Prescriptive Analytics for Strategic Carbon Management: A Business Analytics Approach

Program Riset ITB-Hibah DRI

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Abstract

Cities must pursue economic growth while keeping their emissions within the carbon carrying capacity of their green infrastructure. A system dynamics model is developed to analyze four interacting urban subsystems, i.e., (1) economic activity and emissions, (2) carbon sink and green infrastructure, (3) carbon governance and policy, and (4) urban mobility and transport. The model is applied to Bandung, West Java, Indonesia, a dense metropolitan city with limited green space and severe traffic congestion.

Six policy scenarios, i.e., (1) Nationally Determined Contribution (NDC) unconditional, (2) NDC conditional, (3) green space restoration, (4) transport infrastructure, (5) green finance and low-carbon technology, and (6) integrated, are simulated until 2050.

The results indicate that a dense city must reduce emissions at their source rather than rely on expanding carbon sinks or road capacity. This study offers insights for local governments in designing low-carbon development pathways aligned with Indonesia's NDC targets.

Keywords: system dynamics, carbon carrying capacity, urban carbon sink, low-carbon city.

Introduction

Cities concentrate economic activity, energy use, and transport demand, and are therefore central to the low-carbon transition. As regional economies grow, business expansion and vehicle ownership raise emissions, while development pressure converts green space into built-up land and reduces the city's capacity to absorb carbon.

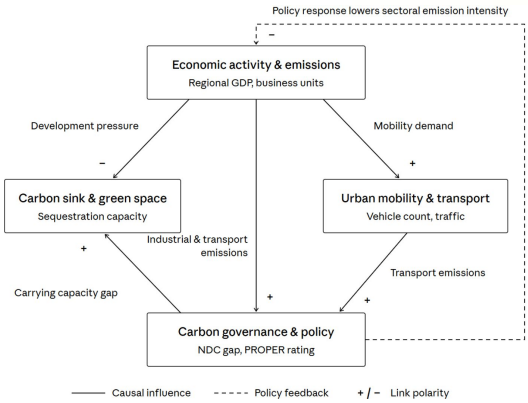
Bandung illustrates this tension. Its public green space covered only 2,032 ha in 2015, about 12% of the city area and far below the 30% green open space mandate, while its GRDP almost doubled from IDR 195.8 trillion in 2015 to IDR 371.8 trillion in 2024, and traffic congestion costs an estimated IDR 4 trillion per year.

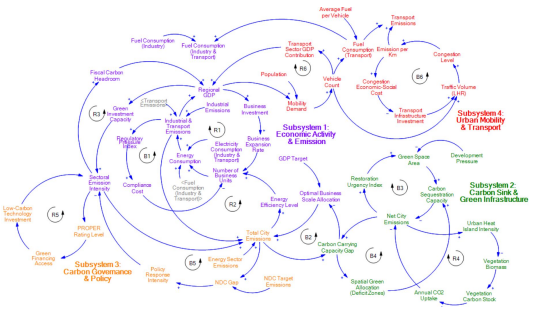


https://www.rth.bandung.go.id/

Research Method

The model consists of four subsystems connected through total city emissions, the carbon carrying capacity gap, and sectoral emission intensity.





Picture 1. Causal loop diagram

Six scenarios are compared with business as usual (BAU) from 2025 to 2050: S1 and S2 apply the unconditional (31.89%) and conditional (43.20%) NDC targets; S3 doubles green space restoration; S4 raises road investment from 7.5% to 10% of the city budget; S5 increases green finance by 1.5 times; and S6 combines S2–S5.

Discussion & Result

Under BAU, total city emissions reach 8.62 $MtCO_2$/year in 2030 and 22.0 $MtCO_2$/year in 2050, while green space absorbs only about 7% and 2% of them. The carbon carrying capacity gap therefore widens from 8.0 to 21.6 $MtCO_2$/year.

Doubling green space restoration adds 475 ha by 2050 and raises CO_2 absorption by 21%, yet closes only 0.4% of the gap. Road capacity expansion increases the vehicle count by 9.3% and transport emissions by 9.7% in 2030 instead of reducing congestion, a pattern consistent with induced demand, and raises total emissions by 10.6% in 2050.

Green finance yields the largest reduction (18.5% in 2030 and 62.7% in 2050), but its magnitude depends on the assumed effect of green investment on emission intensity. Stricter NDC targets alone change emissions by less than 1%, and the integrated package (S6) reduces 2030 emissions by 15.5%, as induced transport demand offsets part of the green finance effect. No scenario reaches the 31.89% NDC reduction in 2030.

