year. These research models will be developed for this research with case studies in the MM2100 BEFA Industrial Area.

Based on the background described previously, this research has several research objectives. The first objective is to examine the reduction of CO_2 emissions through the application of rooftop solar panels on an industrial area scale. The object that will be used as the study area is located in the MM2100 BEFA Industrial Area, which is the second largest industrial area in Bekasi Regency. Apart from that, this research also aims to develop strategies related to sustainable industry at the industrial area scale by referring to previous literature. This research is expected to provide energy transition planning by utilizing rooftop solar panels that meet the principles of economically profitable, socially acceptable, environmentally sustainable and technologically manageable.

2. Methods

The research method is divided into two focuses based on the previous objectives. The first focus is on the role of renewable energy in mitigating greenhouse gas emissions, and the second focus is on the concept of achieving net-zero-emission targets. Both aspects are interconnected, as transitioning energy is required to achieve the net-zero-emission target. Either greenhouse gas mitigation and the achievement of net-zero-emission targets in this study are applied at the industrial area scale.

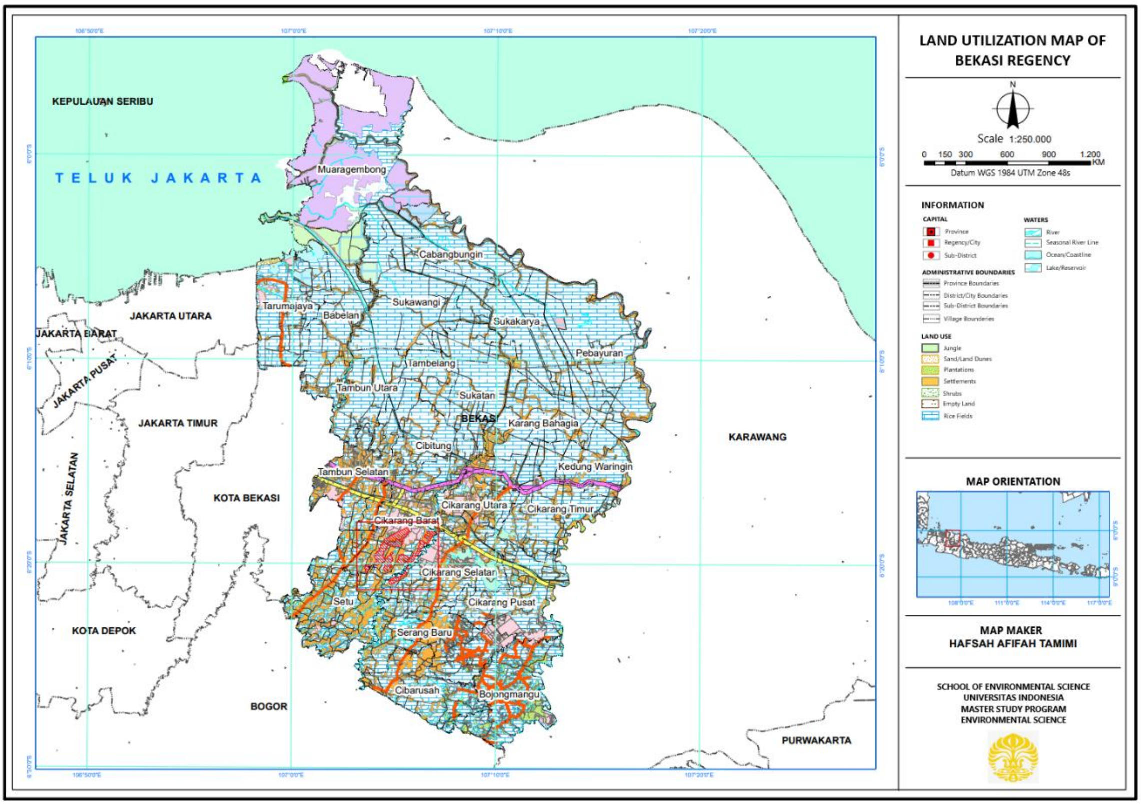

Fig. 2. Land use map of Bekasi Regency

Related to the role of renewable energy in mitigating greenhouse gas emissions, an analysis of the potential electricity generation from rooftop solar panels was conducted on existing buildings in the research site. The research site for this study is the MM2100 BEFA Industrial Area located in Cikarang Barat, Bekasi Regency, West Java Province (Figure 2). The study covers 1700 hectares of area with a total of 137 companies having their own buildings as tenants. This research was conducted using data obtained during a two-month access period in October and November 2023.

