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Modelling Domestic Emission of City-Level Residential Area Based on Spatial Policy

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Abstract

This study investigates the impact of spatial plan on domestic carbon emissions in the residential areas of Bandar Lampung, Indonesia, through a system dynamic modelling approach. Utilizing spatial planning policies of Bandar Lampung City and carbon emission data, the system dynamic model simulates emissions from residential areas between 2014 and 2041 with VENSIM software. The research highlights how spatial plans affect high-density residential developments can slightly increase emissions. Two scenarios are analysed: one adhering to the city's spatial plan limiting building coverage ratio (BCR) to 60%, and another allowing 100% BCR, simulating a scenario with no green space. Results show a marginal increase in emissions under denser conditions, with the current policy yielding emissions of 1,422 Gg CO2 and the denser scenario producing 1,423 Gg CO2 by 2041. The study emphasizes that while spatial planning plays a role in mitigating carbon emissions, further research is needed to integrate broader land use planning elements and other urban characteristics to comprehensively address emission reduction efforts. This study develops a new city-scale simulation framework that connects spatial planning with carbon emissions, offering valuable implications for sustainable urban development strategies.

Keywords: Carbon Emission, Residential Area, Spatial Planning Policy, System Dynamic

Abstrak

Penelitian ini mengkaji dampak rencana tata ruang terhadap emisi karbon domestik di kawasan permukiman Kota Bandar Lampung, Indonesia, dengan pendekatan system dynamic modelling. Dengan memanfaatkan kebijakan penataan ruang Kota Bandar Lampung dan data emisi karbon, model system dynamic mensimulasikan emisi dari kawasan permukiman antara tahun 2014 hingga 2041 menggunakan perangkat lunak VENSIM. Hasil penelitian menunjukkan bahwa rencana tata ruang memengaruhi perkembangan permukiman berintensitas tinggi yang dapat sedikit meningkatkan emisi. Dua skenario dianalisis: pertama, mengikuti rencana tata ruang kota yang membatasi building coverage ratio (BCR) hingga 60%, dan kedua, mengizinkan BCR 100% yang mensimulasikan kondisi tanpa ruang terbuka hijau. Hasil menunjukkan adanya peningkatan emisi yang relatif kecil pada kondisi yang lebih padat, di mana kebijakan saat ini menghasilkan emisi sebesar 1.422 Gg CO_2, sementara skenario lebih padat menghasilkan 1.423 Gg CO_2 pada tahun 2041. Penelitian ini menegaskan bahwa meskipun perencanaan tata ruang berperan dalam mitigasi emisi karbon, diperlukan penelitian lebih lanjut untuk mengintegrasikan elemen perencanaan penggunaan lahan yang lebih luas serta karakteristik perkotaan lainnya guna secara komprehensif mendukung upaya pengurangan emisi. Studi ini mengembangkan kerangka simulasi skala kota yang menghubungkan tata ruang dengan emisi karbon, sehingga memberikan implikasi penting bagi strategi pembangunan perkotaan berkelanjutan.

Kata kunci: *Emisi karbon, kawasan permukiman, kebijakan tata ruang, system dynamic*

1. INTRIDUCTION

Carbon emissions are gases formed as a result of the combustion of carbon compounds. These gases are one of the main contributors to greenhouse gases, which are a significant factor in global warming(Labiba & Pradoto, 2018). The increasing human population has led to a rise in greenhouse gas emissions, particularly carbon and carbon dioxide emissions. Human activities such as industries, and goods consumption induced the anthropogenic carbon cycles which must be fed back into its natural cycles (Tomkins & Müller, 2019). The anthropogenic carbon cycle refers to the human-influenced part of the global carbon cycle—specifically, the ways in which human activities alter the natural movement of carbon between the atmosphere, oceans, land, and biosphere. Therefore, carbon emissions from human activities directly contribute to the accumulation of greenhouse gases in the atmosphere, accelerating the process of global warming.

