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Enhancing energy efficiency in Asia-Pacific: Comprehensive energy policy analysis

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ABSTRACT

The Asia-Pacific (APAC) region has undergone remarkable economic growth over the past three decades, significantly reducing poverty levels. However, the concurrent rise in energy consumption and its environmental impact necessitate the development of a sustainable energy system to sustain and accelerate this progress. Recognizing the critical role of energy efficiency, governments in the region have increasingly formulated and implemented energy policies, encompassing laws, regulations, and action plans. However, understanding the precise influence of these policies on energy efficiency remains a challenge. This study employs an endogenous stochastic frontier analysis (SFA) model using data from the Asia Pacific Energy Portal Policy database covering 23 emerging economies from 2000 to 2017 to assess how energy policies affect energy efficiency in the APAC region. The findings indicate that implementing energy policies correlates with an average increase in energy efficiency by 0.158%. However, the impact varies depending on whether the policies are laws, regulations, or strategies. Though the region's average energy efficiency standing is at 0.34, there has been a consistent upward trend observed from 2000 to 2017. Furthermore, optimizing aggregate energy policies has resulted in substantial energy savings, averaging 0.15 quadrillion Btu. In light of these results, we proposed some policy actions.

1. Introduction

The Asia-Pacific (APAC) region is crucial in the fight against climate change due to its high-energy consumption and carbon emissions (Frei et al., 2013; Yang et al., 2020). By 2050, APAC will account for about 50% of global economic growth, increasing energy demand by 45% (APERC, 2019). Despite the benefits of renewable energy, its share in the region's energy mix fell from 22.7% in 2000 to 16% in 2020 (Chen et al., 2022). The United Nations (2018) warns that APAC countries relying on conventional energy face climate and energy security issues. To address these, the region needs to improve energy efficiency.

The Intergovernmental Panel on Climate Change (IPCC) report highlights energy efficiency as a key approach to reducing greenhouse gas emissions, given the challenges of quickly transitioning to renewable energy sources (Ford et al., 2016). Energy efficiency focuses on reducing energy consumption rather than increasing production, making it a pragmatic and economical choice. Enhancing energy efficiency not only reduces energy demand but also promotes sustainability and mitigates climate change (Liu et al., 2023; Bekun, 2024). The IEA (2018) predicts that without improvements in global energy efficiency since 2000, environmental degradation and energy consumption would have risen by 12% in 2016. Therefore, improving energy efficiency is essential for achieving the Sustainable Energy for All (SE4All) and climate goals.

Over the last twenty years, the APAC region has implemented numerous energy and climate-related policies and initiatives in response to climate change and global warming (Yang et al., 2020). These energy policies aim to restructure the energy sector to meet Sustainable Development Goal (SDG) 7 and to reduce greenhouse gas emissions. Energy policy measures have significantly increased (as observed in Fig. 1) and now encompass various strategies such as developing standards and labels for electrical equipment, implementing energy-efficient building regulations, providing financial assistance for energy-efficient activities, among others.

For example, India introduced the Energy Conservation Act of 2001 to reduce energy intensity through building codes, energy labelling, and appliance standards (UNDP, 2013). The Philippines established a comprehensive national regulatory framework for demand-side energy management in 1996, including audits, voluntary agreements, energy

