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Research article

Transitioning Science and Technology Parks in Indonesia Towards a Low-Carbon Economy: An Emissions Accounting Framework and Recommendation

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Abstract

Science and technology parks (STPs) are primarily intended to foster innovation and support a knowledge-based economy. However, activities within STPs also contribute to greenhouse gas (GHG) emissions, which necessitate strategic mitigation efforts. This study aimed to develop a framework for calculating GHG emissions in STPs in Indonesia and to explore implementable low-carbon strategies. In this study, it was found that the main source of emissions in STPs was electricity consumption (68%), followed by emissions from refrigerants and other fugitive emissions (84% of direct emissions). The results led to the identification of four main pillars to support low-carbon strategies in STPs based on environmental initiatives: targeted environmental policies, technology and infrastructure governance, education and collaboration, and revenue streams. This study highlights the importance of a holistic approach to emissions management in STPs to support the transition to a low-carbon economy and ensure long-term sustainability.

Keywords: science and technology park; greenhouse gas emissions; low-carbon strategy; sustainability; GHG emissions accounting

1. Introduction

Science and technology parks (STPs) are key areas that support sustainable economic growth through the development and application of science and technology across various sectors (Henriques et al., 2018). Several institutions defined STPs differently (UNIDO, 2021). Terms such as "technology park," "technopole," "research park," and "science park

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represent a broad concept and are used interchangeably within this context (IASP, 2018). The acronym STP (science and technology park) refers to all of these variations. Moreover, each country has its own characteristics and models of STP development (Pitaloka & Humaedi, 2020). STPs function as innovation hubs that foster the growth of technology-based start-ups and have been shown to contribute to economic growth in various countries (Ratinho & Henriques, 2010; Yan & Chien, 2013).

According to Presidential Regulation (Perpres) Number 106 of 2017 concerning Science and Technology Areas, a science and technology park (STP) is referred as Kawasan Sains dan Teknologi (KST) in Indonesia, which is a professionally managed center designed to promote sustainable economic growth through innovation, the application of science and technology, and the development of technology-based start-ups. The development of STP areas is a strategic initiative aimed at promoting the downstream commercialization of research and technological innovations into industrial applications. STPs in Indonesia are expected to generate various competitive innovations and technologies. Their development also supports the implementation of a national economy based on innovation and technology, as outlined in the 2020-2024 National Medium-Term Development Plan (RPJMN). Since STPs are centers of technology-based industrial activity, evaluating their environmental impact is crucial, especially their GHG emissions.

In Indonesia, a developing country, the national technopark is still in the early stages of physical development. However, its functional development has progressed further (Maninggar, 2019). As part of the national research institution, the National Science and Technology Park (NSTP) supports various technopark functions, acting as a bridge between technological innovation and industry, and serving as an incubator for SMEs. Nevertheless, some facilities, such as buildings and laboratories, are still under construction (Maninggar, 2019). STP development in Indonesia exists at multiple levels, including district/city-level technoparks, provincial-level science parks, and NSTP (Muhammad et al., 2017). STPs in Indonesia exhibit distinct characteristics compared to those in other countries. For instance, Indonesian STPs focus on regional economic development based on innovation, with the primary objective of enhancing regional competitiveness through research and technology to support sustainable economic growth (Baluch et al., 2015). In contrast, STPs in developed countries, such as China and the United States, often integrate industrial zones within their facilities. This difference arises from varying policy approaches and planning strategies for STP development (Dhewanto et al., 2016). Moreover, the infrastructure and facilities of STPs In Indonesia are generally tailored to support technological innovation, with sector-specific adjustments. The main infrastructure typically includes tenant spaces, internet access, laboratories, meeting and conference rooms, and cafés to facilitate informal interactions. Most STPs in Indonesia are government-funded and operated, with strong public sector involvement (Sutopo et al., 2018; Mursalim et al., 2023). This differs significantly from STPs in Europe and the United States, where funding is more diversified and includes private sector investment, venture capital, and research institutions (Parry, 2020). Additionally, the primary activities in Indonesian STPs are centered around business incubation and training for tenants, with the goal of fostering an ecosystem conducive to the growth of technology-based start-ups (Putera et al., 2022).

Most research on STPs in Indonesia has focused on policy (Arianto et al., 2023; Rahmani et al., 2023), institutional models (Kusharsanto & Pradita, 2016; Mursalim et al., 2023), and stakeholder collaboration models (Pitaloka & Humaedi, 2020). However, studies on the inventory of GHG emissions in this area are still limited. Since STP is a center of technology-based industrial activities, evaluating environmental impacts, including GHG emissions, is crucial.

In recent decades, rising concentrations of GHGs in the atmosphere have become the primary driver of global climate change, largely due to unsustainable production patterns, excessive fossil fuel consumption, and environmental degradation (Tol, 2016). Several studies suggest that energy efficiency and economic development can be pursued simultaneously by promoting high-tech industries within STPs (Yan & Chien, 2013). Therefore, it is important to reveal the characteristics of GHG emissions and explore the potential for emission mitigation in this area.

GHG inventories are the first step in identifying the main sectors contributing to emissions and in formulating effective mitigation strategies. Emission inventory methods have been developed at various geographical scales. The Intergovernmental Panel on Climate Change (IPCC) recommended an emissions inventory framework for national-level reporting (IPCC, 2006). Additionally, the National Development and Reform Commission (NDRC) issued guidelines for provincial GHG inventories in China (Shan et al., 2017). Some studies also focus on smaller scales, such as cities (Li et al., 2013; Li & Chen, 2013; Chen et al., 2019). However, regional-level methodologies still face major challenges due to limited data on activities and company-specific emission factors (Yu et al., 2020). Moreover, national or city-level approaches are often unsuitable for specific areas like STPs (Wei et al., 2022). The carbon footprint of a region includes both direct (territorial) and indirect (embedded) emissions related to production and consumption activities (Wiedmann & Minx, 2007; Galli et al., 2012). Despite the critical role of STPs in innovation and sustainability, studies on their emissions remain scarce. Thus, there is a clear need for a framework tailored to GHG emissions accounting in STPs.

A GHG emissions calculation framework is vital for STPs to ensure accurate and consistent measurement and to identify the primary sources of emissions from various activities (IPCC, 2006; Shan et al., 2017). With a structured approach, emission mitigation strategies, such as the implementation of renewable energy and enhancement of energy efficiency, can be developed more effectively (Chen et al., 2019; Pleerux & Aimkuy, 2021). Additionally, this framework can help STP meet international regulations and standards such as ISO 14064, which is part of the global commitment to sustainability (ISO, 2006).