Indonesia is an archipelagic country with 98 cities, covering vast land areas and a large population. Urban characteristics are essential domain for the government as policymakers in emission regulation, considering various urban attributes in efforts to reduce carbon emissions. Numerous initiatives have been proposed to address this issue, including the transition to more environmentally friendly energy sources to minimize emissions. However, data limitations remain a challenge. The available data from the Central Bureau of Statistics (BPS) only provides total emissions from various sources. It shows that Indonesia has produced an average of 1,164,908,000 tons of CO_2 annually from 2000 to 2019 (BPS, 2022). These emissions come from multiple sectors, including energy, industrial processes and product use, agriculture and forestry, other land use sectors (AFOLU), forest fires, and waste management. Consequently, the reported data are aggregated at the national level, without detailed figures for each province or city. Meanwhile, the dataset from the Ministry of Environment reports carbon emissions only from forest fires in each province from 2018 to 2022 (KLHK, 2022).

Bandar Lampung City is the capital of Lampung Province which is currently developing and facing several environmental issues. The population of Bandar Lampung has increased from 962,709 in 2014 to 1,214,330 in 2024. With a fixed land area and a continuously growing population, the city's population density has increased over time. Statistical data shows there are 18-22% denser population in several districts namely Teluk Betung Timur, Tanjung Senang, and Sukarame (BPS Kota Bandar Lampung, 2025). Thus, various environmental issues have emerged in urban areas such as air, water, and soil pollution. Most recent issues happened in Bandar Lampung were floods caused by inadequate drainage infrastructure and insufficient catchment area (Jaya & Hardiyanto, 2025). However, emission to community activities was not properly recorded and having lacked attention.Various research implied there are links between population rise and higher carbon emissions especially in city (Sikdar & Mukhopadhyay, 2016; Ziyuan et al., 2022). There are positive relations between household size and household energy consumption to the rise of carbon emission. Moreover, urban households are likely to have higher energy consumption than rural households. Therefore, the high number and growth rate of the population require special attention due to their impact on emissions and global warming in urban areas.

Population growth affects urban spatial structures which are correlated to carbon emissions. With rapid population growth, the demand for residential areas is also increasing significantly. Urban land cover gradually changes from undeveloped areas to developed ones to accommodate housing needs which transforms urban spatial structure. Thus, the ability of urban area's carbon sinks is decreasing while carbon emission is rising resulting in a higher carbon emission of the city (Hong et al., 2022). Hong et al., (2022) also mentioned the importance of conducting quantitative research of urban spatial structures linked to carbon emissions by utilizing building density indicators such as floor area ratio (FAR), building height or building area coverage (BCR). This quantitative method is rarely applied in recent research. In Indonesia spatial policy, minimum FAR, building height and BCR is regulated in city's spatial plans or RTRW Kota *(Rencana Tata Ruang Wilayah Kota)*. It indicates that there is a chance to incorporate spatial planning policy for carbon emission reduction intervention.

In Indonesia's current spatial planning framework, spatial analysis is the most employed method to support decision-making processes. However, its effectiveness could be significantly enhanced through integration with modeling approaches that enable future projections. Modeling is essential for quantitatively estimating and forecasting carbon emissions. It provides a systematic basis for anticipating changes in urban dynamics and emission patterns, thereby informing the development of emission reduction policies that align with principles of sustainable development. Various methods for estimating CO2 emissions include field testing and mathematical modeling (Rahmadani et al., 2024; Sidqi et al., 2024). However, previous studies have simplified model structures by only considering a limited number of activities related to urban characteristics. Previous models have not accounted for city-level spatial policy constraints when simulating domestic emissions. This study fills that gap by creating a spatially based system dynamics model for forecasting domestic CO_2 emissions. Additionally, the rise in CO2 emissions is directly proportional to population growth, making further research necessary to estimate CO2 gas production in residential areas of Bandar Lampung.