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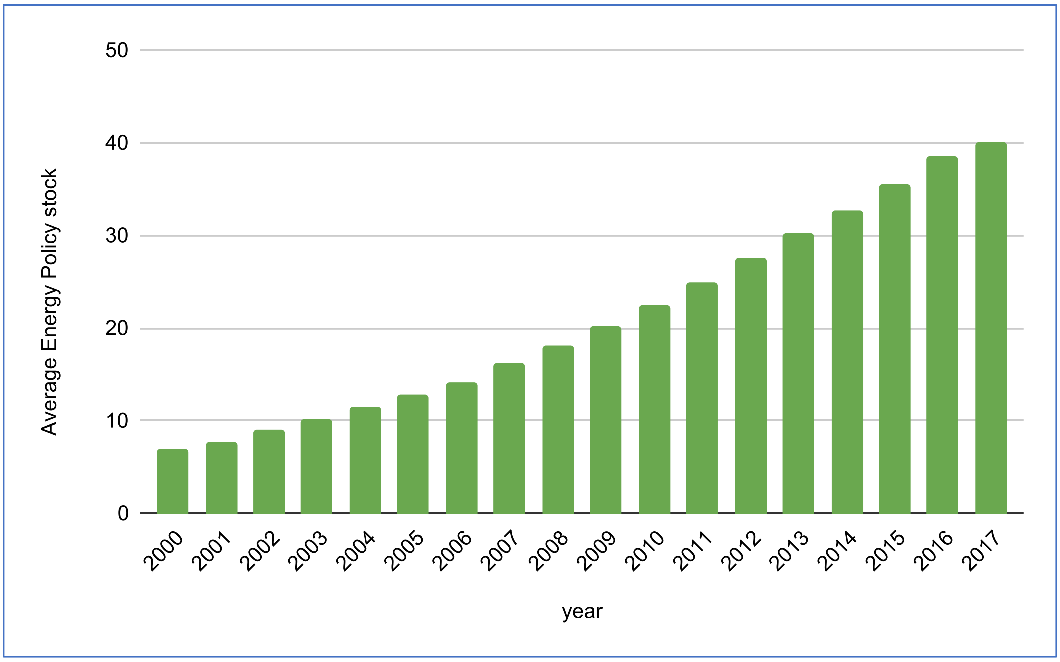

Fig. 1. Average stock of energy policies for sampled APAC countries in this study over the years (2000–2017) (Source: Asia Pacific Energy Portal Policy database)

management training, standards and labelling for residential appliances, peak demand reduction initiatives, and accreditation for energy-efficient structures (Passey et al., 2011). Thailand implemented the Energy Conservation Promotion Act of 1992 and the Twenty-Year Energy Efficiency Development Plan (2011−2030), aiming for a 25% energy reduction from the 2005 baseline. Indonesia's Directorate General of New Renewable Energy and Energy Conservation, founded in 2010, aims to reduce energy consumption to the level of a 2000-MW power plant. Energy auditing is practiced in Bangladesh, Fiji, India, and Indonesia (UNDP, 2013). Recently, Bangladesh and India implemented combined heat and power (CHP) systems to enhance energy efficiency and reduce waste (Adnan et al., 2021).

While the energy-related policy efforts described above reflect the region's commitment to achieving SDG 7, particularly target 7.3, their impact on energy efficiency over the past two decades remains ambiguous due to lack of comprehensive studies. The ever-changing energy environment, regulatory frameworks, and significant institutional, economic, and resource differences among countries pose challenges in constructing a comprehensive regional study framework. Also, variations in energy efficiency levels among countries further complicate regional investigations.

The purpose of this study is to estimate the impact of energy policies on energy efficiency in the APAC region. Our analysis utilizes data from the Asia Pacific Energy Portal Policy database, covering 23 emerging economies from 2000 to 2017. For better examination, following (Chen et al., 2022),we categorize energy policies into four types: laws, regulations, strategies, and “others”. Laws are policies enforced by courts, regulations consist of detailed guidelines issued by agencies, and strategies are plans that often rely on voluntary compliance (Reiche and Tenenbaum, 2006). The “others” category includes energy policies that do not fit into the first three types. According to Huhta (2022), the effectiveness of energy laws, regulations, and strategies in promoting energy efficiency varies considerably due to differences in how these policies are implemented. As a result, our empirical approach—which draws from recent literature—offers further insights into the factors that influence energy efficiency and enhances the representation of various energy policy kinds.

We also examine the aggregate effect of energy policies by calculating their counterfactual effect, comparing energy efficiency with and without these policies. This helps us determine whether the policies have significantly contributed to improvements in energy efficiency or if other variables play a more critical role. Furthermore, in light of the growing significance of energy conservation, we look into the possible energy savings that could be realized through improved energy policies. By projecting the potential impact of improved policies, we highlight the critical role that strategic policy-making plays in achieving energy conservation goals and mitigating environmental impacts.