Based on the research objectives outlined in the Introduction section, two methods will be employed to achieve these goals. The first method is a literature review, aiming to analyze concepts applicable to achieving a low-carbon industrial area. This method entirely utilizes secondary data by leveraging existing regulations and previous research studies. Meanwhile, the second method involves using spatial-based primary data to analyze the potential for electricity generation and GHG emission reduction through the utilization of rooftop solar panel technology.

The concept for evaluating the potential use of solar panels on industrial building rooftops is based on the study by Raksakulkarn et al. (2022). In this research, the potential use of solar panels on building rooftops was evaluated using two approaches. The first approach involves using low-level information accuracy, where data collection, especially the area of the factory, is done by tracing company profiles published by the industrial area. Meanwhile, for the determination of the area using the second approach, area calculations were performed using spatial analysis based on Geographic Information System (GIS), calculating the built-up roof area based on satellite image observations and analyses. In relevant literature, GIS-based concept development has been shown to enhance the validity of spatial planning, leading to increased stakeholder participation (Kyriakopoulos, 2023).

In the first approach method, the following assumptions are used: the total roof area is 40% of the total overall area (Raksakulkarn et al., 2022), assuming that the remaining 60% is non-building areas such as roads, parking lots, and other utilities. Then, in both the first and second approaches, the total roof area obtained is reduced due to factors such as roof slope, shadowing potential, and other obstacles, assuming that the usable roof area for rooftop solar panels is only 20% (Raksakulkarn et al., 2022). The calculation of the electricity potential is performed using assumptions and other factors outlined in Table 1.

Table 1. Assumed factors for calculating solar panel potential

Assumption	Factor	
	1st Methods	2nd Methods
Percentage of roof area per total area	40%	GIS mapping result
Percentage of roof area with rooftop solar installed per total roof area	20%	
Rooftop solar panel sizes	1.65 m^2/panel	
Maximum power of rooftop solar panels	275 W/panel	
Duration of rooftop solar panel use	6 hour/day, 250 day/year	
Temperature reduction factor	89%	
Dirt and dust reduction factor	93%	
Mismatch reduction and losses from wiring factor	95%	
DC to AC conversion efficiency	90%	

Note: Maximum power is calculated based on 275 W/polycrystalline panel, 1,65 m^2/panel (166,67 W/m^2)

Calculation of the electrical potential of rooftop solar panels is carried out using the following Equation 1. The total amount of electricity generated (E) is determined by the total roof area (A), the percentage of the roof area covered by solar panels (I), and the power capacity of each solar panel (P) relative to the panel size (S). Additionally, factors such as temperature reductions (f_{temp}), dirt and dust accumulation (f_{dirt}), mismatches and losses from wiring (f_{mis}), and DC to AC conversion efficiency (f_{inv}) are considered based on standard test conditions (STC). The duration of electricity generation per day (t) and the number of sunny days in a year (d) are also incorporated into the calculation to estimate the total electricity production..

$$E = \frac{A \cdot I \cdot P \cdot f_{temp} \cdot f_{dirt} \cdot f_{mis} \cdot f_{inv} \cdot t \cdot d}{S} \quad \text{(Eq. 1)}$$

The GHG emission mitigation potential is calculated using the following formula.

$$GHG = AD \cdot EF \quad \text{(Eq. 2)}$$

Where: GHG amount of GHG emission ($kgCO_2e$); AD is activity data from GHG emissions, namely quantitative measurements of activities that produce GHG emissions (unit); and EF is the emission factor of GHG which shows the coefficient of the relationship between activity data and GHG emissions ($kgCO_2e$/unit).