2. LITERATURE REVIEW

2.1 Carbon Emissions Inventory for Climate Change Factor Monitoring

A carbon emissions inventory or greenhouse gas (GHG) inventory is a detailed record of the quantity of greenhouse gases particularly carbon dioxide (CO_2) released into or taken out of the atmosphere during a defined time frame within a specified geographic area e.g., city, region, nation, or organization. The inventory principle is to calculate the amount of the main emission emitter. GHG inventories can assist in managing GHG emissions and serve as a foundation for mitigation strategies. Handling risks arising from GHGs and recognizing mitigation strategies by comprehending the threats of climate change, organizations can implement measures to lessen their vulnerability to these threats (Yaman, 2024).

Carbon emissions inventory report has been done for a long time as an effort to monitor pollution and climate change. Organizations across the world designed emissions management systems and methods, two most adapted frameworks are the greenhouse gas protocol and ISO 14064 (Yaman, 2024). The foundational methodology for greenhouse gas inventory in national scale came from Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2006) while the city level inventory developed by ICLEI (ICLEI, 2019). In Asia, regional emission inventory in Asia version 3 (REASv3) was developed during 1950-2015 to monitor emission in East, Southeast, and South Asia (Kurokawa & Ohara, 2020). Based on Kurokawa & Ohara (2020), Japan and China have most decent data of carbon emission than other countries in Asia. It shows that many countries still struggle to conduct thorough and transparent emissions inventories, even though it had been clearly stated in Paris Agreement 2015.

2.2 Spatial Planning Policy and Carbon Emissions Reduction Efforts

Incorporating spatial planning and carbon emissions inventory will potentially increase the effectiveness of carbon emissions reduction effort. The spatial and land use planning linked to the carbon emissions number, especially the regulation about floor area ratio (FAR) restrictions and urban growth boundaries (UGBs) (Leibowicz, 2017). It shows that UGBs decrease CO2 emissions by increasing urban density, reducing lengthy commutes and downsizing houses. Moreover, FAR limitations increase housing costs and prompt relocation to different urban regions. The impact of this on emissions varies based on the emission intensities of both regulated and unregulated cities.

Current carbon emission reduction action is coordinated nationally by National Agency of Planning or *Bappenas* which reported as an online dashboard on the AKSARA website

(Bappenas, 2025). There are several categories of emission reduction specifically in Bandar Lampung such as preservation of carbon storage, public transport provision, or waste management improvement. Integrating the current act with spatial planning policy could potentially enhance the effectiveness of such emission reduction acts. International agency like World Bank also supports the integration of spatial planning and climate mitigation in Indonesia with ILASP Project (Integrated Land Administration and Spatial Planning) (World Bank, 2024). The project utilizes digital land information systems to support decision making processes of spatial plans.

Carbon emissions projection becomes another complementary mitigation effort for climate change. While carbon emissions inventories play crucial role in collecting historical data of carbon emissions, carbon emissions projection will predict and calculate the emissions through several approaches and estimation. Nagar et al., (2019) research explains that if region conducts accurate and data-based estimates of its emissions, it could implement well-structured mitigation plan.

2.3 Case Study Location

This research is conducted for the domestic emission in Bandar Lampung City—the capital of Lampung Province. As the capital city, Bandar Lampung is considered as the biggest city in its Province. It has been growing rapidly to attract workers and migrant from surrounding city or cities in another province to reside. This phenomenon causing the increasing demand of residential area. Numerous new housing neighbourhoods were being developed by private sector or individuals. Hence, the built area in Bandar Lampung were becoming vast resulting the reduction of the city green space.

