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Applying the resource circularity dimensional index to Sumatra's national strategic projects

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Abstract

Purpose — This study examines the role of coal and water resource circularity in supporting industrial electricity distribution and evaluates the broader economic impacts of National Strategic Projects (PSN) in Sumatra.
Method — Using panel data from seven Sumatra provinces for 2011–2021, the study applies Fixed Effect EGLS estimation using the Coal Circularity Dimension Index (CCDI) and Water Circularity Dimension Index (WCDI), complemented by Interregional Input-Output (IRIO) analysis.
Findings — Coal circularity, water circularity, and PLTU-generated electricity positively and significantly affect industrial electricity distribution. IRIO results also indicate stronger manufacturing linkages, household income, and employment, although weaker effects remain in water supply, waste management, recycling, and related sectors.
Implications — Resource circularity can strengthen the economic benefits of infrastructure development, but greater integration of environmental sectors is required to improve the sustainability of PSN implementation.
Originality — This study integrates resource circularity indices with panel-data and IRIO analysis to assess both provincial resource efficiency and interregional economic impacts of PSN development in Sumatra.
Keywords: Circular economy, dimentional index, IRIO computation
JEL Classification: C51; C63; O18

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Introduction

The strategic focus on infrastructure development in a country serves as a fundamental pillar in fostering regional economic growth. The intent behind infrastructure expansion extends beyond merely facilitating mobility and economic activities; it also encompasses broader socio-economic dimensions.

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Banerjee et al. (2020) provide empirical evidence that China's transport network projects have exerted a positive causal impact on Gross Domestic Product (GDP) across various sectors. In the context of infrastructure development, Indonesia, as an emerging economy, has prioritized the expansion and enhancement of national infrastructure through a large-scale initiative known as the National Strategic Projects (PSN). According to the Committee for Acceleration of Priority Infrastructure Provision (KPPIP), PSN focuses on eight key sectors: water and sanitation, energy, electricity, roads, public transportation, railways, ports, and airports (KPPIP, 2015:35).

The formulation of PSN, from planning to execution and distribution of its public goods, has had a significant impact not only on the national construction sector but also on other industries. Allcott et al. (2016) highlight the importance of electricity infrastructure, emphasizing that power shortages can lead to a decline in economies of scale. This concern is particularly relevant given that the majority of PSN projects require an estimated completion period of 3–5 years (KPPIP, 2015, 2016, 2017, 2018, 2022).

Within the framework of the economic cycle, a 3–5-year period is associated with substantial economic fluctuations, both theoretically and empirically. One of the key challenges faced by policymakers and researchers in evaluating PSN at the national level is the fact that many projects remain incomplete. Consequently, conducting an evaluative study with a focus on provincial or island-level analysis emerges as a feasible option for assessing PSN's output.

Sumatra Island, the westernmost island of Indonesia, comprises ten provinces that, in recent years, have been projected as a new source of economic growth to support the national economy, which has long been dominated by Java Island. Based on KPPIP reports, as of 2022, at least 18 PSN projects have been implemented in Sumatra, with one of the primary focuses being Steam Power Plants (PLTU), whose construction was reported to be completed in 2021 (KPPIP, 2022:58). The prioritization of PLTU development in Sumatra is not without reason. Given that South Sumatra Province has been the dominant coal consumer in Sumatra in recent years (BPS, 2022:162), the focus on PLTU development positions Sumatra as a new energy distribution hub for the national electricity network. Furthermore, studies by Allcott et al. (2016) and Tang & Tan (2013) highlight the importance of ensuring electricity availability to prevent a decline in economies of scale and to sustain long-term economic growth.

Several studies confirm that PLTUs possess the advantage of generating high-capacity electricity with long operational durability. Wu et al. (2015) argue that PLTU mechanisms, when assessed in light of current technological advancements, remain one of the most viable low-pollution power generation options. Additionally, Ahmadi et al. (2017) explore the potential for reducing PLTU carbon emissions by integrating solar farms into the operational mechanism. However, as economic and environmental studies progress, PLTU development is increasingly perceived as a risk to environmental sustainability.