Apart from that, the results of the electricity generation potential analysis will also be used for simple economic calculations with the following Equation 3, where E represents the amount of electricity generated by installing rooftop solar panels in kilowatt-hours (KWh), and Trf_E is the applicable electricity tariff in rupiah per kilowatt-hour (IDR/kWh).

$$Cost\ Reduction = E \cdot Trf_E \quad \text{(Eq. 3)}$$

After analyzing the potential greenhouse gas mitigation from the energy transition, the focus of study shifted to further examine the challenges faced in implementing a net-zero-emission industrial area. These challenges are not only technical but can also be assessed from social, economic, political, and other perspectives. To develop the concept of a net-zero-emission, it is important to understand the challenges faced by previous industrial area that have already implemented the net-zero-emission targets. Therefore, the development of the initial net-zero-emission concept for the MM2100 BEFA industrial area will be built upon reviews of previous literature.

3. Results and Discussion

The results and discussions of this research will be divided into two parts, namely discussions related to the potential mitigation of greenhouse gases through the implementation of rooftop solar panels and discussions related to the industrial area strategy to achieve net-zero emissions. As previously stated in Republic of Indonesia Government Regulation Number 79 of 2014, Indonesia is targeted to have integrated New and Renewable Energy (EBT) by 23% by 2025 into the total fulfillment of national electricity needs. Indonesia itself has renewable energy potential of up to 400,000 Mega Watt (MW) with 50% of it being solar energy potential (EBTKE, 2022). However, the implementation of renewable energy still has many challenges in its development. According to Arsita et al. (2021), several challenges in developing renewable energy are related to economic value, licensing processes, cooperation schemes, and spatial planning such as land acquisition and infrastructure access. Technology to utilize solar power continues to be developed to meet these implementation challenges. In economic terms, the cost of solar panels has decreased by 99% compared to the previous four decades (Chandler, 2018). Apart from that, to address challenges related to spatial planning and land acquisition, solar panel technology has been developed to be installed on roofs, or popularly known as Rooftop Solar Photovoltaic. In contrast to Solar Power Plants, rooftop solar panels can be applied to customers' rooftop buildings so they do not require additional land (Siahaan, 2018).

According to research by Ganesh & Sridhar (2020), Geitner et al. (2017), and Abdelfattah (2013), geospatial technology can support many land-use planning activities, and when utilized through a web interface/platform, it can facilitate coordination among various elements involved in the planning process. The evaluation of the potential use of solar panels was conducted using the approach outlined in the study by Raksakulkarn et al. (2022). The study divided the determination of the area of the object into two approach methods, namely the literature approach and the spatial data approach.

