



## Research article

## Population density and energy consumption: A study in Indonesian provinces

Irfani Fithria Ummul Muzayanah<sup>a,b</sup>, Hooi Hooi Lean<sup>c</sup>, Djoni Hartono<sup>a,b,\*</sup>,  
Kenny Devita Indraswari<sup>a,b</sup>, Ramadani Partama<sup>b</sup><sup>a</sup> Department of Economics, Faculty of Economics and Business, Universitas Indonesia, Indonesia<sup>b</sup> Research Cluster on Energy Modeling and Regional Economic Analysis, Department of Economics, Faculty of Economics and Business, Universitas Indonesia, Indonesia<sup>c</sup> Economics Program, School of Social Sciences, Universiti Sains Malaysia, Penang, Malaysia

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## ABSTRACT

As the world's fourth most populous country, the population growth rate in Indonesia is expected to stay high. Owing to a combination of high-speed urbanization and increasing population density, economic growth is predicted to increase the demand for energy consumption. Thus, it is crucial to understand the relationship between population density and energy consumption in any country. This study evaluates the impact of population density on total energy consumption and the disaggregated electricity and fuel consumption at the provincial level in Indonesia. It uses the extended Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) model. It also employed a balanced panel data of 33 provinces from 2010 to 2018. The results indicated that population density positively impacts energy consumption for total, electricity, and fuel consumption. This study suggests that incorporating population growth into national energy plans is crucial. Additionally, reducing energy inequality and uneven spatial distribution of the population is also needed.

## 1. Introduction

Rapid urbanization, growing global population, and economic growth, especially in developing countries, have increased humanity's hunger for energy to unprecedented levels (Gray, 2017; OECD, 2012). However, the current energy system still heavily depends on fossil fuel, which later significantly contributes to the rising level of greenhouse gases and leads to other environmental challenges (OECD, 2012; Rahman and Vu, 2021). Furthermore, the lack of access to modern energy is a problem, where almost 20% of the global population lacks access to electricity (OECD, 2012; Roser, 2020). Therefore, there is an urgent need to provide affordable, sustainable, and accessible modern energy while combating environmental problems (The World Bank, 2020).

Indonesia, the largest economy in Southeast Asia, also faces similar problems but more challenging than global issues in terms of energy. The country has emerged as a rising middle-income nation, thus increasing energy consumption, particularly electricity (McNeil et al., 2019).

Energy consumption per capita has increased 24% over the past decade, with total carbon emissions up by 5.2% from 2017, accounting for 1.5% of the total global emissions (British Statistical Review, 2019).

Ardiansyah et al. (2012) argued that Indonesia also faced an energy trilemma for balancing energy security, energy poverty, and climate change mitigation. Hence, research related to energy consumption in Indonesia is crucial as the source of primary energy consumption was still dominated by fossil fuels and only 9.17% was based on renewable energy (Ministry of Energy and Mineral Resources, 2019). Furthermore, if the current progression in energy consumption and production continues without finding solutions, it is predicted that all resources (coal, oil, and gas) will be depleted immediately (Arinaldo and Adiatma, 2019; Santika et al., 2020).

Although some empirical studies on energy consumption issues in Indonesia were found (see Jafari et al., 2012; Shahbaz et al., 2013; for example), the analyses mainly focused on the economic growth and did not consider the impact of population density. Indonesia is the world's fourth most populous country and the population growth rate is predicted to remain high for the next 25 years (Jones, 2015). The densely populated island of Java accounts for much of this population growth, which is predicted to be one of the highest densities in the world by 2035 (Jones, 2015). This problem is further exacerbated by uneven spatial distribution and an apparent energy disparity in the energy sector with

\* Corresponding author.

E-mail address: [djoni.hartono@gmail.com](mailto:djoni.hartono@gmail.com) (D. Hartono).

regard to access and quality between Indonesia's western and eastern parts (World Resources Institute, 2018). Therefore, incorporating population density in the analysis of energy consumption is vital because excessive population will increase Indonesia's pressure to satisfy future high demand for energy.

This study contributes to the existing literature in three ways. First, there is a lack of literature incorporating population density in the analysis of energy consumption (Rahman, 2020; Salim and Shafiei, 2014), particularly in the Indonesian context. We consider a specific study case in this issue because targeted policy implications might differ across different stages of development. Moreover, each country faces challenges regarding energy and environmental issues (Li et al., 2021; Wang et al., 2016). Indonesia lacks data on energy, especially demand-side data, which is another critical problem (Ministry of Energy and Mineral Resources, 2020). Therefore, using the only available energy data in an aggregated way at the provincial level, this study explores the effect of population density on energy consumption, which can be used as a reference study in Indonesia. Second, although an extension of the STIRPAT model is widely used in the literature but as a novelty, this study has employed panel IV to fully control for unobserved time-invariant provincial characteristics and obtain more consistent coefficients. The differenced and lagged values of the dependent variables as the instrumental variable are valid as they fulfill the relevance and exogeneity conditions (Li et al., 2021). Hence, the causal effect between population density and energy consumption can be observed effectively.

This study is presented as follows. Section 2 reviews the literature related to population density and energy consumption. Section 3 discusses the conceptual framework of the STIRPAT (Stochastic Regression on Population, Affluence and Technology) model, and Section 4 explains the methodology. The data sources and descriptive analysis are presented in Section 5. Meanwhile, an analysis of the empirical findings is presented in Section 6. The final section summarizes the conclusions and recommendations of the study.