From an operational standpoint, PLTU relies on water resources, which are heated using coal to produce steam that drives electricity-generating turbines. This mechanism indicates potential inefficiencies in coal and water resource utilization, ultimately leading to a high-pollution economy. Tiwari et al. (2013) establish a causal link between coal consumption and carbon pollution. Moreover, regarding water resources, Wada et al. (2013) find that rising national water consumption is a major driver of increased drought risk.

The dual reality of PLTU's vital role in economic activities and its adverse impact on environmental sustainability underscores the need for alternative approaches to bridge this gap. Sustainable economic growth driven by industrial activities can be achieved through the adoption of circular economy principles. The circular economy framework is built on a production-consumption system that maximizes the reuse and recycling of outputs from linear energy consumption (Korhonen et al., 2018). Abokersh et al. (2021) suggest that achieving circularity in thermal energy utilization is possible if industries integrate reusing and recycling principles at the design stage.

Pinto et al. (2022) extend this discussion by proposing a cogeneration strategy as a means of mitigating PLTU-related environmental emissions within the circular economy framework. In the context of Sumatra, Putranto (2021) finds that circular utilization of coal and water resources can drive regional economic growth. These findings highlight the potential of circular economy practices in balancing economic, social, and environmental demands in thermal power plant operations, including PLTU.

This study makes two main contributions to the existing literature. First, it measures the circularity of coal and water resource utilization across seven provinces in Sumatra using the Coal Circularity Dimension Index (CCDI) and Water Circularity Dimension Index (WCDI), thereby providing a quantitative assessment of resource utilization in the context of industrial electricity distribution and coal-fired power plant (PLTU) development. Second, this study integrates the circular economy perspective with Interregional Input-Output (IRIO) analysis to examine how National Strategic Project (PSN) investments in Sumatra affect intersectoral and interregional economic linkages, household income, and employment. By combining resource circularity indices, panel-data estimation, and IRIO analysis, this study provides a more comprehensive framework for assessing the economic and environmental dimensions of infrastructure development in Sumatra.

Methodology

The data used in this study consists of secondary panel data covering seven provinces in Sumatra Island over the period 2011–2021. The selected provinces include Aceh, North Sumatra, Riau, South Sumatra, Lampung, Bangka Belitung, and Riau Islands. This selection is based on publications by BPS (2023) and KPPIP (2022), which indicate that only these seven provinces in Sumatra possess Steam Power Plant (PLTU) facilities. Due to the integration of the 2016 Economic Census (SE) data, the panel data employed in this study is categorized as an unbalanced panel dataset.

Table 1. Details of Variables

Variables	Unit
Coal Circularity Dimension Index (CCDI)	Index
Water Circularity Dimension Index (WCDI)	Index
Electricity Generated by PLTU by Province	GWh
Electricity Distributed to Industrial Groups	GWh

Source: Processed by the author

This study will estimate a panel regression model to examine the effect of circular economy implementation on electricity distribution to industrial players. The construction of the circularity dimension indices in this study follows the methodology outlined by Anand & Sen (1994) as follows. The CCDI and WCDI variables are derived from the ratio between Industrial Value Added (IVA) and the consumption of coal and water by commercial groups. The maximum and minimum values for each variable are required to construct CCDI and WCDI across the time-series dimensions. A CCDI value closer to 1 indicates a higher degree of circular utilization of coal resources in a given province. The CCDI formulation is structured as follows.

$$\text{CCDI} = \frac{\text{actual IVABB} - \text{minimum IVABB}}{\text{maximum IVABB} - \text{minimum IVABB}} \tag{1}$$

Coal Circularity Dimension Index is the observed ratio of industrial value added to coal consumption; and and are the minimum and maximum values of this ratio observed over the study period, respectively. A higher CCDI value indicates greater efficiency and circularity in coal resource utilization. A WCDI value closer to 1 indicates a higher degree of circular utilization of water resources in a given province. The WCDI formulation is structured as follows.

$$\text{WCDI} = \frac{\text{actual IVAAIR} - \text{minimum IVAAIR}}{\text{maximum IVAAIR} - \text{minimum IVAAIR}} \tag{2}$$

The WCDI represents the degree of circularity in water resource utilization and is derived from the ratio of industrial value added to water consumption (IVAAIR). The index is normalized using the minimum and maximum IVAAIR values observed during the study period. A WCDI value closer to 1 indicates that water consumption generates relatively higher industrial value added, reflecting a higher degree of water resource circularity. The stages of data analysis using panel data regression and the advanced IRIO analysis tool in this study are as follows.