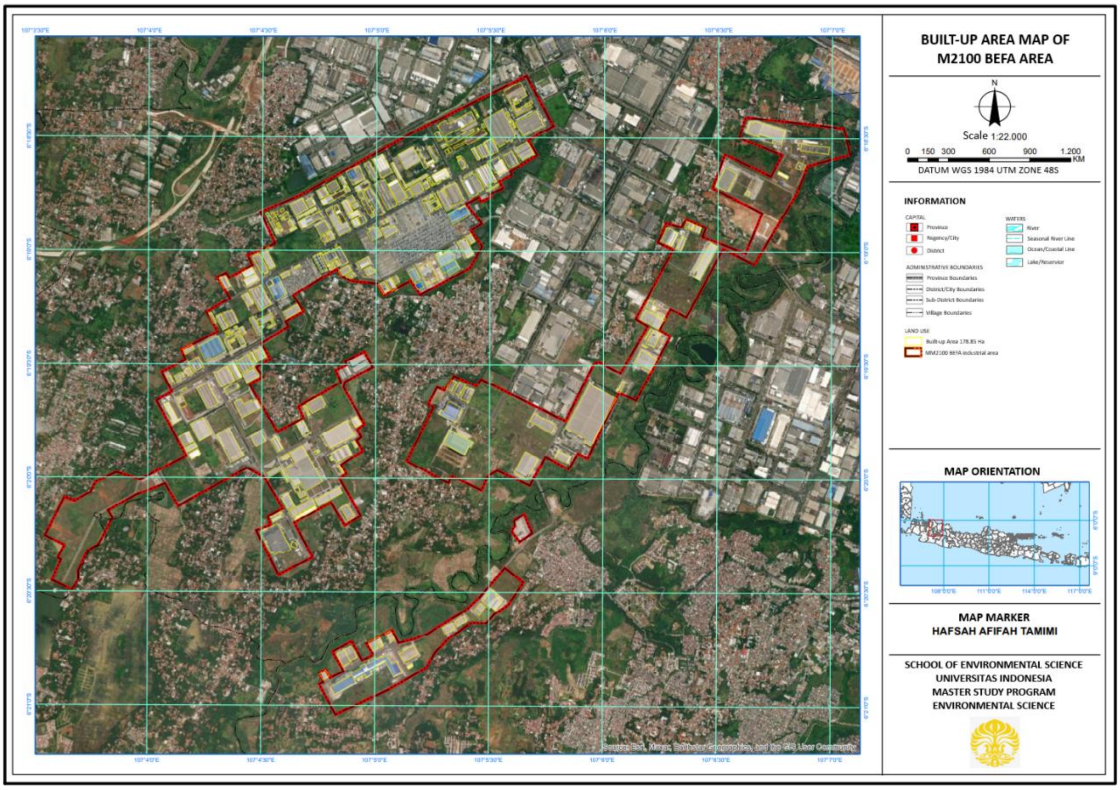

Fig. 3. Map of industrial area built-up area

For the calculation of the first approach method, the literature approach, based on data obtained from the profile of PT Bekasi Fajar Industrial Estate, Tbk. (BEFA), it is known that the area of the MM2100 BEFA industrial area is 1,700.00 ha. Therefore, using the previous assumption, the total theoretical roof area is known to be 680.00 ha. Then, using the second approach method, based on the analysis of satellite imagery using GIS, it is found that the built-up roof area is 178.85 ha. The satellite imagery used in this study was obtained from World Imagery ESRI, MAXAR accessed in 2023 with a scale of 1:22,000 (Figure 3).

Based on the previous roof area calculations, fundamental data were obtained for the analysis of the potential electricity generation and greenhouse gas emission reduction from the use of rooftop solar panels. The results of this potential analysis for the MM2100 BEFA Industrial Area, using both the first and second approach methods (Table 2).

Table 2. Avoided GHG emissions calculation

Factors	Result	
	1st Methods	2nd Methods
Number of industries in the area	137	137
Total industrial estate area (ha)	1,700	1,700
Total rooftop area (m^2)	6,800,000	1,788,500
Potential area of rooftop solar panels (m^2)	1,360,000	357,700
Expected power generation (MW)	160.41	42.19
Annual power generated (GMH/year)	240.61	63.28
Avoided GHG Emission ($MtCO_2e$/year)	0.15	0.04

The potential GHG emissions that can be avoided are the result of the transition from the use of fossil energy to renewable energy. According to the Sustainability Report published by PT Cikarang Listrindo (2022), the electricity supplier in the MM2100 BEFA area, the emission factor produced for each unit of electricity is 0.64 $kgCO_2e/kWh$. The calculation of the amount of CO_2 emissions that can be avoided based on the first approach method with a total roof area of 6,800,000 m2 is 240.61 GWh/year, equivalent to a potential reduction of 0.15 $MtCO_2e$/year. Meanwhile, the calculation results of avoided CO_2 emissions based on the second approach method with a total roof area of 1,788,500 m2 are 63.28 GWh/year, equivalent to a potential reduction of 0.04 $MtCO_2e$/year.

Apart from that, in terms of cooperation, the economic value of these rooftop solar panels has also been supported by PLN (PLN, 2022) and private power generation companies (Cikarang Listrindo, 2022) in the form of cooperation offers with an energy buying and selling scheme. This scheme uses kWh export-import (kWh exim) from excess energy installed on customers' rooftop solar panels, to be resold to electricity producing companies. The targets of this cooperation scheme are on-grid electricity customers supplied by power generation companies, including customers in industrial areas. The calculation results of the potential efficiency from the implementation of rooftop solar panels can be seen in Table 3.