## 2. Literature review

As SDGs have received worldwide attention, the population–energy–environment nexus is debated in the literature has become a significant issue of discussion (Muhammad et al., 2020). Several studies have investigated how economic and demographic changes affect energy consumption and carbon emissions. For example, Yang et al. (2019) found that higher levels of urbanization positively affect residential electricity consumption in both rural and urban areas, especially in the urban areas. Ali et al. (2019) using the Auto Regressive Distributed Lag bound and VECM approach to investigate whether there was a cointegration between urbanization and carbon emissions in Pakistan. The results revealed cointegration among variables in both the short run and long run, which supported the hypothesis that urbanization substantially affects carbon emissions. Furthermore, Wang et al. (2018) and Wang et al. (2022) showed that the link between urbanization, economic growth, energy consumption, and carbon emissions varied between different stages of development.

However, most studies have focused on economic growth and urbanization as economic and demographic indicators, while very few have incorporated population density in the energy consumption analysis (Rahman, 2020; Salim and Shafiei, 2014). For instance, Sarkodie and Adom (2018) showed that although population density and urbanization in Kenya reduce the aggregate fossil fuel energy consumption, an opposite effect on electricity consumption was observed. Mbaka (2021) corroborated this result using the same country case that counties with high electricity consumption levels are closely linked to higher population density. Rahman (2020) showed similar results that national population density has a positive long-term and short-term impact on energy consumption. A recent study by Zarco-Periñán et al. (2021) also supported these earlier findings that higher population density leads to higher per-inhabitant and per-household energy consumption.

Nevertheless, contrasting results also emerge in the literature. Su (2011) explored the effect of population density on energy consumption in terms of household gasoline consumption in urban areas in the United States. The results showed a negative relationship between that population density and household gasoline consumption. Salim and Shafiei (2014) corroborated this result in which higher population density was linked to lower nonrenewable energy consumption. However, there is also exist an insignificant effect of population density on energy consumption. For example, Azaliah and Hartono (2020) used energy intensity instead of energy consumption and found that density was not a significant predictor of energy intensity and explained that these results were due to the uneven distribution of population in Indonesia. Furthermore, Yongling (2011) showed that population density did not significantly reduce energy consumption. The literature discussed above indicates that these studies remained inconclusive because population density appeared to have mixed results with energy consumption. Yang et al. (2017) argued that taking specific samples is necessary to develop policy implications because different observations may lead to different results. Hence, it merits further discussion.

In the context of Indonesia, there is perhaps only one study that examines the factors determining energy consumption. Azam et al. (2015) confirmed that economic growth, FDI inflows, trade openness, and human capital index show a positive and significant impact on energy consumption in Indonesia. However, this study did not include population density as the determinant. In comparison, other studies have focused on investigating energy consumption and environmental pollutants such as CO<sub>2</sub> emissions (see Jafari et al., 2012; Shahbaz et al., 2013). Hence, it still needs to be investigated, particularly in Indonesia as its population growth is predicted to persist in the upcoming years (Jones, 2015; World Bank, 2016). In contrast, as mentioned earlier, Indonesia is also one of the largest energy consumers in the world and it ranks fifth in Southeast Asia for energy consumption per person (Ariñaldo and Adiatma, 2019), which faces energy issues. This study may provide an insightful understanding for the policy makers in Indonesia to overcome challenges related to population density and energy consumption nexus.

## 3. Conceptual framework

This study investigates the effects of population density on energy consumption in Indonesia from 2010 to 2018. We used the well-known STIRPAT framework for our empirical analysis. This framework was first developed by Ehrlich and Holdren (1971), termed the IPAT model, to analyze the impact of economic activity on the environment. However, this model has limitations: (1) it does not permit hypothesis testing as IPAT is a mathematical identity; (2) all factors in the model have equal influence on the environment; and (3) it cannot determine the factors having a more significant impact on the environment. Therefore, Dietz and Rosa (1997) developed the STIRPAT model to overcome the limitations of the IPAT model. This model is a derivative of the IPAT model, which allows for statistical hypothesis testing. Generally, the STIRPAT model can be written as follows:

$$I_{i,t} = aP_{i,t}^b A_{i,t}^c T_{i,t}^d e_{i,t} \quad (1)$$

where  $a$  is the constant term;  $I$  denotes the environmental impact variable; and  $P$ ,  $A$ , and  $T$  are the determinants of the economic impact on the environment, indicating population, affluence, and technology, respectively. The parameters  $b$ ,  $c$ , and  $d$  describe each factor's elasticity to the environment;  $e$  is another variable that impacts the environmental impact variable ( $I$ ) or error term; and the subscripts  $i$  and  $t$  represent the object and time of analysis, respectively.