Table 1. Scenario result

Outcome	BAU	S1	S2	S3	S4	S5	S6
Total city emissions, 2030 ($MtCO_2$/year)	8.62	8.64 (+0.2%)	8.68 (+0.8%)	8.62 (0.0%)	8.79 (+2.0%)	7.03 (−18.5%)	7.29 (−15.5%)
Total city emissions, 2050 ($MtCO_2$/year)	22.02	22.52 (+2.3%)	22.52 (+2.3%)	22.02 (0.0%)	24.34 (+10.6%)	8.20 (−62.7%)	10.44 (−52.6%)
Cumulative emissions, 2025–2030 ($MtCO_2$)	47.51	47.55 (+0.1%)	47.66 (+0.3%)	47.51 (0.0%)	47.87 (+0.8%)	42.86 (−9.8%)	43.30 (−8.9%)
Cumulative emissions, 2025–2050 ($MtCO_2$)	347.6	353.7 (+1.8%)	355.5 (+2.3%)	347.6 (0.0%)	365.3 (+5.1%)	195.8 (−43.7%)	214.3 (−38.4%)
Carbon carrying capacity gap, 2030 ($MtCO_2$/year)	8.03	8.05 (+0.3%)	8.10 (+0.8%)	8.01 (−0.3%)	8.21 (+2.2%)	6.42 (−20.1%)	6.65 (−17.2%)
Carbon carrying capacity gap, 2050 ($MtCO_2$/year)	21.63	22.15 (+2.4%)	22.14 (+2.4%)	21.54 (−0.4%)	24.01 (+11.0%)	7.51 (−65.3%)	9.67 (−55.3%)
CO_2 absorption, 2030 (ktCO₂/year)	586.9	586.5 (−0.1%)	585.6 (−0.2%)	613.8 (+4.6%)	583.1 (−0.6%)	611.3 (+4.2%)	634.5 (+8.1%)
CO_2 absorption, 2050 (ktCO₂/year)	388.4	375.8 (−3.2%)	375.8 (−3.2%)	471.3 (+21.4%)	331.0 (−14.8%)	693.3 (+78.5%)	766.4 (+97.3%)
Green space area, 2030 (ha)	2,239	2,239 (0.0%)	2,239 (0.0%)	2,334 (+4.2%)	2,239 (0.0%)	2,239 (0.0%)	2,334 (+4.2%)
Green space area, 2050 (ha)	2,601	2,601 (0.0%)	2,601 (0.0%)	3,076 (+18.3%)	2,601 (0.0%)	2,601 (0.0%)	3,076 (+18.3%)
Vehicle count, 2030 (million units)	1.66	1.66 (0.0%)	1.66 (0.0%)	1.66 (0.0%)	1.82 (+9.3%)	1.66 (0.0%)	1.82 (+9.3%)
Transport emissions, 2030 ($MtCO_2$/year)	1.76	1.76 (0.0%)	1.76 (0.0%)	1.76 (0.0%)	1.93 (+9.7%)	1.76 (0.0%)	1.93 (+9.7%)
Relative emission intensity, 2030 (index)	0.289	0.290 (+0.4%)	0.292 (+1.2%)	0.289 (0.0%)	0.288 (−0.1%)	0.203 (−29.7%)	0.207 (−28.1%)
Relative emission intensity, 2050 (index)	0.255	0.254 (−0.4%)	0.254 (−0.4%)	0.255 (0.0%)	0.251 (−1.7%)	0.061 (−76.0%)	0.061 (−76.2%)

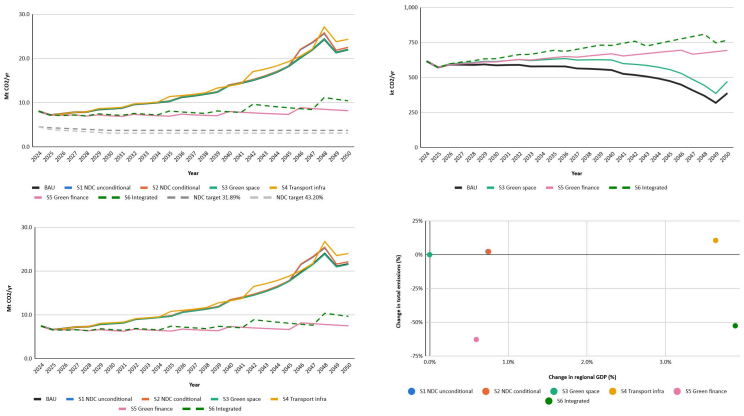
Note: Values in parentheses are changes relative to BAU.

Conclusion

Two findings stand out. First, the sink capacity of a dense city is structurally limited: Bandung's green space absorbs a small share of its emissions, so restoration cannot close the carbon gap. Second, road expansion induces additional vehicle ownership and raises emissions rather than relieving congestion.

City governments should therefore prioritize emission reductions at the source, i.e., in business energy use and transport; position green space mainly as an adaptation and co-benefit strategy, such as heat mitigation; and manage congestion through demand-side and public transport measures rather than road expansion.

Future work will validate the emission trajectory against city inventories, ground these parameters empirically, and add spatial data and policy costs.



Picture 2. Total emissions (upper left), CO_2 absorption (upper right), carbon gap (bottom left), and economic vs emission outcome in 2050 (bottom right)