STP with robust emission accounting and mitigation strategies will also be more globally competitive, as more investors and companies prioritize sustainability (Yu et al., 2020). However, most existing methods are designed for larger scales (national or municipal) and do not reflect the unique characteristics of STPs, such as high-tech industry concentration and innovation-centric operations. Therefore, a tailored framework is necessary to accommodate the complexity of STPs and manage carbon emissions more effectively (Wei et al., 2022). This study not only proposes a GHG emissions framework specifically designed for STPs but also offers practical recommendations to support low-carbon development in these innovation-driven environments.

2. Materials and Methods

2.1 Scope and data collection

This study focused on the inventory of emission sources and emission management practices in STPs, with particular emphasis on data collected during the year 2023. The scope included an evaluation of the environmental performance of STPs by identifying major sources of greenhouse gas (GHG) emissions and examining the management practices implemented to support low-carbon development strategies within these areas.

In this study, STP management is categorized into four main functions: building maintenance, area service, area management, and national vital object maintenance.

1. Building maintenance involves overseeing various utility systems within the facility, such as plumbing and sanitation, fire prevention mechanisms, air conditioning and ventilation, lighting and electrical systems, security systems, and communication networks. These systems are essential for ensuring a comfortable and safe environment for academics and researchers.

2. Area service provides necessary support for the daily activities of researchers and academics. This includes the provision of office supplies, meeting room equipment, drinking water, and sanitation items like toiletries. Additional services may include guest house accommodation and transportation facilities such as buses, intra-park shuttles, and inter-area vehicles.

3. Area management focuses on infrastructure and environmental maintenance. It includes managing the clean water supply, waste treatment systems, road maintenance, and the care of parks and green spaces within the STP area.

4. National vital object maintenance focuses on securing and protecting the area, including strategic land management and security aspects of national vital assets.

To assess emission sources and management practices, the authors conducted structured surveys and semi-structured interviews with area managers. Additionally, the data collected included the emission factors used in compiling the emission inventory. These emission factors were sourced from the Intergovernmental Panel on Climate Change (IPCC, 2006), and from national guidelines including the Greenhouse Gas Inventory Calculation and Reporting Guidelines issued by the Ministry of Energy and Mineral Resources and other relevant sources (Supriadi et al., 2015; MEMR, 2018).

2.2 GHG inventory framework

The GHG inventory framework adopted a systematic approach to calculating GHG emissions at STPs in Indonesia. Emission sources are categorized based on the GHG Protocol into direct emissions (Scope 1) and indirect emissions (Scope 2 and Scope 3) (see Figure 1). Direct emissions (Scope 1) referred to emissions originating from sources owned or controlled by the STP. These included emissions from stationary combustion, mobile combustion, and refrigerant leaks or other fugitive emissions. Meanwhile, indirect emissions produced by STPs come from the use of electricity (Scope 2 emissions) and vehicle mobility within the STP area, where the vehicles are not owned or rented by the STP manager (Scope 3 emissions). Based on an analysis of KST's operational functions, Figure 1 showed an inventory of potential emissions produced by STP.

2.2.1 Direct emissions calculation

Direct emissions from the STP included emissions from stationary combustion, mobile combustion, and refrigerant leaks. Stationary combustion emissions are generated by equipment such as generators and boilers. The primary fuels used are biodiesel (B30) and Pertalite. The formula for calculating emissions from stationary combustion is shown in equation 1:

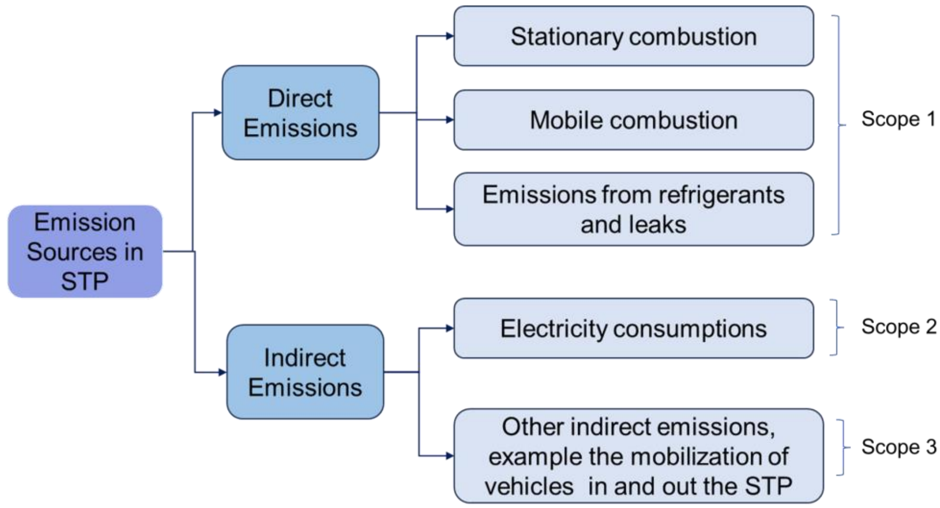

Figure 1. Scope of GHG emissions inventory in STP

$$E_{stationer,CO_2e} = \sum_{i,y} \left(F_i \ x \ NCV_i \ x \ \rho_i \ x \ EF_{i,y} \ x \ GWP_y x \ 10^{-9} \right) \quad (1)$$

Where $E_{stationer}$ = emissions from stationary (ton CO_2e); F = fuel consumption in 1 year (kiloliters); NCV = net calorific value of fuel (TJ/Gg); ρ = fuel density (kg/m^3); EF = emission factor (kg emission/TJ); GWP = conversion value of emissions to CO_2e (tons of emissions/tons of CO2e); i = type of fuel in stationary equipment; y = type of emission (CO_2, CH_4, N_2O).

Mobile combustion emissions originated from operational vehicles within and outside the STP area, such as cars, motorcycles, and forklifts. The fuel types varied by vehicle. Equation 2 is used to calculate emissions, as follows:

$$E_{combustion,CO_2e} = \sum_{c,y} \left(F_c \ x \ NCV_c \ x \ \rho_c \ x \ EF_{c,y} \ x \ GWP_y x \ 10^{-9} \right) \quad (2)$$

Where $E_{combustion}$ = emissions from mobile combustion (ton CO_2e); c = type of fuel in vehicles.

Refrigerant emissions are also considered under direct emissions. In the calculation of refrigerant emissions, the quantity of leaked gas is assumed to equal the amount of gas replaced in these systems by HVAC or chiller maintenance company (NCASI, 2005). This is due to the unavailability of recorded data regarding the amount of freon leaking during the charging process or at the end of the freon's service life. In many cases where maintenance records or leakage data are incomplete or unavailable, assuming full charge loss provides a “worst case” approach. This approach is consistent with some environmental reporting practices, particularly in initial assessments or when establishing baselines (World Resources Institute, 2004). Hence, the annual emissions included all refills, without additional end-of-life leakage in the same year. Equation 3 is used to calculate emissions from refrigerants and leaks as follows:

$$E_{Refrigerant} = \sum_{r} R_r \; x \; C_r \; x \; EF_r \; x \; 10^{-3} \quad (3)$$

Where, $E_{Refrigerant}$ = total refrigerant emissions (ton CO_2e); R = percentage of refrigerant replaced or refilled in the system (percentage); C = amount of refrigerant filled in the system (kgs); EF = emissions factor (kg CO_2 per kg), and r = type of refrigerant used.