The panel data regression model selection test begins with the Chow Test, which calculates the significance level of the F-statistic (Baltagi, 2005). If the Chow Test results are significant, the selected panel data regression model is the Fixed Effect Model (FEM). The next step is to conduct the Hausman Test. The Hausman statistic, as formulated by Baltagi (2005).

The selected panel data regression model in this study will be estimated using the EGLS (*Estimated Generalized Least Squares*) method to address deviations in classical assumption tests, particularly autocorrelation, which frequently occurs in panel data. The application of the EGLS method ensures efficient regression coefficients, especially when used in studies with a sufficiently large sample size (Gujarati & Porter, 2009: 453).

The goodness of fit of panel data regression model is determined by the significance level of the F-statistic test and the adjusted R^2 (Gujarati & Porter, 2009: 115–125). The significance of the F-test will determine the appropriateness of the panel data regression model used. The next step is to compute the adjusted R^2. Following this, a partial test is conducted to assess the significance of each independent variable on the dependent variable using the t-test.

The IRIO computation in this study will refer to the publications of BPS (2016) and Hewings (2013). The general structure of the IRIO table can be formulated into four quadrants as follows (Hewings, 2013: 877).

Table 2. IRIO Table

	Industry 1	Industry *i*	Industry *N*	Final Demand	Total
Industry 1	·	Quadrant 1	·	Quadrant 2	$x1$
Industry *i*	·	z_{ij}	·	y_{iq}	xi
Industry *N*	·	·	·	·	xN
Import	·	Quadrant 3	·	Quadrant 4	M
Value Added	·	v_{pj}	·	y_{pq}	Y
Total	$x1$	xj	xN	C I G	E

Source: Hewings (2013)

The analysis based on the regional IRIO table is conducted by simulating the impact of increased investment in Sumatra due to the PSN initiative. The investment magnitude is derived from the total value of PSN projects located in Sumatra, as reported in KPPIP publications. The analysis of the Sumatra IRIO table in this study includes interlinkage analysis and impact analysis for household income and employment absorption.

The CCDI and WCDI developed in this study can be positioned within the broader literature on resource efficiency and sustainability indicators. Resource efficiency indicators generally assess the economic value generated relative to the amount of natural resources consumed, thereby reflecting the ability of an economic system to generate greater output with lower resource requirements. In this study, the ratios of industrial value added to coal and water consumption capture this resource-efficiency dimension, while their normalization into CCDI and WCDI provides comparable measures across provinces and periods.

Accordingly, higher index values indicate that greater industrial value added is generated relative to coal or water consumption. Within the circular economy framework, these indices are used as resource-use circularity indicators that capture the efficiency dimension of circularity rather than directly measuring material reuse, recycling, or closed-loop resource flows. This interpretation provides a more precise conceptual basis for using CCDI and WCDI as sustainability-related indicators while acknowledging the scope and limitations of the indices.

Results and Discussion

Based on the statistical computations at each stage of data analysis, the results of the statistical tests are obtained as follows.