To simulate the domestic carbon produced by the residential area, we are limiting the case study location inside the residential area based on spatial planning policy. Spatial planning policy of Bandar Lampung or RTRW stated under Government Regulation number 4-year 2021(Rencana Tata Ruang Wilayah Kota Bandar Lampung 2021-2041, 2021). It defines the size of residential area as much as 10,266 hectares from 2021 until 2041 (see figure 1). Furthermore, the spatial plan also limits the density of buildings coverage ratio (BCR) inside the residential area as much as 60%. BCR is the ratio of each housing unit area and the building which also explain the building density (Paramita et al., 2022)

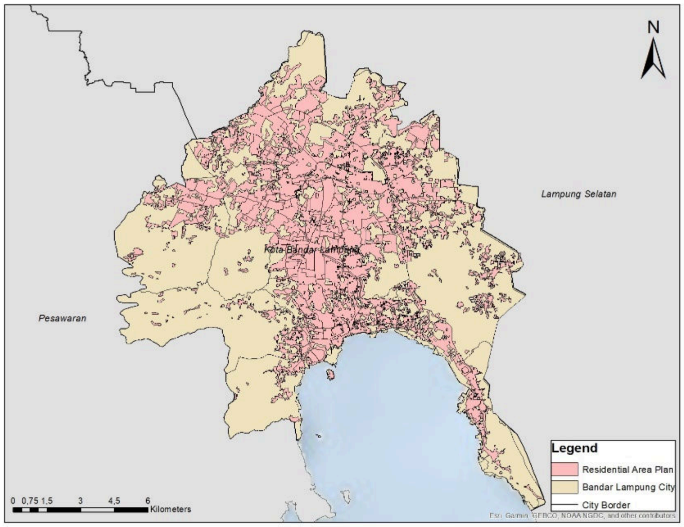


Figure 1. Residential Area Plan of Bandar Lampung City
Sumber: *(Rencana Tata Ruang Wilayah Kota Bandar Lampung 2021-2041, 2021)*

3. METHOD

This study employs the system dynamics approach to analyze and model the dynamics of carbon emissions in urban areas. System dynamic itself was first created by James Forester in 1961. Forrester (Forrester, 1968) developed the methodology of system dynamics with the aim of designing enterprises by analysing and addressing the time-dependent (dynamic) behaviours inherent in industrial organizations. In term of carbon emission prediction, this method could provide a detailed simulation based on urban activities (Lee et al., 2021). This approach enables a deeper understanding of the complex interactions among factors driving emissions, such as population growth, carbon emission data, and land-use changes. In this research, the system dynamics model generated with VENSIM software.

3.1. Forecasting Model

In system dynamic, creating the causal flow of the model is very important in system dynamics method to ensure the system flow. There are three categories of variables in dynamic systems: stocks, flows, and feedback loops. Stocks represent accumulation, flows represent source and sink, and feedback loops represent cause and effect. These three elements form a set of components and relationships derived from the observed problem. In this model, domestic emissions serve as the unit of observation and act as the stock. Meanwhile, the flows in this model consist of inflows and outflows. The inflows originate from two sources: electricity consumption and LPG consumption. According to the regulations of the Ministry of Environment (Karliansyah et al., 2019), household emission sources can be identified based on the number of family cards, the use of emission-producing appliances other than stoves, LPG sales, and the use of firewood or charcoal. As a city, 98% of Bandar Lampung's population use LPG so the use of firewood or charcoal can be neglected. Meanwhile for electricity consumption in residential area actually did not directly produce emission, whilst it emerges from the power plants activities. However, it possible to include the emission from electricity consumption for inventory needs (Karliansyah et al., 2019).

The outflow in this model represents the absorption of carbon emissions generated by households. Naturally, the environment has the capacity to absorb carbon. It is determined by the type of vegetation, environmental conditions, and most important the availability of green spaces. Green spaces are directly correlated to spatial planning. Therefore, we will compare two scenarios of green space availability based on current spatial planning policy and without policy intervention.

The diagram for the model is linear because there are no causal loops in the model. The model diagram of the model could be seen in the figure 2.