2.2.2 Indirect emissions

Indirect emissions generated by KST come from electricity usage (scope 2) and vehicle mobility within the area where the vehicles are not owned/rented by the STP manager (scope 3). Scope 2 emissions are calculated based on the total electricity consumption using the following equation 4:

$$E_{Electricity} = DA_{Electricity} \; x \; EF_{Electricity} \; x \; 10^{-3} \quad (4)$$

Where, $E_{Electricity}$ = electricity emission (ton CO_2e); $DA_{Electricity}$ = electricity consumption (kWh); $EF_{Electricity}$ = emission factors from the energy sources used (kg CO_2e/kWh).

Scope 3 emissions involved the mobilization of vehicles that are not owned or operated by the STP. Data collection was conducted for 120 working days in a year. It is assumed that each vehicle entering the STP travels an average of 30 km within the area. Fuel consumption is estimated for this distance, and emissions are calculated using the same formula as mobile combustion under Scope 1.

3. Results and Discussion

3.1 Emissions generated by the science and technology parks

Science and technology parks (STPs) are typically large-scale facilities, and their considerable size significantly contributes to their overall energy consumption (Verbeeck & Hens, 2010). Analyzing the management functions within Indonesian STPs reveals that while emissions are not extensive, the primary activities within these parks are centered on research, new product development, and tenant training and mentoring. Consequently, major emission sources within these parks are relatively limited. It is crucial for organizations to calculate and report all major sources of scope 1 and scope 2 emissions within their organizational and operational boundaries (World Resources Institute, 2004). While scope 3 emissions (those in the value chain) are also important, the GHG Protocol emphasized that scope 1 and scope 2 emissions are typically the most direct and significant sources of emissions for most organizations. In this study, calculations based on the available data for Scope 1 and Scope 2 emissions provide a representative overview of the primary emission sources within the relevant STP.

Figure 2 presented the total absolute greenhouse gas emissions in this STP for 2023, which amounted to 37,513.59 tons of CO_2e. The most significant contributor to the total GHG emissions was indirect emissions from purchased electricity, accounting for 27,912.84 tons of CO_2e (68%). The next major source of emissions was direct emissions contributing 6,397.67 tons of CO_2e (19%). Lastly, indirect emissions from activities in the STP's value chain amounted to 3,203.08 tons of CO_2e (8%).

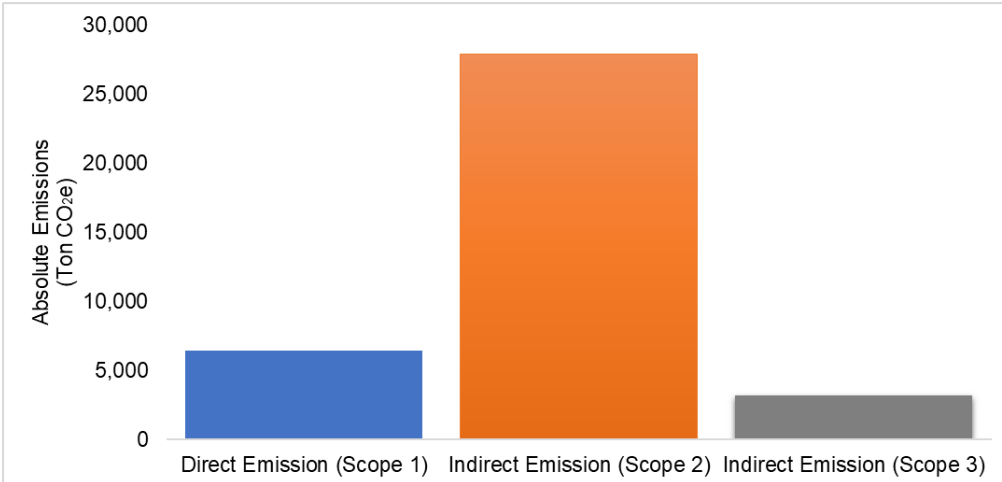

Figure 2. Total GHG emissions in the STP in 2023

The emission intensity from the STP amounted to 9.76 tons of CO_2e per employee. This number was significantly higher compared to the DTU Science Park, Denmark, which recorded an emission intensity of only 0.7 tons of CO_2e per employee (DTU Science Park, 2024). This discrepancy was primarily due to the STP in this study still relying on energy from coal-fired power plants, whereas the DTU Science Park has transitioned to renewable energy sources. Additionally, the use of inefficient equipment and the lack of effective implementation of decarbonization and energy efficiency strategies further contribute to the higher emissions produced by the STP.

Direct emissions (scope 1) in this STP were primarily derived from refrigerant and fugitive emissions, which accounted for 84% of emissions, followed by mobile combustion at 15%, and stationary combustion at 1% (see Figure 3). The most commonly used refrigerant in the STP buildings was R32 freon, followed by R410A freon. Both of these refrigerants are considered environmentally friendly due to their zero ozone depletion potential (ODP), meaning they do not harm the ozone layer. However, R32 freon has a lower environmental impact compared to R410A because it possesses a significantly lower global warming potential (GWP) (Dekhkanova & Marupova, 2021). Despite this, the study identified that some facilities within STPs still use R22 freon, which is not considered environmentally friendly. R22 freon (Chladon 22) is classified as a Class 4 hazardous substance on the toxicity scale and poses potential health risks (Dekhkanova & Marupova, 2021). Exposure to high concentrations of R22 freon could lead to symptoms such as fatigue, memory impairment, insomnia, and even shortness of breath. Additionally, direct contact with R22 freon in its liquid form can cause frostbite, blisters, and necrosis on the exposed skin.

Emissions from mobile combustion in STP primarily resulted from the fuel usage of operational vehicles within the area (see Figure 4). The largest contribution to emissions came from shuttle buses (39.3%), which served as inter-building transportation for STP users. The second-largest source of emissions was operational vehicles (30.5%), which were used for research and non-research activities involving destinations outside the city. The next category was management vehicles (29.7%), including trucks, pick-up vehicles, and multi-purpose vehicles, which were used for logistics and operational tasks within the STP. Lastly, forklifts contributed the smallest share of emissions, accounting for just 0.4%.