Eq. (1) can be converted to an econometric model by transforming it into a logarithmic form. The transformation into the logarithmic form has several implications. First, logarithmic transformations make interpreting the model's coefficients more straightforward than the percentage

change in the independent variable affects the dependent variable. Second, logarithmic transformations can minimize the possibility of multicollinearity occurring in the model (Liu et al., 2021). After taking the logarithmic form, Eq. (1) can be expressed as follows:

$$\ln I_{i,t} = \ln a + b(\ln P_{i,t}) + c(\ln A_{i,t}) + d(\ln T_{i,t}) + e_{i,t} \quad (2)$$

Another advantage of the STIRPAT model is that the study can extend the model by adding multiple variables other than A and P to express T (York et al., 2003). For example, some studies have incorporated urbanization as an additional variable in the STIRPAT model (Poumanyong and Kaneko, 2010; Yang et al., 2017; Zhang and Lin, 2012). Liddle (2013) added an urban density variable to the extended STIRPAT model. This study used an extended STIRPAT model by adding a population density variable (denoted as D). Neill et al. (2012) argued that using the population variable (P) only acts as a scale factor because a change in the population growth has a proportional effect on the growth of energy consumption. Therefore, if the study is interested in accurately capturing the impact of population growth on energy consumption, it should incorporate the indirect effects of population processes, such as population density (Liddle, 2014; Neill et al., 2012). Furthermore, Liddle (2014) suggested that it would be preferable to directly include population density in the model. Accordingly, Eq. (2) can be rewritten as follows:

$$\ln EC_{i,t} = \alpha_0 + \alpha_1(\ln D_{i,t}) + \alpha_2(\ln A_{i,t}) + \alpha_3(\ln IND_{i,t}) + \alpha_4(\ln SV_{i,t}) + e_{i,t} \quad (3)$$

where *EC* is the total energy consumption, and the subscripts *i* and *t* represent the province and year of observations, respectively. Following the original IPAT model from Ehrlich and Holdren (1971), we used energy consumption as a proxy for the environmental impact variable (*I*). Similarly, Zhang and Lin (2012) and Li and Lin (2015) also used energy consumption as a proxy for the *I* variable. This study employed the population density (*D*) variable in the model to proxy the *P* variable. The regional GDP per capita is used to measure *A*. Following Zhang and Lin (2012), Poumanyong and Kaneko (2010), and Shi (2003), *T* is proxied using the share of the industrial (*IND*) and services sector in the economy (*SV*). A sector with high energy intentions is indicated by the share of the industrial sector to the GDP; meanwhile, the share of the service sector to GDP indicates low energy intentions (Shi, 2003; Zhang and Lin, 2012).

Furthermore, this study disaggregated the total energy consumption into electricity and fuel consumption. Hence, to identify the impact of Eq. (3) on electricity consumption (*ELECT*) and fuel consumption (*BBM*), respectively, the following equations must be separated from Eq. (3) as follows:

$$\ln ELECT_{i,t} = \beta_0 + \beta_1(\ln D_{i,t}) + \beta_2(\ln A_{i,t}) + \beta_3(\ln IND_{i,t}) + \beta_4(\ln SV_{i,t}) + e_{2i,t} \quad (4)$$

$$\ln BBM_{i,t} = \gamma_0 + \gamma_1(\ln D_{i,t}) + \gamma_2(\ln A_{i,t}) + \gamma_3(\ln IND_{i,t}) + \gamma_4(\ln SV_{i,t}) + e_{3i,t} \quad (5)$$

This disaggregation stands on the following arguments: (1) electricity and fuel are energy sources consumed by all economic sectors; (2) electricity and fuel have accounted for 66% of the total energy consumption, on average, during the past 5 years in Indonesia (Ministry of Energy and Mineral Resources, 2020); (3) the share of electricity and fuel compared with the total energy consumption during 2018 and 2019 reached 70% (Ministry of Energy and Mineral Resources, 2019). Therefore, the study findings may provide insightful policy recommendations for evaluating the effect of population density on not only total energy but also fuel and electricity consumption.

#### 4. Methodology

To analyze the impact of population density on energy consumption at the provincial level in Indonesia, this study estimates the models using

three dependent variables: total energy consumption, fuel consumption, and electricity consumption. Furthermore, we used six estimation methods: Pooled Ordinary Least Squares (POLS), POLS with time and island control, Fixed Effect (FE), Feasible Generalized Least Squares (FGLS), linear regression with Panel-Corrected Standard Errors (PCSE), and the Instrumental Variable (IV) panels.

The simplest estimation was achieved using POLS as the first step. However, POLS cannot solve the heterogeneity problem between province, and may lead to biased estimation results (Zhang and Lin, 2012). We used the POLS estimation with time and island control and the FE estimation to effectively overcome this problem. Following Zhang and Lin (2012), several statistical tests were also performed to identify some issues in FE estimation, including the autocorrelation panel test (Wooldridge, 2002), the heteroscedastic test (Greene, 2008) and the cross-sectional dependence test with the Pesaran technique (Pesaran et al., 2004). The results showed that all models in FE estimation confirmed the existence of these problems. Therefore, the results in the FE estimation were unbiased but inefficient.

To solve these problems, we applied the FGLS estimation. However, the standard error in this estimation would underestimate the true variability unless the time dimension (*T*) is equals or exceeds the cross-sectional dimension (*N*) (Beck and Katz, 1995; Li and Lin, 2015). This problem is relevant to this study because the number of time dimensions (*T*) used is not equal to the number of cross sections (*N*). The PCSE estimation was used to address this issue. Moreover, to evaluate the consistency of the coefficients, we used panel IV with the lag of the population density variable as the instrumental variable to ensure the exogeneity of the regressors. Therefore, the results show the causal effect while controlling for time-invariant provincial characteristics. Li et al. (2021) argued that using lagged-dependent variables as instruments could be helpful as valid external instruments because finding the IVs is commonly challenging. Therefore, the differenced and lagged values of the dependent variables satisfied the conditions of relevance and exogeneity. Using the F-stat first-stage rule from Stock and Motohiro (2005), it is statistically shown that the lag of the population density as an IV is not a weak instrument. This result shows that the IV estimation is the preferred method. However, only the main result using this estimation was discussed in the analysis.