Finally, unlike previous research, which typically uses a two-step approach to analyze energy efficiency, our study adopts a one-step methodology. The conventional two-step approach first estimates energy efficiency through stochastic frontier analysis (SFA) or data envelopment analysis (DEA). Subsequently, these estimates are used to explore the relationship between various determinants and energy efficiency. Despite its simplicity, the two-step approach has some drawbacks. First, in the case of the DEA method, it does not account for stochastic noise in its initial calculation of energy efficiency, making the results susceptible to outliers (Sun et al., 2019). Second, discrepancies in the underlying assumptions of the methods used in the two steps can lead to internal conflicts and estimation biases (Kuang et al., 2023). Third, considering the determinants of efficiency only in the second step can lead to omitted variable bias, as their influence is not included during the initial efficiency estimation with DEA or SFA (Schmidt, 2011). In our research, we employ endogenous stochastic frontier analysis to study the relationship between energy policies and energy efficiency, enabling us to estimate efficiency while addressing endogeneity and avoiding biases typical of the two-step process.[1]

With the above analysis and contributions to the literature, the study seeks to answer the following research questions:

[1] While endogenous SFA is a useful for analyzing efficiency and productivity, it comes with some limitations. One major concern is its dependence on the correct specification of the model. If the functional form is mis-specified, it can result in biased and inconsistent estimates. To mitigate this risk, our study utilizes both the Translog and Cobb-Douglas production functions to ensure more robust results. Additionally, as part of our robustness checks, we employ the traditional two-step approach to further examine the relationships between energy policy and efficiency.

- How effective are APAC's energy policies in improving energy efficiency?
- Do different energy policy types have varying effects on energy efficiency?
- What are the annual policy-induced energy savings from 2000 to 2017 compared to a no-policy scenario?
- What potential energy savings could be realized with improved energy policies?

The rest of the paper is structured as follow: Section 2 discusses the literature. Section 3 discusses the method and data. Section 4 presents the results of the study. Section 5 concludes the study with some policy implications.

2. Literature review

2.1. Theoretical framework

Energy users seek to maximize value from energy services by improving efficiency, which involves maximizing output while minimizing energy input. Evaluating technical efficiency requires establishing a benchmark, observing the current state, and documenting the difference from the benchmark (Adom, 2019).

To illustrate this, consider Fig. 2, which depicts two crucial curves: the isoquant curve (**iq**) and the isocost curve (**ic**). The isoquant curve represents combinations of capital input (**k***) and energy input (**e***) that produce a specific level of output. The isocost curve represents combinations of inputs that cost the same. The intersection at point **q*** indicates the most efficient production point, optimizing both technical (minimizing inputs for a given output) and allocative efficiency (optimal input mix based on prices). Observations at point $\mathbf{q^1}$ reveal inefficiency, where the firm uses excessive inputs and fails to achieve the optimal mix of goods based on prices.

Focusing on technical efficiency, we use a normative benchmark represented by point $\mathbf{q^3}$. If production is observed at $\mathbf{q^1}$, the firm is technically inefficient. The degree of inefficiency at $\mathbf{q^1}$ can be assessed using Farrell (1957) input-oriented radial measure, which calculates the ratio of the distance from the origin to $\mathbf{q^0}$ to the distance from the origin to $\mathbf{q^1}$, and Kopp (1981) non-radial method, which compares optimal energy use ($\mathbf{kq^3}$) to observed energy use ($\mathbf{kq^1}$), considering the efficiency of each input individually. Enhancing efficiency from $\mathbf{q^1}$ to $\mathbf{q^3}$ involves reducing energy input from $\mathbf{e^1}$ to $\mathbf{e^0}$ while maintaining constant levels of other factors, such as technology and output. This is where energy policies come into play, influencing various elements of technical efficiency. These policies can enhance energy efficiency by setting standards (Beerepoot and Beerepoot, 2007), providing financial incentives such as grants and subsidies (Girod et al., 2017), promoting best practices (Castro Verdezoto et al., 2019), and funding research and development (Du et al., 2018). Energy policies can shift the isoquant and isocost curves. For example, regulations mandating energy efficiency can potentially shift the isoquant curve as firms adopt more efficient technologies, improving technical efficiency by reducing energy input from $\mathbf{e^1}$ to $\mathbf{e^0}$ and moving operations from $\mathbf{q^1}$ to $\mathbf{q^3}$.

However, the reverse is possible when policies do not have any impact or even negatively impact energy efficiency. For instance, if subsidies for efficient technologies are removed or if high transaction costs hinder policy effectiveness (Valentová et al., 2018), the isocost curve may shift unfavorably. Similarly, if there are delays in technological advancements or the adoption of energy-efficient practices, the isoquant curve may not shift as expected, resulting in sustained or even increased inefficiency at point $\mathbf{q^1}$.