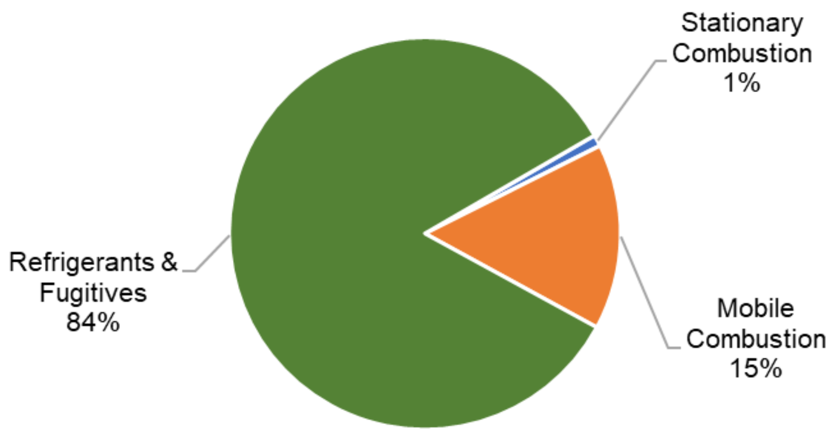

Figure 3. GHG emission from direct emissions

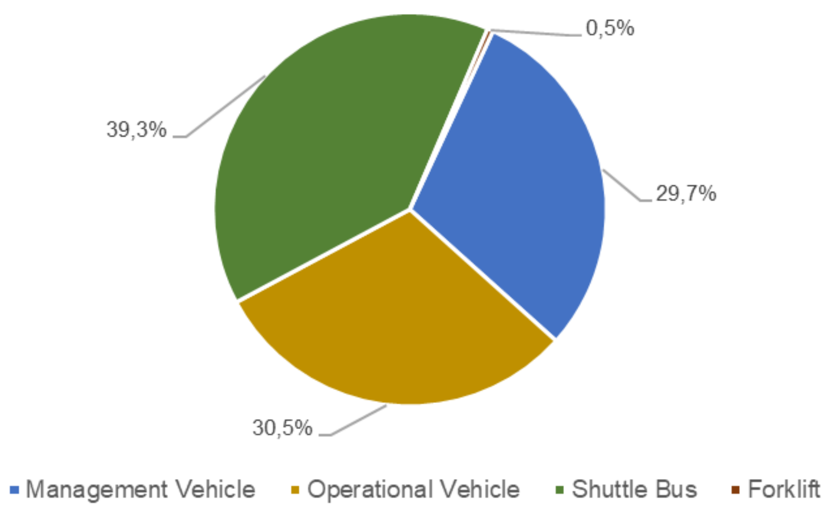

Figure 4. GHG contribution in mobile combustion

Indirect emissions from electricity consumption (scope 2) accounted for 68% of total greenhouse gas (GHG) emissions at the STP. The energy intensity of indirect emissions was recorded at 9.13 MWh per employee, which was higher compared to the DTU Science Park, where it stood at only 8.3 MWh per employee (DTU Science Park, 2024). This difference was caused by the extensive use of aging equipment that was inefficient in terms of energy consumption. Additionally, suboptimal operational standards, the lack of building automation systems, and outdated building infrastructure also contributed to the higher energy consumption per employee.

An analysis of energy consumption by building type revealed that laboratory buildings were the largest consumers of electricity, accounting for 67% of total consumption (See Figure 5). This was primarily due to the high electrical demand of laboratory equipment, such as reactors, analytical instruments, and cooling systems. Office buildings contributed 22% of the total electricity consumption, with high usage driven by air conditioners (AC), electronic devices, and power requirements for meeting rooms and co-working spaces. Operational buildings contributed 11% of total scope 2 emissions, with the majority of electricity consumed by the water treatment process (WTP).

Vehicles entering and exiting the STP area generated indirect emissions under scope 3. Most of these vehicles were motorcycles and fossil-fueled cars, while the use of electric vehicles remained very limited. The calculations show that gasoline-fueled motorcycles contribute the most to scope 3 emissions, accounting for 75.6% of the total emissions in this category (see Figure 6).

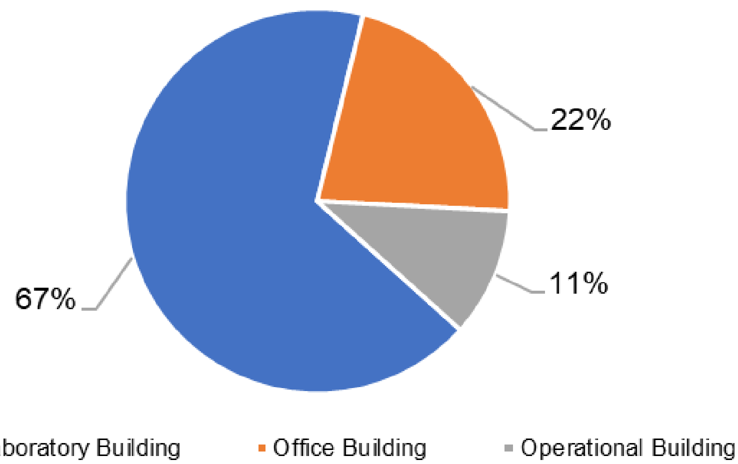

Figure 5. GHG emissions by building type from indirect emissions (scope 2)

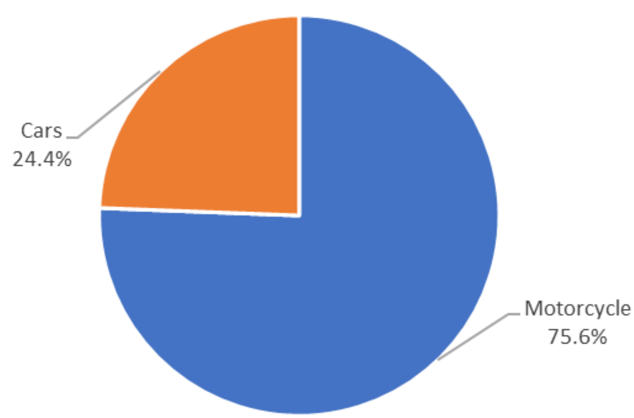

Figure 6. GHG contribution in mobilization of vehicles (scope 3)

3.2 Challenges in implementing low-carbon strategies for science and technology parks (STPs)

The implementation of low-carbon strategies in STPs faced several significant challenges that could interfere with a successful transition toward a more sustainable economy. These challenges included difficulties in GHG emissions inventory and reporting, limited financial resources, insufficient stakeholder collaboration, and a lack of knowledge regarding low-carbon technologies.

One of the primary challenges in implementing low-carbon strategies in STP is the difficulty in collecting an accurate and comprehensive GHG emissions inventory. Without reliable data, measuring carbon footprints and identifying areas for improvement becomes a complex task (Wright et al., 2011). In this study, it was observed that data regarding GHG emissions were fragmented and not properly collected. This highlighted that GHG emissions recording was still limited and the lack of an efficient management system hampered efforts to meet emission reduction goals. In fact, carbon accounting practices could be applied and provide benefits in efforts to reduce emissions in green buildings (Yusuf et al., 2024).