### 5. Data source and descriptive analyses

#### 5.1. Data source and definition of variables

This study used balanced panel data of 33 Indonesian provinces from 2010 to 2018. The provincial data on total energy consumption, electricity consumption, and fuel consumption were collected from the Handbook of Energy and Economic Statistics of Indonesia, published annually by the Ministry of Energy and Mineral Resources (MEMR) of the Republic of Indonesia. This handbook is a part of the efforts to provide more accurate and reliable data on the energy economy initiated by the Data and Information Center of the MEMR of the Republic of Indonesia. Moreover, data regarding regional GDP, total population, population density, the share of industry, and services were obtained from Statistics Indonesia (*Badan Pusat Statistik*). Table 1 shows all variables used in this study, including their definitions and sources.

#### 5.2. Descriptive analysis

Table 2 presents descriptive statistics for all variables in this study. The mean, standard deviation, minimum value, and maximum values are shown for continuous variables. Owing to data limitations, this study only covered data at the provincial level from 2010 to 2018, resulting in a total number of 297 observations. Table 2 reveals that the average value of fuel consumption is higher than that of electricity. From 2010 to 2018, the highest total energy consumption was found in the province of Central Java in 2014, while the lowest consumption was in North Maluku

**Table 1.** Definition of the variables used in this study and the sources.

Variables	Definition	Sources
Energy Consumption (EC)	Total energy, electricity, and fuel consumption for each province in Indonesia (in a million SBM units)	Handbook of Energy and Economic Statistics of Indonesia
Population Density (D)	Population per km <sup>2</sup> for each province in Indonesia	Statistics Indonesia
Total Population (P)	The total population for each province in Indonesia (in a million units)	Statistics Indonesia
Gross Regional Domestic Product Per Capita (A)	Real GRDP per person for each province in Indonesia (in a million Rupiah, Constant 2010)	Statistics Indonesia
Share of Industry Value-Added (IND)	The proportion of industry value-added by GRDP for each province in Indonesia	Statistics Indonesia
Share of Service Value-Added (SV)	The proportion of service value-added by GRDP for each province in Indonesia.	Statistics Indonesia

in 2013. Similarly, the highest fuel consumption was recorded in Central Java in 2014 and the lowest in North Maluku in 2013. Furthermore, in terms of electricity consumption, West Java ranked at number one in 2018 and the lowest in West Sulawesi in 2010. However, the data showed that most provinces in Java Island dominated the top 10 ranks in terms of the highest energy consumption. Meanwhile, regions with the lowest energy consumption were located in the eastern part of Indonesia.

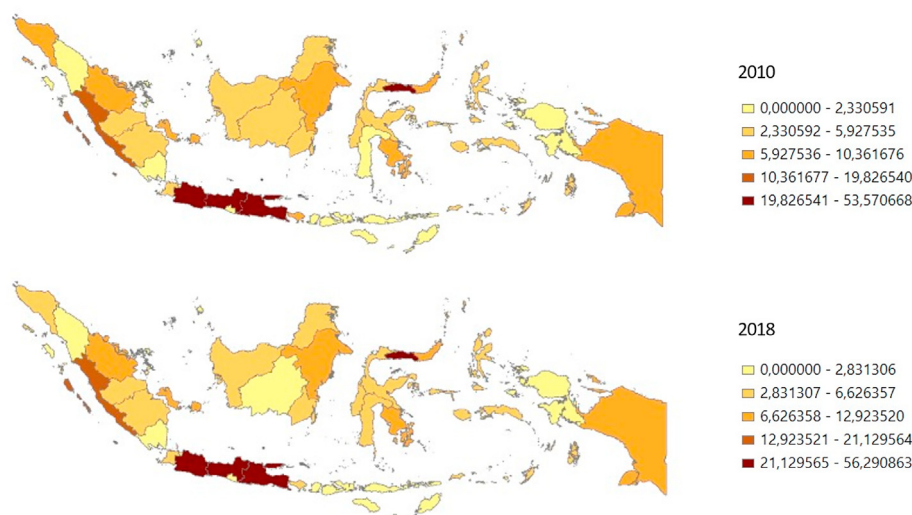
This energy pattern might be in accordance with Indonesia’s uneven distribution of its population. Table 2 reveals that the average population density is 725 people per km<sup>2</sup>. Jakarta had the highest population density from 2010 to 2018, and this trend continued to increase throughout the year. Jakarta, the capital of Indonesia, continues to grow as a megacity with persistent urban expansions and has become the center of economic activities for its surrounding regions (Rustiadi et al., 2021). Furthermore, as most of the population is concentrated in Java, economic activities are also located here, thus contributing to 59% of Indonesia’s GDP (Ranggasari, 2020). Therefore, it is not surprising that Java consumed more energy than other parts of Indonesia. Meanwhile, the lowest population density is in the eastern part of Indonesia: Papua and West Papua.

In terms of per capita income, there was a fairly high gap between the provinces. In 2018, Jakarta had the highest regional GDP per capita, while the province of East Nusa Tenggara had the lowest. This finding indicates a notable inequality in the regional GDP per capita across Indonesia. In the share value-added sector to regional GDP, the average share of the service sector was higher than that of the industrial sector. This result data align with the Indonesian economic structure, which is currently dominated by the service sector (World Bank, 2016).