Table 3. Chow Test

Effects Test	Statistic	d.f.	Prob.
Cross-section F	27.607	(6.58)	0
Cross-section Chi-square	91.773	6	0

Source: Processed by the author

Table 4. Hausman Test

Test Summary	Chi-Sq. Statistic	Chi-Sq. d.f.	Prob.
Cross-section random	6.985	3	0.070

Source: Processed by the author

The results of the Chow Test and Hausman Test indicate significance at the 5 percent level for the Chow Test and the 10 percent level for the Hausman Test. This confirms that the selected panel data regression model in this study is the Fixed Effect Model (FEM). The estimation results of the panel data regression using the Fixed Effect Model (FEM) with the EGLS method produce efficient regression coefficient estimators, particularly in addressing serial correlation issues. Where LOG(LDI) is electricity distributed to the commercial sector and LOG(TLD) is electricity generated by coal-fired power plants (PLTU), the estimation results of the panel data regression using the EGLS method are as follows.

Table 5. EGLS Estimation

Variables	LOG(LDI)
CCDI	0.304**
	(0.030)
WCDI	1.349**
	(0.020)
LOG(TLD)	0.208***
	(0)
C	4.453***
	(0)
Weighted Statistics	
Adjusted R-squared	0.842
F-statistic	40.87
Prob(F-statistic)	0
Notes:	
Regression coefficient shown	
Probability t – statistics in parentheses	
* significant at =10%	
** significant at =5%	
*** significant at =1%	

Source: Processed by the author

Based on the estimation results in Table 5, all resource circularity variables and electricity production from coal-fired power plants (PLTU) exhibit a positive and significant impact on electricity distribution to industrial players in Sumatra. The regression coefficient of the CCDI variable indicates a directional relationship consistent with the proposed hypothesis. This means that when the CCDI index increases by 1 unit, ceteris paribus, signifying a more circular utilization of coal resources, electricity distribution to industrial players in Sumatra will increase circularly by 0.304 percent, and vice versa.

In this study, the positive and significant impact of the CCDI variable on electricity distribution to industrial players in Sumatra suggests that the industrial value-added generated from every IDR 1 million worth of coal consumption remains sufficient to sustain electricity distribution that meets industrial needs, thus driving manufacturing sector activity. This finding contrasts with Putranto (2021), who argued that coal consumption in Sumatra, when compared to industrial value-added, fails to create a circular economic climate that stimulates economic activity.

On the other hand, Yuan et al. (2018) found that in the case of China's economy, even under more environmentally friendly coal usage scenarios, coal consumption for electricity generation is projected to rise to 1,280 million tons of coal equivalent. The author contends that an increase in coal consumption will still provide a circular effect on electricity distribution growth if industrial value-added increases at a greater rate than coal consumption.

The regression coefficient of the WCDI variable also exhibits a directional relationship consistent with the proposed hypothesis. This implies that when the WCDI index rises by 1 unit, ceteris paribus, meaning that water resource utilization becomes more circular, electricity distribution to industrial players in Sumatra will increase circularly by 1.349 percent, and vice versa. The positive and significant effect of WCDI on industrial electricity distribution in Sumatra indicates that industrial value added from water consumption supports electricity supply and manufacturing activity.

This phenomenon is likely due to PLTU projects and industrial players in Sumatra incorporating elements of intellectual capital into more circular and efficient operational innovations. These findings align with Chang et al. (2015), who explained that innovations in coal-fired power plants, specifically in heating water to drive turbines, will facilitate a transition from water-intensive power plants to more differentiated power generation systems. Hertwich et al. (2015) further elaborated on the "BLUE map" scenario, an innovation in power plant operations that ensures increased electricity distribution while simultaneously reducing emissions. Moreover, the BLUE map scenario, which includes ecotoxicity and eutrophication processes for clean water, initially requires more material than conventional methods. However, this approach is expected to provide long-term energy sustainability, with global electricity availability reaching stability by 2050.

The regression coefficient of electricity generated by PLTUs also aligns with the proposed hypothesis. This indicates that when PLTU-generated electricity increases by 1 percent, ceteris paribus, electricity distribution to industrial players in Sumatra will increase circularly by 0.208 percent, and vice versa. This finding suggests that the concentration of PLTU projects within the PSN electricity sector serves as a viable option for supporting industrial electricity demand in Sumatra. Wu et al. (2015) stated that PLTU mechanisms currently represent the most feasible power generation method with relatively low pollution levels, considering current technological availability.