Limited financial resources were another major barrier to implementing low-carbon strategies. Insufficient funding often made it difficult to develop green infrastructure and adopt low-carbon technologies (Sureeyatanapas et al., 2021). In Indonesia, although the government provides initial support, private sector involvement and venture capital for low-carbon financing in STP are not widespread (Dhewanto et al., 2016). This reliance on limited resources further stifles efforts to create efficient and environmentally friendly facilities (Chen & Liu, 2021). Without adequate investment, the implementation of green technologies and sustainable infrastructure is exceedingly challenging.

Collaboration between industry, academia, and government is crucial for successful low-carbon strategy implementation. However, building strong partnerships among these parties within STPs was often a significant challenge (Fadoli et al., 2019). The private sector was not sufficiently involved in policy discussions, while the government sometimes lacked the technical expertise necessary to leverage innovations from the research sector (Dhewanto et al., 2016). Furthermore, universities and research institutions sometimes struggle to collaborate effectively with industry, limiting the potential for green technology development (Kusharsanto & Pradita, 2016). The inability to foster robust collaborations often delays the adoption of low-carbon technologies and broader emission reduction strategies. However, a dedicated organization could serve as a bridge, promoting low-carbon development within STPs by facilitating stakeholder engagement and securing governmental support for research and infrastructure development (Soenarso et al., 2013).

Finally, the lack of knowledge and skills among key stakeholders, such as STP managers, tenants, and government officials, was a critical barrier. Many individuals did not fully understand the potential of low-carbon technologies and their benefits, particularly in terms of cost savings and GHG reduction (Yusuf et al., 2024). The absence of training and education in green technologies and accurate emissions calculations often results in hesitancy toward adopting environmentally friendly innovations (Wang et al., 2021).

3.3 Recommendation of low-carbon strategies for Science and Technology Parks

Adopting a low-carbon development strategy is essential for a STP to ensure long-term sustainability and maintain competitiveness in an increasingly environmentally conscious global economy (Huong, 2023). STPs need this approach to mitigate their environmental impacts and enhance operational sustainability.

A thorough analysis of carbon emission patterns is crucial for identifying the primary sources of emissions within each STP. This understanding forms the foundation for designing effective emission reduction policies. When developing a low-carbon strategy, two main emission categories should be considered: direct emissions (from sources owned or controlled by the STP) and indirect emissions (resulting from electricity consumption and the mobilization of vehicles not owned or controlled by the STP).

By implementing structured policies, STPs could evolve into greener innovation ecosystems, improve energy efficiency, reduce dependence on fossil fuels, and reduce GHG emissions from various activities within the park (Feng et al., 2023; Kut et al., 2024). To address the challenges in implementing low-carbon strategies in Indonesian STPs, we recommend four main pillars to support low-carbon strategies, including policy based on environmental, technology and infrastructure governance, education and collaboration, and revenue stream.

Environmental policy: One key approach to achieving a low-carbon STP is through targeted environmental policies. STP managers should establish progressive emission reduction targets that align with national carbon reduction plans and enforce internal regulations that ensure compliance with these targets (Sówka & Bezyk, 2018; Nagar et al., 2019). As a center for developing science and technology, STP also strategically encourages a sustainable waste management system. A zero-waste policy based on a circular economy is one of the main solutions to ensuring that the waste produced can be recycled or reused, thereby reducing the environmental impact caused by STP operations (Noor & Anjum, 2024).

In addition to environmental policies, the optimization of technology and infrastructure plays an important role in reducing carbon emissions. Technology and infrastructure governance policies should ensure that STPs adopt the best available technologies to support low-carbon operations. Renewable energy sources, such as solar power, are crucial strategies for reducing scope 2 emissions (Nagar et al., 2019). Currently, electricity consumption is one of the largest sources of emissions, especially in Indonesia, which still relies heavily on coal-fired power plants (Farizal et al., 2022; Febijanto et al., 2024). According to the International Energy Agency, the transition to renewable energy could contribute up to 32% of reduction in global carbon emissions (Wei et al., 2022). Therefore, STPs must actively develop green, energy-based infrastructure to support operational efficiency (Lü et al., 2023). Moreover, as science and technology-driven regions, STPs should prioritize the development of Internet of Things (IoT) technologies to enhance energy efficiency and environmental monitoring (Adeyanju et al., 2021). The implementation of innovative grid systems enables more intelligent electricity distribution, optimizes energy consumption, and reduces waste (Huaroc et al., 2024). By incorporating smart metering in every building, STP could monitor energy use in real-time and manage it more effectively, thereby not only improving efficiency but also reducing carbon emissions.

Refrigerant and fugitive emissions dominate direct emissions in the STPs and are often overlooked in carbon management strategies. Refrigerants used in air conditioning systems, laboratories, and low-temperature storage facilities can release greenhouse gases with significantly higher global warming potential (GWP) than carbon dioxide (CO_2) (Dilshad et al., 2020; Maneejantra et al., 2024). To address this challenge, STPs need to implement more stringent refrigerant and fugitive emissions management strategies, such as adopting low-GWP refrigerants like hydrofluoroolefins (HFOs) or ammonia-based alternatives (Dong et al., 2021).

Transportation is another crucial aspect of climate change mitigation. In many STPs, direct emissions from fossil fuels used in internal transportation constitute a major source of direct emissions. According to an analysis of 79 cities worldwide, emissions from the transportation sector contribute between 20%-45% of total greenhouse gas emissions (Arioli et al., 2020). Therefore, STP managers must develop a more efficient and environmentally friendly transportation system (Quynh et al., 2024). Utilizing electric shuttle vehicles or other zero-emission technologies is a key strategy for reducing the carbon footprint of internal transport. Additionally, developing bicycle and pedestrian lanes can reduce reliance on fossil fuel vehicles, support the transition to clean energy, and lower greenhouse gas emissions. The low penetration of electric vehicles in STPs remains a challenge to reduce transportation-related emissions. Thus, strategies to increase EV adoption, the provision of adequate charging infrastructure, and the strengthening of sustainable mobility policies are essential for advancing decarbonization in the transportation sector.

A systematic educational and collaborative approach aims to raise awareness, build capacity, and encourage innovation among researchers, academics, investors, and other stakeholders when implementing low-carbon development in STPs. Management must actively provide comprehensive education on GHG emissions reduction and low-carbon development strategies (low-carbon development plans) to all stakeholders, including tenants, researchers, industry players, academics, and surrounding community. This education should include a deep understanding of the importance of clean energy transitions, resource efficiency, and applying environmentally friendly technologies in every aspect of STP operations. In addition, STPs need to develop sustainable training programs, seminars, and interactive workshops that discuss green energy innovations, circular economy-based waste management, and carbon offsetting mechanisms. This step will ensure that each party has the awareness, skills, and commitment to contribute to realizing a more sustainable ecosystem and supporting the net-zero emission target in the future (Nalintippayawong et al., 2023; Ganesh et al., 2024).