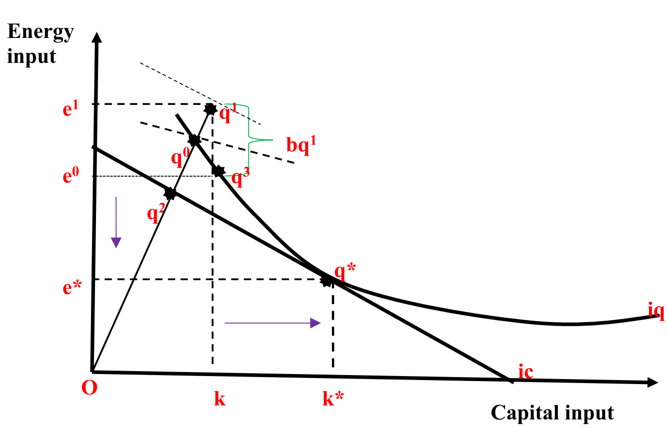

Fig. 2. Technical and allocative productive efficiency (Adom, 2019).

2.2. Related literature

Extensive academic research has investigated the impact of energy policies on energy efficiency across diverse industries and sectors. Beerepoot and Beerepoot (2007) examined how stringent energy regulations in the Dutch building sector spurred improvements in energy performance in the Netherlands. Fleiter et al. (2012) highlighted the efficacy of grants for energy audits in German SMEs, demonstrating significant energy savings, CO2 reductions, and cost-effectiveness. Lawrence et al. (2019) emphasized the success of Sweden's voluntary agreement program in reducing power consumption in energy-intensive industries. Valentová et al. (2018) identified high transaction costs as a barrier to the effectiveness of major energy efficiency subsidies in the Czech Republic. In China, Li et al. (2014) found that policies targeting energy efficiency in energy-intensive industries do not necessarily translate to proportional emissions reductions. Cao et al. (2016) evaluated the role of differentiated technology policies in promoting energy efficiency in Chinese heavy industries, while Napp et al. (2014) assessed the effectiveness of government initiatives in fostering the adoption of energy-saving technologies. Duc Luong (2015) reviewed the evolution of Vietnam's Energy Efficiency and Conservation policies, outlining challenges and offering recommendations for more effective implementation. Yang (2006) analyzed industrial energy efficiency regulations and investments in India, concluding that existing policies require enhancement to stimulate further investment and technological development in energy efficiency. Castro Verdezoto et al. (2019) conducted a bottom-up analysis of Ecuador's residential energy matrix and policy scenarios, providing insights into potential efficiency improvements.

There are also broader regional and comparative studies which offer valuable insights. For instance, Verma et al. (2018) conducted a comparative analysis of energy efficiency initiatives among OECD countries, specifically Iceland, Norway, and New Zealand, concluding that policy synchronization with technological advancements is crucial for improving energy efficiency. Noailly (2012) examined the building sector in seven OECD countries from 1989 to 2004, investigating the effects of energy standards, energy prices, and public energy R&D expenditures on patent activities. Girod et al. (2017) evaluated the impact of energy-efficiency policies on innovation in 21 European countries from 1980 to 2009, revealing a strong influence of policy types such as financial subsidies and energy labels. Filippini et al. (2014) assessed the energy efficiency of the EU residential sector and concluded that energy performance standards significantly promote efficiency improvements. Bertoldi and Mosconi (2020) noted that EU energy efficiency policies have led to substantial energy savings, with consumption estimated to be 11% higher in their absence. Aydin and Brounen (2019) examined the impact of specific policies on electricity and non-electricity energy consumption, focusing on mandatory energy efficiency labels for household appliances and building standards across Europe. Laes et al. (2018) reviewed the effectiveness of individual policies or policy packages for CO2 emission reduction and energy savings in the EU residential sector. In the United States, Croucher (2012) assessed the influence of energy efficiency standards on electricity usage. Du et al.

(2018) evaluated the impact of Chinese government-funded research initiatives on the country's energy efficiency, finding that research funding significantly reduces energy inefficiency. Bertoldi (2022) review existing policies in OECD countries and concludes that energy efficiency policies are necessary but not sufficient to reduce energy consumption. Mandel and Pató (2024) investigate the Energy Efficiency First (EE1st) principle in the EU and argue that achieving parity between energy efficiency and energy supply necessitates a comprehensive energy policy approach.