However, the author notes that special attention is required regarding the estimation results, which indicate that the regression coefficient for water resource utilization is higher. The lower regression coefficient for electricity generation by PLTUs suggests that while water resources are relatively abundant, they are not yet adequately balanced by coal availability, which is expected to become increasingly scarce and impose higher operational costs in the future.

The IRIO computation results in this study aim to deepen the analysis of the impact of PSN in Sumatra on the island's regional economy specifically and the national economy more broadly. The computation results for the investment addition scenario in Sumatra's infrastructure are as follows.

Table 6. Interlinkage Analysis

Sector	Sensitivity	Dispersion
Sumatera Island		
Manufacturing	2.30	1.11
Water Supply, Waste Management, and Recycling	0.60	0.99
Java Island		
Manufacturing	5.69	1.03
Water Supply, Waste Management, and Recycling	0.61	0.95
Bali and Nusa Tenggara Island		
Electricity and Gas Supply	1.54	2.16
Water Supply, Waste Management, and Recycling	0.60	1.02
Kalimantan Island		
Manufacturing	2.50	1.08
Public Administration, Defense, and Mandatory Social Security	0.61	1.09
Sulawesi Island		
Manufacturing	1.36	1.10
Water Supply, Waste Management, and Recycling	0.60	0.95
Maluku and Papua Island		
Water Supply, Waste Management, and Recycling	1.30	1.80
Health Services and Social Activities	0.60	1.11

Source: Processed by the author

Based on the interlinkage analysis following the implementation of the National Strategic Projects (PSN) in Sumatra from 2017 to 2020, the results indicate that PSN in Sumatra has strengthened the Manufacturing Industry sector, making it a sector with high Sensitivity Index and Dispersion Index in Java (5.69 and 1.03), Kalimantan (2.50 and 1.08), and Sulawesi (1.36 and 1.10). These results are likely due to the PSN projects being designed to stimulate economic activity by encouraging industrial players in Sumatra. Furthermore, as national industries become more productive due to PSN in Sumatra, stronger input-output linkages are formed, leading to increased industrial value-added.

On the other hand, the analysis also shows that PSN in Sumatra has resulted in the Sensitivity Index and Dispersion Index in the Water Supply, Waste Management, and Recycling sector of Java (0.61 and 0.95), Bali and Nusa Tenggara (0.60 and 1.02), and Sulawesi (0.60 and 0.95). This finding aligns with the study by Berliandaldo & Hendrix (2022), which explains that the development of coal-fired power plants (PLTU) and toll roads has negative externalities such as air quality degradation, water pollution, and noise disturbances.

Ironically, this sector could serve as a key pillar supporting the overall circularity of the national industrial system. The computed results of the household income impact analysis from the National Strategic Projects (PSN) in Sumatra significantly affected household income in the manufacturing industry sector in Java, which increased by 300.54% from 2018 (IDR19,485.39 million) to 2019 (IDR78,045.85 million). Similarly, in Maluku and Papua, household income increased by 385.52% from 2017, 2018, and 2020. These findings align with Calderón & Servén (2014), who explain that infrastructure development can drive household income growth and promote social welfare distribution.

The computation results also indicate that PSN in Sumatra has had a relatively small impact on household income in the water supply, waste management, and recycling sectors, particularly in Java, where a decline of 24.95% was recorded, from IDR581.77 million to IDR726.49 million in 2020. The analysis of the impact of the National Strategic Projects (PSN) in Sumatra on employment absorption has shown relatively satisfactory results.

The manufacturing industry sector, wholesale and retail trade, and motor vehicle and motorcycle repair have been strongly affected by the PSN development in Sumatra. This can enhance investor confidence, as the construction of toll roads and coal-fired power plants (PLTU) supports the investment climate. In 2019, the employment absorption impact analysis revealed that PSN in Sumatra increased employment by 26,919 workers in the wholesale and retail trade, motor vehicle, and motorcycle repair sector in Java.