One of the main challenges in implementing low-carbon strategies in STPs is the funding aspect (Zaini & Ismail, 2024). The flexibility in the organizational structure of STP is reflected in their funding patterns, which often require integration from various sources to support environmental-based projects or interventions (UNIDO, 2021). In addition to obtaining funding from the government's operational budget, STP managers can also seek external funding from public and private sources. Revenue can be obtained through various mechanisms, including competitive funds, revolving funds, foreign investment, angel investors, and government grant programs. Furthermore, many STPs in Indonesia have green areas with significant environmental and economic value. These green areas can be used as a source of carbon credit, which can be traded in the national carbon trading scheme. With this mechanism, STPs not only contribute to climate change mitigation but also obtain sustainable financial benefits. Therefore, it is important for STPs to implement a revenue stream based on environmental policy, which allows them to obtain funding from sustainability-based activities.

By adopting a comprehensive strategy, STPs in Indonesia can be transformed into globally competitive green technology-based innovation centers. Through environmentally based regulations, optimization of technology and infrastructure, strengthening education and collaboration, and innovation in environmentally based financing, STPs can contribute significantly to supporting the transition to a low-carbon economy while driving sustainable growth in the future.

4. Conclusions

Science and Technology Parks (STPs) hold significant potential for driving green technology and sustainability-based innovation. However, this study highlights that STPs currently contributed substantially to greenhouse gas emissions, particularly from electricity consumption (indirect emissions) and refrigerant and fugitive emissions (direct emissions). The emission inventory analysis reveals that fossil fuel use remains dominant in STP operations, with conventional fuel-based cooling and transportation systems exacerbating the area's carbon footprint. Based on the study's findings, several key strategies are recommended to reduce emissions in STPs:

1. Renewable energy integration: Prioritize the adoption of renewable energy sources, such as solar panels and smart grids, as a cornerstone of the transition to low-carbon STPs.
2. Green transportation optimization: Enhance green transportation by promoting the use of electric vehicles and improving pedestrian infrastructure to reduce emissions from mobility within STPs.
3. Refrigerant and fugitive emissions mitigation: Employ low-GWP refrigerants and implement IoT-based monitoring systems for cooling equipment to minimize leakage and reduce refrigerant-related emissions.

In addition to these technical measures, strengthening policy frameworks is essential. Implementing environmental-based regulations that set clear emission reduction targets and encourage gradual reductions is crucial. Collaboration with academics, investors, and industry stakeholders is necessary to accelerate the adoption of green technologies in STPs. Furthermore, innovative funding mechanisms, such as carbon credit trading, can provide financial support for sustainability initiatives and enhance the global competitiveness of STPs. By adopting a comprehensive approach that includes robust regulations, technological innovations, education, and sustainable funding models, STPs in Indonesia can transform into leading green innovation hubs. This transformation will not only reduce environmental impacts but also create new economic opportunities in the sustainable technology sector, contributing significantly to global climate change mitigation.

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6. Authors' Contributions

Arie Rakhman Hakim: Data curation, Methodology, Formal Analysis, Writing-Original draft preparation, Visualization; Adelina Noor Rahmahana: Data curation, Formal Analysis, Writing-Original draft preparation; Isyalia Dwi Handayani: IDH: Data curation, Formal Analysis, Writing-Original draft preparation, Writing-Review; Ayu Erliza: Conceptualization, Data curation, Formal Analysis, Writing-Original draft preparation, Writing-Review, Editing, and Supervision.

7. Conflicts of Interest

The authors declare that there is no conflict of interest in this study.

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References

Adeyanju, I. A., Emake, E. D., Olaniyan, O. M., Omidiora, E. O., & Adefarati, T. (2021). Digital industrial control systems: Vulnerabilities and security technologies. *Current Applied Science and Technology*, 21(1), 188-207.

Arianto, A., Rusli, B., Bainus, A., Ningrum, S., & Iskandar, D. (2023). Policy networks in comparing science techno parks management in universities and regional governments in Indonesia. *Russian Law Journal*, 11(5), 3071-3077.

Arioli, M. S., D'Agosto, M. D. A., Amaral, F. G., & Cybis, H. B. B. (2020). The evolution of city-scale GHG emissions inventory methods: A systematic review. *Environmental Impact Assessment Review*, 80, Article 106316. https://doi.org/10.1016/j.eiar.2019.106316

Baluch, N., Abdullah, C. S., & Abidin, R. (2015). Technology parks of Indonesia, Malaysia, and Singapore: A critical discourse. *Jurnal Teknologi*, 77(27), 41-50. https://doi.org/10.11113/jt.v77.6887

Chen, F.-H., & Liu, H.-R. (2021). Evaluation of Sustainable Development in Six Transformation Fields of the Central Taiwan Science Park. Sustainability, 13(8), 4336. https://doi.org/10.3390/su13084336

Chen, G., Shan, Y., Hu, Y., Tong, K., Wiedmann, T., Ramaswami, A., Guan, D., Shi, L., & Wang, Y. (2019). Review on city-level carbon accounting. *Environmental Science and Technology*, 53(10), 5545-5558. https://doi.org/10.1021/acs.est.8b07071

Dekhkanova, N. N., & Marupova, M. A. (2021). Freons, environmental aspects and classification in CN FEA. *The American Journal of Applied Sciences*, 3(4), 91-97. https://doi.org/10.37547/tajas/Volume03Issue04-12

Dhewanto, W., Lantu, D. C., Herliana, S., & Permatasari, A. (2016). The obstacles for science technology parks in a developing country. *International Journal of Technological Learning, Innovation and Development*, 8(1), 4-19. https://doi.org/10.1504/IJTLID.2016.075180

Dilshad, S., Kalair, A. R., & Khan, N. (2020). Review of carbon dioxide (CO_2) based heating and cooling technologies: Past, present, and future outlook. *International Journal of Energy Research*, 44(3), 1408-1463. https://doi.org/10.1002/er.5024

Dong, Y., Coleman, M., & Miller, S. A. (2021). Greenhouse gas emissions from air conditioning and refrigeration service expansion in developing countries. *Annual Review of Environment and Resources*, 46(1), 59-83. https://doi.org/10.1146/annurev-environ-012220-034103

DTU Science Park. (2024). *Sustainability Report 2024: Sustainability – in daily operations*.

Fadoli, Raharja, S. J., Purnomo, M., & Auliana, L. (2019). Supply chain management issue: Development science techno park (STP) through small, medium enterprises (SMEs), case study of Puspiptek Serpong Indonesia. *International Journal of Supply Chain Management*, 8(3), 958-965.