Table 3. Potential efficiency from the application of rooftop solar panels

Energy management model	Energy savings (units/year)	Unit	Energy savings (Billion IDR/year)	GHG reduction potential ($MtCO_2e$/year)
Methods 1 (Literature approach)	240.61	GWh	477.73	0.15
Metode 2 (GIS-based approach)	63.28	GWh	125.64	0.04

Note: PT Cikarang Listrindo electricity tarif (2022) IDR 1,985.48/kWh

Based on the analysis of the potential electricity generation and GHG emission reduction from the utilization of rooftop solar panels, it is known that there is a significant margin between the two methods. The literature approach yields greater potential for electricity generation and emission reduction, reaching 3.8 times the calculation with the spatial data approach. This indicates that the accuracy of the literature data used is relatively low. The assumption that 40% of built-up land constitutes roof coverage may not be applicable in the calculation for the MM2100 BEFA Industrial Area. This is because the area profile with a land ownership of 1,700 ha, there are still undeveloped plots and empty land. Meanwhile, although the potential results obtained from GIS-based approach are smaller, the analysis is more accurate as it is derived through direct mapping of the built-up roof area using satellite imagery representation. If a rooftop solar panel program is to be implemented in the MM2100 BEFA Industrial Area in the future, it is recommended to conduct the analysis using spatial data.

From an economic standpoint, application of rooftop solar panels can yield greater advantages when viewed through a social approach. Walch & Rüdisüli (2023) research on strategy to generate clean energy using rooftop solar panel shows that solar panel installation is better done collaboratively between the electricity users. Collaborative installation and use of electricity allows solar panels to be installed on a smaller roof area (46% of the total roof area) compared to if the installation was carried out randomly (84% of the total roof area). Rooftop solar panel are installed on roofs with the highest absolute solar yield. Collaborative solar panel installation also reduces initial investment, operational and maintenance costs (Biswas, 2023).

In further discussion related to the concept of net-zero emission target, industrial ecology is intrinsically linked to the concept of clusters or regions. There is a lot of literature regarding the importance of industrial clusters in supporting economic development (Roberts, 2004). However, industries have long been shielded from strong energy and climate policies due to concerns about job losses, national competitiveness, and cross-border carbon leakage (Sovacool et al., 2023a). Implementing transformative innovation globally is difficult because not all countries are able to adopt it quickly. Developing countries face enormous social, political and economic obstacles that hinder the implementation of decarbonization interventions (Sovacool et al., 2023a). Financial constraints, inadequate infrastructure, lack of necessary workforce skills, lock-in effects, and political economy considerations are global challenges that require specific solutions (Green et al., 2022). Developing countries are especially important considering that by mid-century based on current policy projections, the majority of industrial emissions will come from ten developing countries, including China, Brazil, India and South Africa (International Energy Agency, 2021).

In an effort to reduce greenhouse gases in the industrial sector, a collective effort is needed to increase the renewable energy transition through the development of knowledge, investment, maintenance and management of jointly borne energy infrastructure (Butturi et al., 2019). Individually, each company is able to create its own emissions reduction program. However, on a regional scale, industry is often seen as a sector that is difficult to reduce emissions to reach net-zero emissions because of its very diverse characteristics (Sovacool et al., 2023b). The net-zero emissions plan on an industrial area scale has several big challenges like a megaproject. Application on an industrial area scale has a very high level of technological novelty, complex structures, systems that must be integrated, and implementation must be accelerated in order to meet government targets and investment expectations (Geraldi et al., 2011; Flyvbjerg, 2014; Sovacool et al., 2022).

Despite the high challenges, commitments to net zero emissions have begun to be targeted by several types of industry since 2019 and this has triggered the development of policies related to industrial decarbonization in recent years (International Energy Agency, 2021). The UK is one of the pioneers of the net zero emissions movement on an industrial scale (Sovacool et al., 2023a). The approach used to achieve net zero emissions in the UK is based on a cluster/regional approach, so it includes technical, spatial and socio-political dimensions (Sovacool et al., 2023b). By focusing the net zero emissions target on the right geographic location, collective results can be achieved that have a high contribution to climate resilience. For example, in the UK, more than 50% of direct CO_2 emissions are generated from just six specific industrial areas (HM Government, 2021), so if focused the emissions reduction program on these six areas, the national targets related to climate resilience will be easier to achieve.