We also present the spatial distribution of energy consumption in Indonesia for total energy, fuel energy, and electrical energy consumption in 2010 and 2018 (Figures 1, 2, and 3). These figures also consistently show that in 2010 and 2018, the energy consumption, both in total, fuel and electricity, was mainly concentrated on Java Island. The spatial distributions of fuel and electricity consumption are presented in Figures 2 and 3, respectively. These figures confirm the pattern of an increasing demand for energy consumption both in fuel and electricity

**Table 2.** Descriptive statistics of variables.

Variables	N	Mean	Standard Deviation	Min	Max	Unit
<i>Dependent variables</i>						
Total Energy Consumption	297	12.63	22.81	0.72	227.21	Million SBM
Electricity Consumption	297	3.49	6.18	0.08	29.86	Million SBM
Fuel Consumption	297	9.13	19.07	0.57	215.67	Million SBM
<i>Independent variable</i>						
Population Density	297	724.57	2591.78	7.89	15804.25	Total people per km <sup>2</sup>
Total Population	297	7.77	10.96	0.76	53.77	Million people
Regional GDP Per Capita	297	35.87	28.82	1.23	165.87	Million Rupiah
Share of Industry Value-Added	297	0.16	0.11	0.12	0.44	Proportion
Share of Service Value-Added	297	0.42	0.14	0.0003	0.74	Proportion



**Figure 1.** Total energy consumption in Indonesia, 2010–2018.

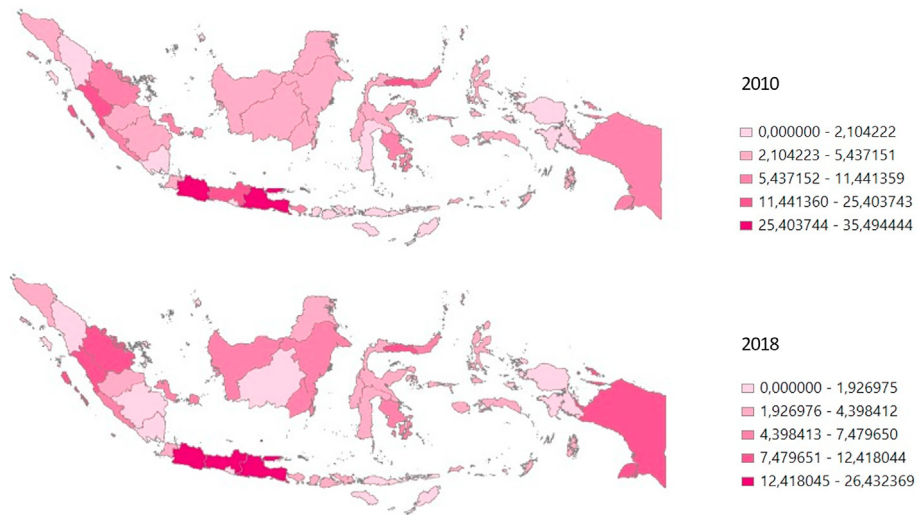


Figure 2. Fuel energy consumption in Indonesia, 2010–2018.

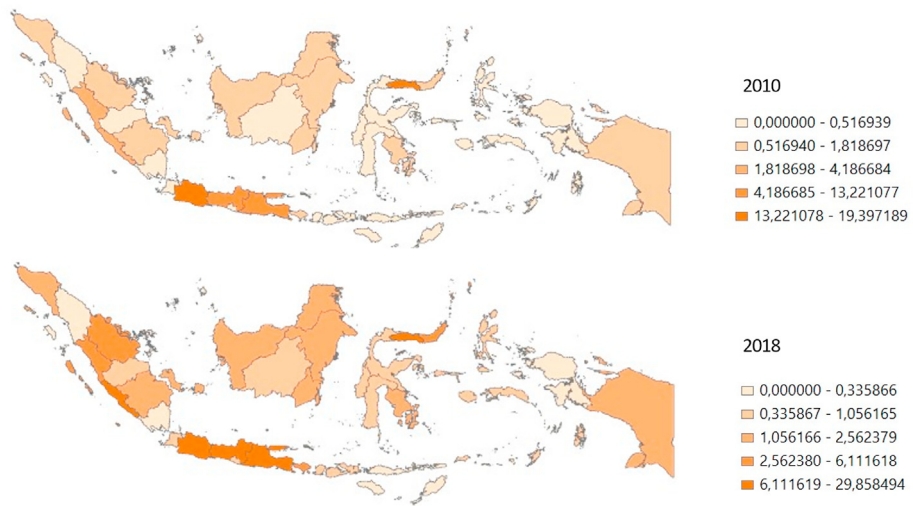


Figure 3. Electrical energy consumption in Indonesia, 2010–2018.