Additionally, the manufacturing industry in Sulawesi saw an increase of 15,247 workers in 2019, while Maluku and Papua reached a peak with an increase of 72,085 workers in 2018. The study by Srinivasu et al. (2013) explains that infrastructure development has a significant indirect impact on increasing the productivity of production factors, including labor. The findings of this study are broadly consistent with international evidence showing that circular economy practices can enhance the economic benefits of infrastructure and industrial development, although such benefits do not automatically translate into stronger environmental-sector performance.

Evidence from China, for example, shows that circular economy practices in coal-fuelled power industrial parks can reduce life-cycle carbon footprints when resource recycling and the substitution of carbon-intensive inputs are effectively implemented. Similarly, studies of urban industrial symbiosis in China demonstrate that integrating resource and waste flows across industries can generate environmental benefits while supporting regional industrial development. These international findings are consistent with the positive effects of coal and water resource circularity on industrial electricity distribution identified in Sumatra.

However, the IRIO results of this study reveal an important qualification: while PSN investment strengthens manufacturing linkages across several Indonesian regions, the water supply, waste management, and recycling sector remains relatively weak. This suggests that infrastructure-led economic expansion alone is insufficient to establish a fully circular regional production system.

Compared with international experiences in which industrial symbiosis connects energy, material, and waste flows across sectors, the Sumatra case indicates that stronger integration between infrastructure investment, manufacturing activities, and environmental-service sectors is required. Therefore, the contribution of circular economy principles to infrastructure development should be evaluated not only through improvements in resource efficiency and industrial output, but also through the extent to which infrastructure investment strengthens recycling, waste management, and other environmental linkages within the wider regional economy.

Conclusion

The findings of this study indicate that improvements in coal and water resource efficiency are positively associated with electricity distribution to industrial activities in Sumatra, highlighting the economic role of electricity infrastructure in supporting regional industrial development. However, these economic benefits should not be interpreted as evidence that coal-fired power plants (PLTU) are environmentally sustainable or as a justification for their continued expansion. The dependence of PLTU operations on coal and water resources entails environmental costs that must be considered alongside their contribution to electricity supply and industrial activity.

Therefore, the findings point to an important trade-off: while PLTU-related infrastructure may support industrial production, employment, and regional economic linkages, these benefits may be accompanied by environmental pressures associated with resource consumption, emissions, and waste generation. The IRIO results reinforce this trade-off. Although PSN development in Sumatra strengthens interregional linkages in the manufacturing sector and contributes to household income and employment, its effects on water supply, waste management, recycling, and other environmentally related sectors remain relatively weak.

The findings provide several policy implications for integrating circular economy principles into future National Strategic Projects (PSN). First, resource-efficiency and circularity indicators should be incorporated into the planning and evaluation stages of infrastructure projects, particularly for projects with intensive coal and water requirements. Indicators such as CCDI and WCDI, complemented by measures of emissions, waste generation, reuse, and recycling, could be used to assess whether improvements in economic output are accompanied by more efficient and sustainable resource use. Second, future PSN investment should strengthen linkages between infrastructure and environmental-service sectors, particularly water supply, waste management, and recycling, which remain relatively weak in the IRIO results. This could include integrating water reuse, waste recovery, and recycling systems into project design rather than treating environmental management solely as a downstream activity. Third, PSN evaluation should extend beyond conventional indicators of investment, output, and employment by incorporating interregional environmental and resource-use impacts into project assessment.

Finally, for energy-related PSN, improvements in resource efficiency should be accompanied by cleaner technologies and a gradual reduction in dependence on carbon-intensive energy sources. These measures would allow circular economy principles to serve not merely as an efficiency mechanism, but as a framework for aligning infrastructure-driven economic growth with environmental sustainability.

AI declaration

The authors declare that artificial intelligence (AI) tools were used solely to assist in language refinement, grammar checking, and improving the clarity of writing. The use of AI did not influence the research design, data collection, data analysis, interpretation of results, or the development of conclusions. All intellectual contributions, including conceptualization, methodology, analysis, and final content, remain the full responsibility of the authors.

Conflict Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper. The research was conducted independently without any financial, commercial, or personal relationships that could be construed as a potential conflict of interest.

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