Linear diagram of the System Dynamic Model

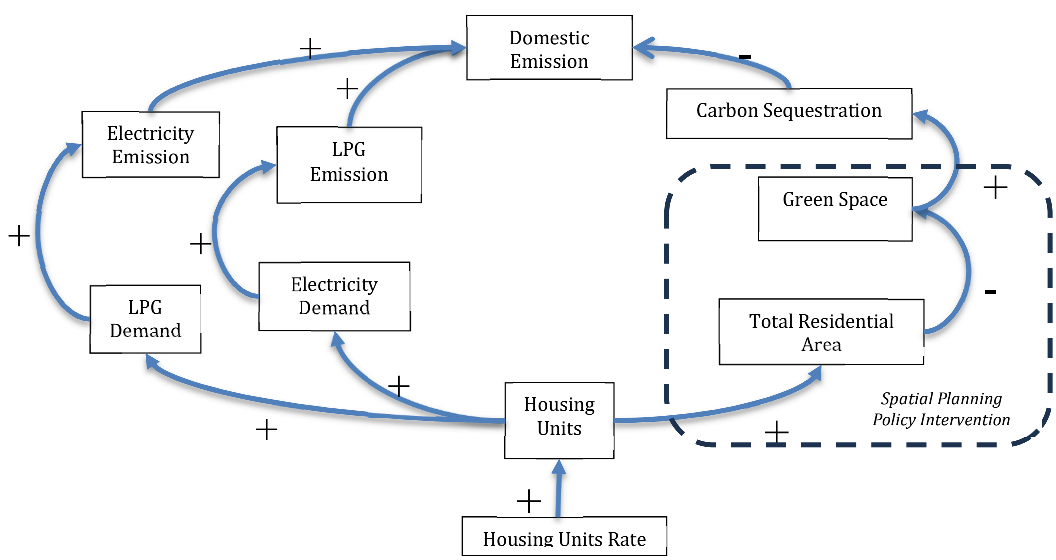


Figure 2. The system dynamic model of domestic carbon emission
Source: Analysis Result, 2025

Additionally, this research applied methods of emission calculation by area into the simulation model. The method is based on the technical guidelines from the Ministry of Environment (Karliansyah et al., 2019) which adapted from the IPCC 2006 (IPCC, 2006).

Tabel 1. The carbon emissions calculation formula

	Source	Formula
1	Electricity	C= consumption (kWh) x emission factor (Kg/kWh)
2	LPG	C = Consumption (Kg/year) x energy conversion (TJ/Kg) x Emission factor (Kg/TJ)

3.2 Data Sources

The data sources used in this research came from various dataset and report. We utilize the year 2014 as the base year of the projection 7 year before the spatial plan was implemented due to the limited historical data. The main data sources in this paper are:

Tabel 2. Data and Sources for Domestic Carbon Emission

	Data	Unit	Year	Source
1	Housing units	Unit	2014-2020	Bandar Lampung City Official Statistics
2	Electricity consumption	kWh	2014-2024	Bandar Lampung City Official Statistics
3	LPG consumption	MT	2024-2025	Pertamina cited from local news

a. **Housing unit rates,** the data source of housing rates came from Bandar Lampung City official statistics. Housing units of Bandar Lampung City is considered to be equal to the number of families live in the city. In 2014, there are 226,034 families with growth rate as much as 1.88% (Kota Bandar Lampung, 2025).
b. **Electricity Demand and LPG Demand,** it was calculated based on the rate of housing demand over electricity and LPG in Bandar Lampung City. We utilize PLN electricity consumption which shows that one household on average will require 4,012.03 kWh/year (Kota Bandar Lampung, 2025). For LPG consumption, the data source came from the news report since Pertamina as the primary national gas and petrol company did not have any open access report. The news report the total consumption of LPG is for Lampung Province is 699 MT/day in 2024, and 892 MT/day in 2025 (Sunaryo & Ade, 2024)(Khoiriah, 2025).
c. **Emission factors,** Based on data from the Directorate General of Electricity, the average value of PLN's electricity emission factor ranges from 0.85 - 1.0 kg CO_2 per kWh. For LPG the emissions factor is 63,100 Kg CO2/TJ (Karliansyah et al., 2019)
d. **Vegetation Sequestration Rate,** Urban green spaces, such as city parks or gardens, have lower carbon sequestration rates than tropical forests. Carbon sequestration is about 1 to 5 tonnes of CO_2 per hectare per year, depending on tree species, plant density, and green space maintenance.