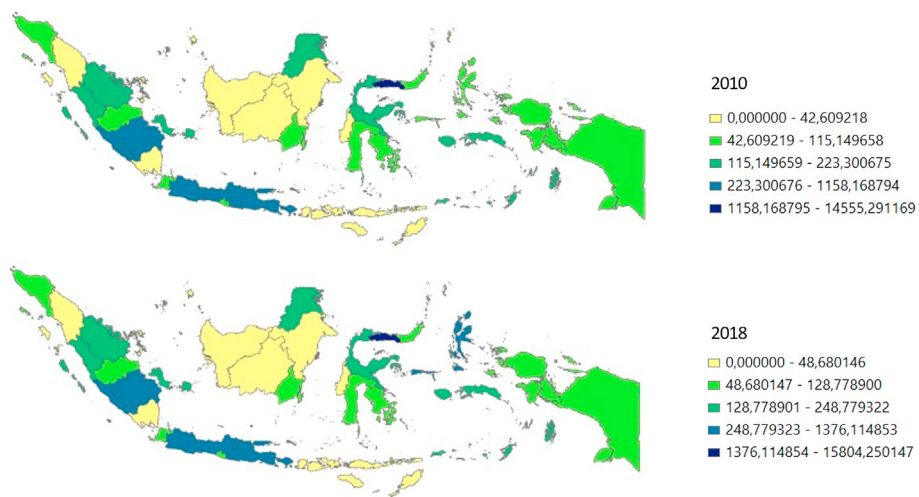


Figure 4. Population density in Indonesia, 2010–2018.

**Table 3.** Correlation table of dependent and explanatory variables.

	lnEC	lnD	lnA	lnIND	lnSV
lnEC	1.00				
lnD	0.68	1.00			
lnA	0.28	0.07	1.00		
lnIND	0.58	0.29	0.48	1.00	
lnSV	-0.14	0.20	-0.33	-0.35	1.00

consumption in 2010 and 2018. In Figure 2, although increasing fuel consumption occurred in some parts of the Sumatera, Kalimantan dan Papua, Java still dominated, as shown by the darkest color in the figure. Similarly, this pattern also appeared for electricity consumption in 2010 and 2018. When we compare energy consumption figures to the spatial distribution of population density in Figure 4, it is unsurprising that regions with higher population density consume more energy. These figures indicate that the population density might positively affect energy consumption in Indonesia.

**6. Results and discussion**

This study investigates how population density affects energy consumption. The regression result for total energy consumption is presented in Table 4. We also divided the total energy consumption into two categories, namely, fuel and electricity, and performed separate regression for both categories (Tables 5 and 6). As explained earlier in the methodology section, only the main result in column 6 in each table is analyzed. However, we also provide the correlation table between the independent variables. The result in Table 3 indicates a positive correlation between population density and energy consumption. Moreover, no severe multicollinearity exists between independent variables as all values are less than 1.

The regression results in Table 4 revealed that population density positively affects total energy consumption in Indonesia (significant at 1% level). For instance, a 1% increase in population density increases the total energy consumption by 0.36%. Interestingly, this finding contradicts most previous studies that found a negative relationship between

population density and energy consumption (Kunvitaya and Dhakal, 2017; Ohlan, 2015; Otsuka, 2018). Instead, the study findings indicate that higher population density leads to higher energy consumption. However, this result is consistent with our earlier map in Figures 1 and 4, which shows that high-density regions consume more energy. Additionally, this finding supported the study of Rahman (2020), who found that population density has a significant and positive effect on energy consumption.

Furthermore, a similar result is obtained for electricity and fuel consumption. The result in Tables 5 and 6 revealed that the higher the population density, the greater the electricity and fuel consumption. However, the elasticity of electricity is higher than that of fuel consumption. An increase in population density increases the demand for electricity and fuel consumption by 0.77% and 0.25%, respectively. These results reflect the previous findings from Sarkodie and Adom (2018) and Mindali et al. (2004), who found that population density positively affects electricity consumption. Moreover, a report published by the National Energy Council (2019) might support this result, which shows that in Indonesia, the share of electricity consumption to total energy consumption is the highest; the sectors accounting for energy consumption include household (42%), commercial (25%), transportation (0.12%), and industrial (33%). It is also estimated that the growth in demand for electricity is the highest among other energy sources, with an estimated growth of 6%–7% by 2050 (National Energy Council, 2019).

The increase in energy consumption, particularly electricity, may be triggered by the rise in living standards of the middle-class income groups, with monthly incomes between Rp 1.2 million and Rp 6 million (McNeil et al., 2019). Indonesia’s middle class has been proliferating with an annual growth of around 10%. In other words, one in every five Indonesians is from the middle-class group (World Bank, 2019). Batih and Sorapipatana (2016) used the samples from seven populated cities in Indonesia (Denpasar, Yogyakarta, Surabaya, Jakarta, Bandar Lampung, Bandung, and Palembang) and found that the most significant consumption of electricity for all income classes is derived from appliances that serve three primary purposes: lighting, space cooling, and entertainment. These explanations support the study by Sarkodie and Adom

**Table 4.** Regression results of total energy consumption.

lnEC	(1)	(2)	(3)	(4)	(5)	(6)
	OLS	OLS + Control	FE	FGLS	PCSE	Panel IV-Density Lag
lnD	0.417** (0.0278)	0.388*** (0.0400)	0.168* (0.0891)	0.345*** (0.0269)	0.382*** (0.0231)	0.369*** (0.0690)
lnA	0.443** (0.0680)	0.303*** (0.0747)	-0.0377 (0.124)	0.327*** (0.0541)	0.383*** (0.0608)	0.248*** (0.105)
lnIND	-0.263** (0.120)	-0.311** (0.143)	0.0170 (0.0280)	-0.0331 (0.0274)	-0.0306 (0.0359)	0.00788 (0.0292)
lnSV	0.417** (0.0278)	0.388*** (0.0400)	0.168* (0.0891)	0.345*** (0.0269)	0.382*** (0.0231)	0.369*** (0.0690)
Constant	0.247 (0.358)	0.201 (0.356)	0.767 (0.665)	-0.197 (0.305)	-0.182 (0.372)	0.263 (0.637)
Island Dummies	-	YES	-	-	-	-
Year Dummies	-	YES	-	-	-	-
Autocorrelation Test			F(1,32) = 36.233***			
CSD Test			CD = 28.072***			
Heteroscedasticity Test			$\chi^2$ (33) = 4147.76***			
First-stage F-stat	-	-	-	-	-	1115.91
Observations	297	297	297	297	297	264
R-squared	0.630	0.688	0.015		0.585	
Number of id province	33	33	33	33	33	33

Notes: Standard errors are shown in parentheses. \*\*\*p < 0.01, \*\*p < 0.05, \*p < 0.1.