Farizal, F., Hakim, A. R., Erliza, A., & Setiawan, I. D. (2022). Lubricant products distribution route determination using Tabu Search Algorithm. *Evergreen*, 9(1), 204-212. https://doi.org/10.5109/4774235

Febijanto, I., Rosmeika, R., Nadirah, N., Yanuar, A. I., Sihombing, A. L., Susila, I. M. A. D., Bahua, H., Kurniawati, I. Z., Barkah, A., Santoso, A. D., Herdioso, R., Rustianto, B., Oktaufik, M. A. M., Suryana, Y., Syamsudin, E., Aditiyawan, A., Gazali, N., Soedjati, D., & Soleh, M. (2024). The environmental perspective on biomass co-firing operations at coal-fired power plants in the Banten region, Indonesia: a life cycle approach. *Energy, Ecology and Environment*, 9(4), 439-454. https://doi.org/10.1007/s40974-024-00329-5

Feng, D., Xu, W., Gao, X., Yang, Y., Feng, S., Yang, X., & Li, H. (2023). Carbon emission prediction and the reduction pathway in industrial parks: A scenario analysis based on the integration of the LEAP model with LMDI decomposition. *Energies*, 16(21), Article 7356. https://doi.org/10.3390/en16217356

Galli, A., Wiedmann, T., Ercin, E., Knoblauch, D., Ewing, B., & Giljum, S. (2012). Integrating ecological, carbon and water footprint into a "footprint family" of indicators: Definition and role in tracking human pressure on the planet. *Ecological Indicators*, 16, 100-112. https://doi.org/10.1016/j.ecolind.2011.06.017

Ganesh, R., Fiorna, V., Al-Talib, A. A., Haslinda, A., & Natarajan, E. (2024). The contribution of outcome expectation in water saving among Malaysians for sustainable living standard. *ASEAN Journal on Science and Technology for Development*, 41(2), Article 12. https://doi.org/10.61931/2224-9028.1561

Henriques, I. C., Sobreiro, V. A., & Kimura, H. (2018). Science and technology park: Future challenges. *Technology in Society*, *53*, 144-160. https://doi.org/10.1016/j.techsoc.2018.01.009

Huaroc, K. B. P., Bonifacio, R. J. M., & Villanueva, M. C. T. (2024). Implementation of a low-cost electronic speed controller for a low-voltage three- phase induction motor in a reused vehicle. *ASEAN Journal on Science and Technology for Development*, 42(1), Article 4. https://doi.org/10.61931/2224-9028.1611

Huong, T. T. (2023). Assessment of eco-industrial park (EIP) performance at the preliminary step in Vietnam. *Current Applied Science and Technology*, 23(6), 1-17. https://doi.org/10.55003/cast.2023.06.23.004

IASP. (2018). *Science Park definitions: How IASP defines our key terms*. https://www.iasp.ws/our-industry/definitions/science-park

IPCC. (2006). *2006 IPCC guidelines for national greenhouse gas inventories*. Institute for Global Environmental Strategies (IGES).

ISO. (2006). *ISO 14064–1:2006. International standard on greenhouse gases- part 1: specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals*. International Standard Organization (ISO).

Kusharsanto, Z. S., & Pradita, L. (2016). The important role of science and technology park towards Indonesia as a highly competitive and innovative nation. *Procedia - Social and Behavioral Sciences*, 227, 545-552. https://doi.org/10.1016/j.sbspro.2016.06.113

Kut, P., Pietrucha-Urbanik, K., & Zeleňáková, M. (2024). Assessing the role of hydrogen in sustainable energy futures: A comprehensive bibliometric analysis of research and international collaborations in energy and environmental engineering. *Energies*, 17(8), Article 1862. https://doi.org/10.3390/en17081862

Li, J. S., & Chen, G. Q. (2013). Energy and greenhouse gas emissions review for Macao. *Renewable and Sustainable Energy Reviews*, 22, 23-32. https://doi.org/10.1016/j.rser.2012.11.072

Li, J. S., Chen, G. Q., Lai, T. M., Ahmad, B., Chen, Z. M., Shao, L., & Ji, X. (2013). Embodied greenhouse gas emission by Macao. *Energy Policy*, 59, 819-833. https://doi.org/10.1016/j.enpol.2013.04.042

Lü, W., Fan, Y., Yan, S., Si, W., Zhao, W., Chai, Y., & Zhu, R. (2023). Low carbon research of science and technology park in southern cities. *E3S Web of Conferences*, 393, Article 01002. https://doi.org/10.1051/e3sconf/202339301002

Maneejantra, S., Charoenpun, T., Bualert, S., Choomanee, P., Janyasuthiwong, S., & Chommon, W. (2024). Potential estimation of secondary pollutant formation of BVOC from *Peltophorum pterocarpum* in urban area. *Current Applied Science and Technology*, 24(5), Article e0260120. https://doi.org/10.55003/cast.2024.260120

Maninggar, N. (2019). Accelerating economic development through technopark: The staging of national science-technopark formation process in Indonesia. *IOP Conference Series: Earth and Environmental Science*, 328, Article 012047. https://doi.org/10.1088/1755-1315/328/1/012047

MEMR. (2018). *Pedoman penghitungan dan pelaporan inventarisasi gas rumah kaca*. Direktorat Jenderal Ketenagalistrikan, Ministry of Energy and Mineral Resources (MEMR).

Muhammad, N. A., Muhyiddin, M., Faisal, A., & Anindito, I. A. (2017). The study of development of science and technopark (STP) in Indonesia? *Jurnal Perencanaan Pembangunan: The Indonesian Journal of Development Planning*, 1(1), 14-31.

Mursalim, S. W., Karlina, N., Muhtar, E. A., & Utami, S. B. (2023). Institutional model of science techno park local governments in Indonesia. In *Proceedings of the fourth international conference on administrative science (ICAS 2022)* (pp. 253-270). https://doi.org/10.2991/978-2-38476-104-3_26

Nagar, P. K., Sharma, M., Gupta, S., & Singh, D. (2019). A framework for developing and projecting GHG emission inventory and preparing mitigation plan: A case study of Delhi City, India. *Urban Climate*, 28, Article 100462. https://doi.org/10.1016/j.uclim.2019.100462

Nalintippayawong, S., Kladyoo, N., & Phengkhlai, J. (2023). Examining the critical success factors of e-learning using structural equation model: A case study on the mandatory use. *Current Applied Science and Technology*, 23(6), 1-21. https://doi.org/10.55003/cast.2023.06.23.001

NCASI. (2005). *Calculation tools for estimating greenhouse gas emissions from pulp and paper mills*. https://ghgprotocol.org/sites/default/files/2023-03/Pulp_ and_Paper_Guidance.pdf

Noor, I. M., & Anjum, S. (2024). SDGs and circularity in fashion industry: Bruneian perspective based on basic values. *ASEAN Journal on Science and Technology for Development*, 41(1), Article 6. https://doi.org/10.61931/2224-9028.1579

Parry, M. (2020). Science and technology parks and universities – Facing the next industrial revolution. In A. Badran, E. Baydoun, & J. Hillman (Eds.). *Higher education in the Arab world* (pp. 109-140). Springer. https://doi.org/10.1007/978-3-030-37834-9_5

Pitaloka, A. A., & Humaedi, M. A. (2020). Science and technpology park (STP): transformation to quadruple helix approach for habituation of science and technology in Indonesia. *Jurnal Sosioteknologi*, 19(1), 201-217.