Each variable is calculated by an arithmetic operation and function to simulate the domestic emission in 2041. To ensure the model validation, this study employed Mean Absolute Percetage Error (MAPE) which compare the actual and predicted value.

4. RESULT AND DISCUSSION

4.1 Result

The simulation of emission conducted for the last 10 years start from 2014 to test the validation. The comparison of actual and the predicted emission result is presented in the table below:

Tabel 3. The comparison of actual and predicted result of carbon emissions

Year	Household Units	Electricity Consumption	LPG Consumption	Actual Electricity Emission	Predicted Electricity Emission	Actual LPG Emission	Predicted LPG Emission
		(kWh)	(Kg)	(Gg CO2)			
2014	226,034	778,532,694	34,583,202	661.75	770.90	103.21	103.22
2015	230,354	685,098,524	35,244,162	582.33	785.09	105.19	105.12
2016	234,756	1,001,063,412	35,917,668	850.90	799.53	107.20	107.05
2017	239,242	1,041,149,515	36,604,026	884.97	814.25	109.24	109.02
2018	243,814	1,074,447,878	37,303,542	913.28	829.24	111.33	111.03
2019	248,473	1,069,276,526	38,016,369	908.88	844.50	113.46	113.07
2020	253,221	1,098,847,656	38,742,813	934.02	860.04	115.63	115.15
2021	257,969	1,103,943,238	39,469,257	938.35	875.87	117.80	117.27
2022	262,806	1,242,810,414	40,209,322	1056.38	891.99	120.01	119.43
2023	267,734	1,254,860,119	40,963,264	1066.63	908.41	122.26	121.63
2024	272,754	1,278,388,688	41,731,342	1086.63	925.13	124.55	123.87

Overall, the model shows reasonably good performance for most variables, but certain variables have high MAPE. The model is considered highly accurate when the MAPE is less than 10%, good model has MAPE ≥10% and < 20%, reasonable forecasting ≥20% and < 50%, while MAPE ≥50% means inaccurate forecasting. In this study, the accumulation of MAPE score is 4% which indicates that the simulation could be considered as a good forecasting.

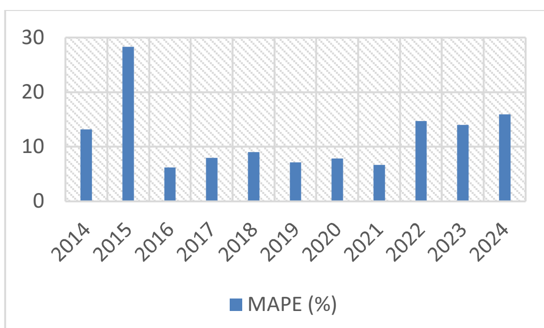


Figure 3. MAPE Value

The forecasting continued to simulate the emission from residential area as the implementation of Bandar Lampung Spatial Planning which applied since 2021 to 2041. This study makes two scenarios to unpack the difference of produced carbon emissions based on the BCR in spatial planning. One simulation applied the current policy with 60% BCR. To see the impact of spatial planning policy on domestic emissions production, we changed the variable of BCR to exceed the existing spatial plan, so it becomes 100%. It means that one area of house is 100% become built area with no green space. It usually happens when a city could not control urbanization, and the density of residential area is extremely dense and populated.

The modelling simulation presents that the aggregate carbon emissions from residential area did not have a significant difference. In 2041, the estimated domestic emissions reach up to 1,422.23 Gg CO2 under the current policy, while if the residential area become denser it could reach 1,423.69 Gg CO2.