**Table 5.** Regression results of electricity consumption.

lnELECT	(1)	(2)	(3)	(4)	(5)	(6)
	OLS	OLS + Control	FE	FGLS	PCSE	Panel IV-Density Lag
lnD	0.591** (0.0258)	0.514*** (0.0408)	1.305*** (0.0754)	0.591*** (0.0282)	0.602*** (0.0398)	0.776*** (0.0714)
lnA	0.480** (0.0692)	0.343*** (0.0722)	-0.305*** (0.105)	0.401*** (0.0577)	0.413*** (0.0845)	-0.0527 (0.100)
lnIND	-0.238** (0.0595)	-0.287*** (0.107)	0.0321 (0.0237)	-0.0354 (0.0312)	-0.0376 (0.0446)	0.0126 (0.0257)
lnSV	0.591** (0.0258)	0.514*** (0.0408)	1.305*** (0.0754)	0.591*** (0.0282)	0.602*** (0.0398)	0.776*** (0.0714)
Constant	-3.202** (0.395)	-3.046*** (0.372)	-11.09*** (0.562)	-3.944*** (0.325)	-3.879*** (0.594)	-6.774*** (0.631)
Island Dummies	-	YES	-	-	-	-
Year Dummies	-	YES	-	-	-	-
Autocorrelation Test			F (1,32) = 4.491**			
CSD Test			CD = 17.676***			
Heteroscedasticity Test			$\chi^2$ (33) = 19723.33***			
First-stage F-stat	-	-	-	-	-	860.39
Observations	297	297	297	297	297	264
R-squared	0.736	0.792	0.634		0.552	
Number of id province	33	33	33	33	33	33

Notes: "ELECT" stands for electricity consumption, "D" for population density, "A" for regional GDP per capita, "IND" for share of industry value-added to regional GDP, and "SV" for share of service value-added to regional GDP. Standard errors are shown in parentheses. \*\*\*p < 0.01, \*\*p < 0.05, \*p < 0.1.

(2018), who argued that higher incomes might cause a backfire in energy consumption.

Regarding fuel consumption, the results in this study also contradict most existing findings in the literature, which showed that fuel consumption is inversely proportional to population density. For example, Sarkodie and Adom (2018) showed that higher density generates economies of scale for total energy and fuel consumption. Additionally,

Dar-Mousa and Makhmreh (2019) found that a high-density population lowers the marginal cost per capita of energy consumption, thus, consuming less energy. In case of Indonesia, rapid economic growth, followed by a growing population in the past decade, might have led to increasing demand for fuel consumption (Akhmad and Amir, 2018). According to data released by The World Bank (2019), 20% of the middle-income group from the MC 1 group (US\$ 7.75–20 per day), 60%

**Table 6.** Regression results of fuel consumption.

lnBBM	(1)	(2)	(3)	(4)	(5)	(6)
	OLS	OLS + Control	FE	FGLS	PCSE	Panel IV-Density Lag
lnD	0.337*** (0.0318)	0.336*** (0.0434)	-0.200** (0.119)	0.250*** (0.0323)	0.280*** (0.0511)	0.257*** (0.0749)
lnA	0.460*** (0.0721)	0.321** (0.0822)	0.125 (0.167)	0.253** (0.0570)	0.380*** (0.0749)	0.435*** (0.125)
lnIND	-0.262* (0.151)	-0.310* (0.162)	0.0379 (0.0375)	-0.0136 (0.0264)	-0.0216 (0.0357)	0.0268 (0.0399)
lnSV	0.337*** (0.0318)	0.336*** (0.0434)	-0.200* (0.119)	0.250*** (0.0323)	0.280*** (0.0511)	0.257*** (0.0749)
Constant	0.859** (0.389)	0.706* (0.385)	4.045*** (0.890)	0.175 (0.329)	0.418 (0.508)	1.846** (0.740)
Island Dummies	-	YES	-	-	-	-
Year Dummies	-	YES	-	-	-	-
Autocorrelation Test			F (1,32) = 52.435***			
CSD Test			CD = 25.250***			
Heteroscedasticity Test			$\chi^2$ (33) = 6839.77***			
First-stage F-stat	-	-	-	-	-	1601.62
Observations	297	297	297	297	297	264
R-squared	0.540	0.605	0.047		0.408	
Number of id_prov	33	33	33	33	33	33

Notes: "BBM" stands for fuel consumption, "D" for population density, "A" for regional GDP per capita, "IND" for share of industry value-added to regional GDP, and "SV" for share of service value-added to regional GDP. Standard errors are shown in parentheses. \*\*\*p < 0.01, \*\*p < 0.05, \*p < 0.1.

from the MC 2 group (USD 20–38), and nearly all upper-class groups own cars, and others travel in a private mode with a consumption share of nearly 9% and 17% of the total consumption for the MC 2 and upper-class groups, respectively.