In a more global view, Feng et al. (2018) explained the general framework and steps to construct a zero-carbon emission industrial area. The first step is to determine whether to build a new zero-carbon emission industrial area or transform an established industrial area into a zero-carbon emission industrial area. The target setting should be referred to the local policy, industry characteristic, and economic situation. A study of the targeted industrial area which includes the industrial character analysis, energy consumption audit, energy supply evaluation, and carbon emission accounting should be conducted. Based on the study, a series of comprehensive measures covering the management level and the technical level are selected to implement. The management measures what kind of enterprises can be admitted, perform the energy management and the monitoring of energy consumption and carbon emission. The technical measures aim to achieve balance of energy supply and demand as well as carbon emission and offset.

Sovacool et al. (2023a) defines a strategy for achieving net zero emissions in sustainable industrial areas in six major steps which can be seen in Table 4. Based on the aforementioned research, the strategy for a sustainable industry that is emission neutral actually involves not only technical aspect, but more social and economic dimensions. In this case, policy makers such as industrial area management play a significant role in regulating and arranging to meet the net zero target. From a financial perspective, industries need to be encouraged to make green investments by providing incentives, discounts and tax relief. Financing institutions are also encouraged to provide facilities to support green energy and low-carbon activities or projects (Chen et al., 2023).

MM2100 BEFA industrial area can consider implementing a net zero emissions target all its industrial areas by following the steps defined in Sovacool et al. (2023a) combined with establishing policies such as collaborative installation of solar panels, providing financial benefits in the form of discounts for tenants which participate in the net zero program, and providing assistance in green investment for tenants. Many aspects need to be considered in implementing a sustainable industrial area, making this research very open to further development both from technological, social and economic dimensions.

Table 4. Six major steps towards net zero emissions for industrial clusters

Dimension	Steps	Explanation
Economy	Quintuple financing	Increasing international financial support for industrial decarbonization.
Techno-economy	Accelerate technology transfer to developing countries	Accelerate the transfer of low-carbon industrial decarbonization technologies worldwide.
Socio-economy	Human resource development investments	Building industrial skills and net zero emissions training systems.
Social	Leverage local roles and industry coalitions	Encourage cities, private sector companies, and other non-state actors to adopt renewable energy, implement energy efficiency, pursue negative emissions (especially through forestry), and invest in alternative fuel infrastructure.
	Increase social acceptance and license to operate	Establish programs and policies that build social support and aim to ensure a just and equitable transition.
Socio-politics	Establish new global agreements and foster climate organizations	Implement new global agreements to decisively address the dangerous global governance problems that arise by coordinating the decarbonization of net zero emissions industries.

4. Conclusions

Rooftop solar panel technology as a renewable energy source can utilize spatial information and existing area conditions as an alternative to achieve sustainable and low-carbon industrial areas. Analysis results from literature-based approach with low accuracy found that the MM2100 BEFA Industrial Area has the potential for energy generation from rooftop solar panels of 240.61 GWh per year, equivalent to a reduction of 0.15 Mt-CO_2e GHG per year. Meanwhile, using a spatial data-based approach with the utilization of GIS, more accurate results were obtained with the potential energy generation from rooftop solar panels of 125.64 GWh per year and a GHG reduction of 0.04 Mt-CO_2e per year.

This energy transition is only the initial step toward achieving a low-carbon industrial area, and more efforts are needed to reach the target of net-zero emissions. To achieve a sustainable and carbon-neutral industrial area, at least six major steps are required: increased funding, technology transfer, investment in human resources, empowerment of local actors and industry coalitions, enhanced social acceptance, and international climate policy updates. The implementation of these aspects needs to be tailored to the specific conditions of each industry. Consideration should be given to the development of a holistic strategy that encompasses economic, social, and environmentally based ecological industrial aspects to achieve a sustainable industrial area.

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Author Contribution

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