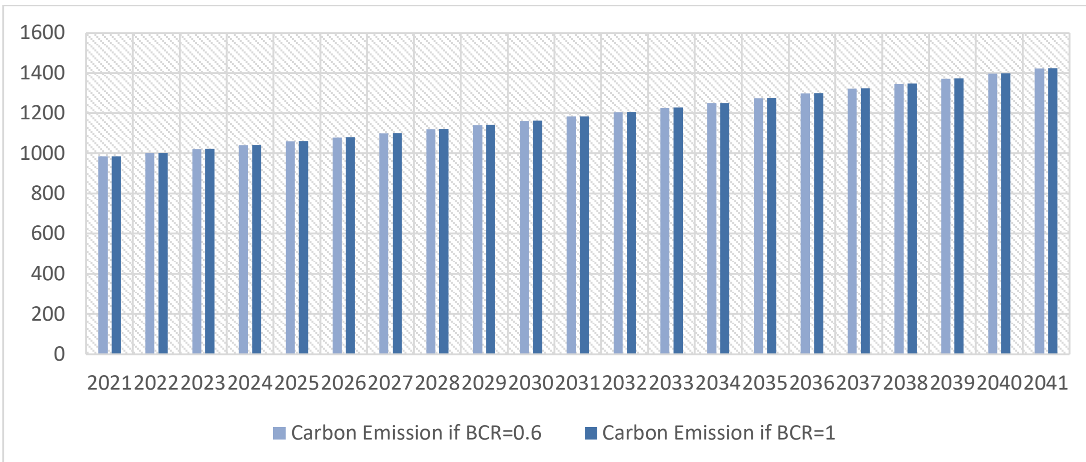


Figure 4. Domestic Emission (Gg CO2 th^{-1})

The sources of domestic carbon emission came from LPG and electricity consumption. LPG consumption releases direct emission to the atmosphere in the residential area, whereas electricity emissions releases at electricity generation process or at the power plant location (Karliansyah et al., 2020). Based on the emission sources, electricity emissions contribute more to the total domestic emissions compared to LPG consumption. In 2041, there will be 1,261.40 Gg CO2 released to the atmosphere from electricity consumption, and 168.89 Gg CO2 from LPG emissions.

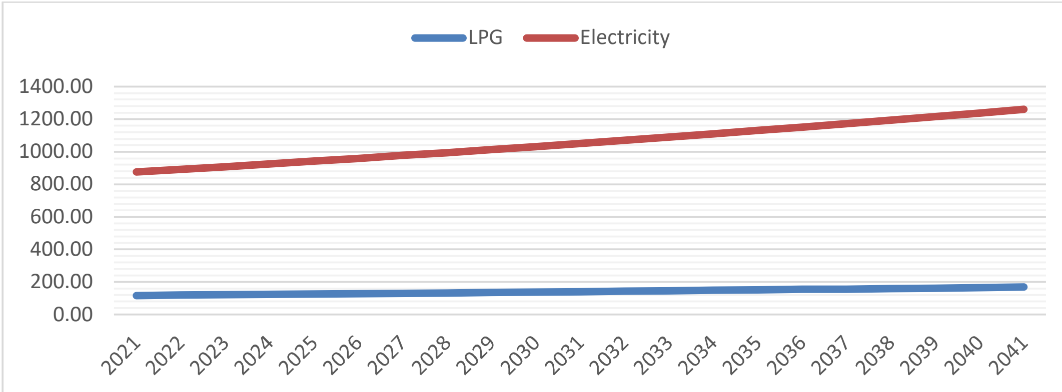
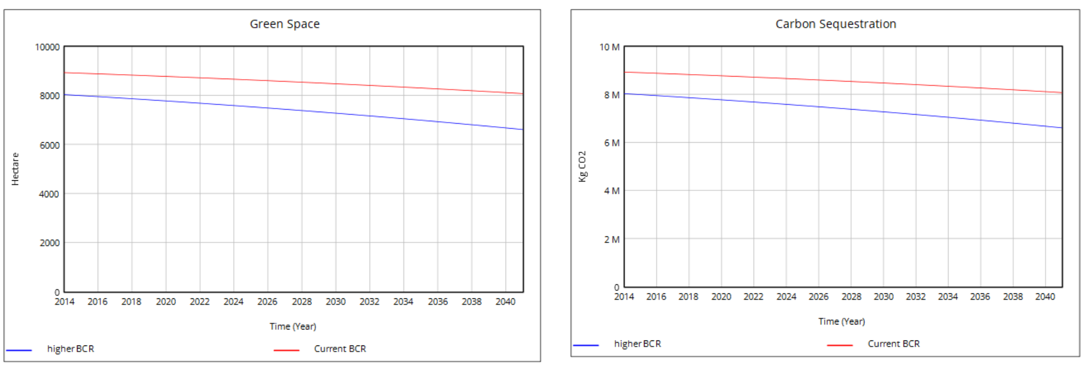