Moreover, all variables, except the share of industry value-added, are statistically significant in the total energy consumption and fuel estimation. Both estimations showed that the affluence factor measured by regional GDP significantly affects energy consumption. The results in Tables 4 and 6 indicate that a 1% increase in regional GDP increases the total energy and fuel consumption by 0.24% and 0.43%, respectively. This finding confirmed that a higher regional GDP positively affects total energy and fuel consumption. This result agrees with the study by Huang et al. (2008), who found a positive relationship between GDP growth and energy consumption in lower-middle-income countries. Additionally, Rahman (2020) revealed a similar conclusion about the positive elasticity of economic growth and energy consumption in India.

However, the share of industry value-added also appeared statistically insignificant in electricity estimations. Meanwhile, an increase in the share of service value-added will increase total energy, electricity, and fuel consumption by 0.36%, 0.77%, and 0.25%, respectively. This consistent outcome in the three estimations is probably in accordance with Indonesia's rapid structural transformation from an agriculture and industry-based economy to a service-based economy (World Bank, 2016). Nevertheless, this result contradicts the argument that structural transformation allows a nation's economy to shift from a low-polluting agriculture sector to a high-polluting industrial sector and then shift back to a lower-polluting tertiary sector (Sunday et al., 2021). The dependence on fossil fuel-based energy consumption might be the reason behind these contradictory results (Sunday et al., 2021).

## 7. Conclusions and policy implications

This study investigates the effect of population density on energy consumption in Indonesia. Although there is some empirical evidence regarding the issue of energy consumption in Indonesia, most studies have not considered population density. Incorporating population density into the analysis of energy consumption is essential because Indonesia's population growth will remain high and is predicted to exceed 270 million by 2025 (Jones, 2015; World Bank, 2016). However, Indonesia faces a challenging in meeting the growing energy demand. Population growth, followed by the rapid growth of the middle-income class, will put tremendous pressure on Indonesia's energy security. Using a widely known STIRPAT model, this study employed panel IV as the remarkable contribution to obtain more robust coefficients by fully controlling for unobserved time-invariant provincial characteristics. Hence, we can effectively find the causal effect between population density and energy consumption.

Interestingly, the study findings contradict those of the existing studies that population density lowers energy consumption (Kunvitaya and Dhakal, 2017; Ohlan, 2015; Otsuka, 2018). Instead, a higher population density will increase energy consumption. In other words, a 1% increase in population density will increase the total energy consumption by 0.36%. This finding supports the study of Rahman (2020) and Rahman and Vu (2021), who found that population density positively increased energy consumption. Similar results also appear for electricity and fuel consumption. The higher the population density, the higher the demand for electricity and fuel energy; this implies that a 1% increase in population density increases the demand for electricity and fuel consumption by 0.77% and 0.25%, respectively. The elasticities of electricity consumption are higher than that of fuel consumption. The domination of middle-class income growth in Indonesia may explain these conflicting results. Unlike many poor and few wealthy groups in Indonesia, a large share of middle-class groups leads to greater domestic consumption because they have a higher marginal propensity to consume than the wealthy people with higher income compared with the poor (World Bank, 2019). Moreover, Senauer and Goetz (2003) argued that most

middle- or upper-class households in developing countries tend to possess more durable goods such as electrical equipment and automobiles, which might increase the demand for energy. Additionally, although not directly focusing on population density and energy consumption, the study by Li et al. (2021), Wang et al. (2022) and Wang and Zhang (2021) emphasized that the direction of influence and causal relationship between variables might differ among countries with different income groups. Moreover, low-income-group countries might have complex relationships that differ from those of high-income-group countries.

The study concludes that the government should consider energy consumption as a function of population density. As regards policy implications, this study suggests that governments should incorporate population growth into national energy plans. Indonesia should meet the demand growth with adequate investments in the energy sector. There is an urgent need for energy diversification to reduce the dependence on fossil fuels and shift into renewable energy resources or other sustainable energy resources. Furthermore, the uneven spatial distribution of the population underlined that there might be no uniform solution to meet the energy demand in each region. The region that already faces a highly dense population will undoubtedly deal with a more challenging problem than the region with low population density. Hence, the population distribution program and reducing energy access inequality are crucial and should be implemented immediately. However, the population distribution program in Indonesia called transmigration has existed since the Dutch colonial era to move people from densely populated to sparsely populated areas. This program should be continued without neglecting equitable development across regions.

Nevertheless, some limitations are also highlighted in this study. As studies on population density and energy consumption in Indonesia are still limited, future studies may consider assessing the impact of population density on various variables such as energy intensity, CO<sub>2</sub> emissions, and renewable energy. The short-run and long-run equilibria may also be gauged to examine the effect during different timelines. Better data availability at a lower micro level is desirable for future studies to clearly explain the impact of population density on energy consumption. Moreover, future research may divide the provinces into several groups based on regional income or density characteristics. This study provides a foundation for further investigation on how population density may affect energy consumption.

## Declarations

### Author contribution statement

Djoni Hartono, Ramadani Partama: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Irfani Fithria Ummul Muzayanah, Kenny Devita Indraswari: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Hooi Hooi Lean: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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### Data availability statement

Data will be made available on request.



**Declaration of interests statement**

The authors declare no conflict of interest.

**Additional information**

No additional information is available for this paper.

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