Pleerux, N., & Aimkuy, N. (2021). Carbon footprint of mangosteen farm level evaluation in eastern Thailand. *Current Applied Science and Technology*, 21(3), 419-430.

Putera, P. B., Widianingsih, I., Ningrum, S., Suryanto, S., & Rianto, Y. (2022). Science, Technology and Innovation (STI) ecosystems in Indonesia (1945-2021): A historical policy analysis. *History of Science and Technology*, 12(2), 302-319. https://doi.org/10.32703/2415-7422-2022-12-2-302-319

Quynh, P. H., Anh, P. N., Thanh, T. K., Mai, C. T., & Bang, H. Q. (2024). Spatial mapping of on-road traffic emission for air quality management: A case of Vinh Phuc Province. *Current Applied Science and Technology*, 24(5), Article e0259482. https://doi.org/10.55003/cast.2024.259482

Rahmani, N. I., Rahayu, K. S., & Prabandari, D. (2023). Potensi pengembangan konsep agro science and technology park (STP) menggunakan analisis swot di arjasari, kabupaten bandung. [Potential Development of the Agro Science and Technology Park (STP) Concept using SWOT Analysis in Arjasari, Bandung Regency]. *Jurnal Sosial Terapan*, 1(1), 18-26. https://doi.org/10.29244/jstr.1.1.18-26

Ratinho, T., & Henriques, E. (2010). The role of science parks and business incubators in converging countries: Evidence from Portugal. *Technovation*, 30(4), 278-290. https://doi.org/10.1016/j.technovation.2009.09.002

Shan, Y., Guan, D., Liu, J., Mi, Z., Liu, Z., Liu, J., Schroeder, H., Cai, B., Chen, Y., Shao, S., & Zhang, Q. (2017). Methodology and applications of city level CO_2 emission accounts in China. *Journal of Cleaner Production*, 161, 1215-1225. https://doi.org/10.1016/j.jclepro.2017.06.075

Soenarso, W. S., Nugraha, D., & Listyaningrum, E. (2013). Development of science and technology park (STP) in Indonesia to support innovation-based regional economy: Concept and early stage development. *World Technopolis Review*, 2(1), 32-42. https://doi.org/10.7165/wtr2013.2.1.32

Sówka, I., & Bezyk, Y. (2018). Greenhouse gas emission accounting at urban level: A case study of the city of Wroclaw (Poland). *Atmospheric Pollution Research*, 9(2), 289-298. https://doi.org/10.1016/j.apr.2017.10.005

Supriadi, A., Darmawan, A., Prasetyo, B. E., Kurniasih, T. N., Kurniawan, F., Oktaviani, K., Isra, A., Aprillia, R., Rabbani, Q., Anggreani, D., & Setiadi, I. (2015). *Data inventory emisi GRK sektor energi* (Vol. 1). Pusat Data dan Teknologi Informasi, Kementerian Energi dan Sumber Daya Mineral.

Sureeyatanapas, P., Yodprang, K., & Varabuntoonvit, V. (2021). Drivers, barriers and benefits of product carbon footprinting: A state-of-the-art survey of Thai manufacturers. *Sustainability*, 13(12), Article 6543. https://doi.org/10.3390/su13126543

Sutopo, W., Erliza, A., Widiyanto, A., Apriandy, R. R., & Ali, A. (2018). The model of investment promotion policy scheme in science and technology park: a case study of technopolis in Indonesia. *Production and Manufacturing Research*, 6(1), 308-327. https://doi.org/10.1080/21693277.2018.1511485

Tol, R. S. J. (2016). The impacts of climate change according to the IPCC. *Climate Change Economics*, 7(1), Article 1640004. https://doi.org/10.1142/S2010007816400042

UNIDO (2021). *A new generation science and technology parks: UNIDO's strategic approach to fostering innovation and technology for Inclusive and Sustainable Industrial Development*. https://hub.unido.org/sites/default/files/publications/Publication_%20New%20Generation%20of%20STI%20parks_2021.pdf

Verbeeck, G., & Hens, H. (2010). Life cycle inventory of buildings: A calculation method. *Building and Environment*, 45(4), 1037-1041. https://doi.org/10.1016/j.buildenv.2009.10.012

Wang, Y., Chong, D., & Liu, X. (2021). Evaluating the critical barriers to green construction technologies adoption in China. *Sustainability*, 13(12), Article 6510. https://doi.org/10.3390/su13126510

Wei, X., Qiu, R., Liang, Y., Liao, Q., Klemeš, J. J., Xue, J., & Zhang, H. (2022). Roadmap to carbon emissions neutral industrial parks: Energy, economic and environmental analysis. *Energy*, 238, Article 121732. https://doi.org/10.1016/j.energy.2021.121732

Wiedmann, T., & Minx, J. (2007). A definition of carbon footprint. In C. C. Pertsova (Ed.), *Ecological Economics Research Trends* (pp. 1-11). Nova Science Publisher.

World Resources Institute. (2004). *The Greenhouse gas protocol. A corporate accounting and reporting standard.* http://pdf.wri.org/ghg_protocol_2004.pdf

Wright, L. A., Kemp, S., & Williams, I. (2011). 'Carbon footprinting': towards a universally accepted definition. *Carbon Management*, 2(1), 61-72. https://doi.org/10.4155/cmt.10.39

Yan, M.-R., & Chien, K.-M. (2013). Evaluating the economic performance of high-technology industry and energy efficiency: A case study of science parks in Taiwan. *Energies*, 6(2), 973-987. https://doi.org/10.3390/en6020973

Yu, X., Zheng, H., Sun, L., & Shan, Y. (2020). An emissions accounting framework for industrial parks in China. *Journal of Cleaner Production*, 244, Article 118712. https://doi.org/10.1016/j.jclepro.2019.118712

Yusuf, A., Atmini, S., & Amirya, M. (2024). Implementation of carbon accounting in green buildings at the Ministry of Public Works and Public Housing (PUPR). *International Journal of Business, Economics and Management*, 7(2), 88-111. https://doi.org/10.21744/ijbem.v7n2.2280

Zaini, R., & Ismail, K. (2024). Innovation barriers obstructing the transfer of technology from university to industry in Asean developing countries (Case study on Brunei Darussalam). *ASEAN Journal on Science and Technology for Development*, 41(2), Article 7. https://doi.org/10.61931/2224-9028.1582