Figure 5. Comparison of LPG and Electricity (Gg CO_2 th^{-1})

In the case of carbon sequestration, the main variables affecting the sequestration level is green space availability. From the simulation, we found that the population rise will increase the residential area and reduce the green space. It also affects the downfall of the carbon sequestration ability. The difference of carbon sequestration from higher BCR compared to current policy is 1.28 Gg CO2 in average each year.



(a) The comparison of green space area

(b) The comparison of carbon sequestration

Figure 6. Comparison of green space area and carbon sequestration (Kg CO2)

By neglecting spatial plan and rising the built area density inside the residential area, we will reduce the ability of environment to absorb the emission. The residential area will be filled with built area whilst green space will be decreasing.

4.2 Discussions

Spatial planning policies, particularly those related to residential areas, may have a modest influence on the reduction of domestic carbon emissions. Indonesia spatial planning document or RTRW divide the spatial plan into built and conservation space pattern allocating every land use including residential area width. Spatial plan also specifies the building coverage ratio (BCR) of the built area. It allows to set the urban density and form which determine the production of carbon emission (Mostafavi et al., 2021). Based on this study, current housing growth under spatial planning of Bandar Lampung City will increase the carbon emissions until 2041. Simulation of system dynamics model obtained the amount of CO2 each year upon different BCR. In Bandar Lampung spatial plan, 60% BCR in residential area led to the availability of 40% green base coefficient. Green base coefficient indicates the green space availability, and it contributes to carbon emission reduction (Liu et al., 2022). Therefore, this study finding there are less 1.28 Gg CO2 in atmosphere if the city effectively utilizes the green space availability and avoid a higher building density of residential area. This finding supports prior research on urban form-emission links (Mostafavi et al., 2021), suggesting that land-use regulation alone is insufficient without integrated energy and transport planning. Therefore, urban planners should combine BCR regulation with incentives for energy-efficient housing and green infrastructure investment.

5. CONCLUSION

This study finds that under current spatial plan which RTRW of Bandar Lampung City year 2021-2041, domestic emissions will reach up to 1,422.23 Gg CO2. It will slightly grow up to 1,423.69 Gg CO2 if the residential area becomes denser. BCR setting in spatial planning plays an important role to reduce carbon emissions in residential area. It determines the availability of green spaces and the provision of carbon sequestration mechanisms. With 60% BCR, Bandar Lampung City will save approximately 1.28 Gg Carbon Emissions each year until 2041.

This relationship between building density and carbon emissions is critical in the discourse on urban sustainability and climate change mitigation, emphasizing the importance of thoughtful urban planning and land-use policies. However, further research is necessary to comprehensively incorporate aspects such as transportation networks and carbon reduction policies in order to achieve a more accurate simulation of domestic emissions. Moreover, to project city-wide carbon emissions, the model must integrate other activities (Lee et al., 2021) or land use and spatial planning components, including industrial development, commercial zones, and service area planning. This study contributes a replicable framework for incorporating land-use policy into carbon emission forecasting. It supports the role of green infrastructure in emission reduction but also reveals the limitations of spatial-only regulation. Suggest future research directions more specifically including integration of transport modeling, industrial zoning, and behavioral energy use data.

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