In general, research shows that energy policies significantly impact energy efficiency by setting standards (Aydin and Brounen, 2019; Beerepoot and Beerepoot, 2007), providing financial incentives like grants and subsidies (Fleiter et al., 2012; Girod et al., 2017), promoting best practices (Castro Verdezoto et al., 2019), and funding R&D (Du et al., 2018; Noailly, 2012). However, high transaction costs can hinder policy effectiveness (Valentová et al., 2018), and energy policies alone are insufficient to reduce energy consumption (Bertoldi, 2022).

Despite extensive research on the impacts of energy policies on energy efficiency, comprehensive studies focusing on the APAC region are scarce (Chen et al., 2022). Existing literature predominantly targets industrialized and developed economies, often overlooking the Global South. The APAC region, representing the most dynamic emerging market, accounts for 60% of global energy demand (United Nations, 2018). By 2035, it aims to reduce energy intensity by 45% from 2005 levels (APERC, 2019). The implementation and enforcement of relevant energy policies are deemed crucial to achieving these targets. Thus, recently, the APAC region has introduced several comprehensive energy policies, including building standards, tax and regulatory measures, information policies, energy certificates, energy efficiency labels for appliances, feedback programs, subsidies for energy-efficient renovations, and support for energy-efficient construction. However, the impact of these policies on regional energy efficiency remains largely unexplored.

Given the evolving energy and carbon emission landscape and the increasing adoption of energy policies in the APAC region, a holistic analysis is essential. Such an analysis can elucidate common trends, best practices, and potential pitfalls, thereby fostering international collaboration for more effective energy management in the region. Also, undertaking this research is critical as global energy markets become more integrated, and the collective responsibility to combat climate change intensifies.

Finally, these energy policies, regardless of their intended goals, can be categorized into three main types: laws, regulations, and strategies (Chen et al., 2022). "Laws" refer to legally binding requirements established via decree and enforced by the court system in line with national objectives. "Regulations" involve the creation of specific rules by the executive branch of government, often with mechanisms outside the legal framework for monitoring, enforcement, and penalties for non-compliance. "Strategies" provide a broad direction and set strategic objectives for energy development, typically including a plan for the coming years. The requirements, implementation techniques, and governance structures of these three policy types—laws, regulations, and strategies—differ significantly (Huhta, 2022). Consequently, their impacts on energy efficiency can vary, necessitating a detailed analysis to determine the specific effects of each policy type on energy efficiency in the region.

3. Methodology

3.1. The model specifications

The study's approach to energy efficiency estimation is theoretically based on framework of Kopp (1981). Kopp (1981) calculates technical efficiency by comparing actual input consumption to the minimum feasible input (benchmark) for a particular set of inputs. Building on Kopp (1981) work, Filippini and Hunt (2015) developed the economic basis for energy efficiency by proposing that energy is a derived demand, which means that rational agents strive to optimize energy services by identifying the optimal level of energy input. This decision-making process, like the standard production maximization theory, considers energy supplies and energy-consuming machinery as inputs from economic agents. As a result, following Filippini and Hunt (2011), we estimated energy efficiency using a non-radial input-specific method and conditional stochastic energy demand frontier (SEDF) with specific inputs. The conditional SEDF represented by Eq. (1), contains the minimal energy necessary for producing energy services in a country (c) at a given time (t) $[f(X_{ct};\beta)(e^{v_{ct}})]$ as well as the extent of divergence from this optimal utilization level $(e^{u_{ct}})$.

$$ED_{ct} = f(X_{ct};\beta)(e^{v_{ct}})(e^{u_{ct}}) \tag{1}$$

where, ED_{ct} represents energy demand, X_{ct} is the deterministic component of the equation/model comprising a set of variables – both exogenous and endogenous - within the frontier equation. β is a vector containing frontier parameters. The term v_{ct} represents a two-sided error that is expected to conform to a normal distribution, while u_{ct} quantifies the degree of divergence from the ideal or benchmark energy usage level. This deviation is represented unidirectional error term, precisely a half-normal distribution (Battese and Coelli, 1988).

3.2. Empirical considerations

Following the standard demand theory, we incorporate several factors into the vector X_{ct}. Specifically, the deterministic component of the equation is assumed to be dependent on energy price (P_{ct}) and income (Y_{ct}), as well as other factors such as service ($Serv_{ct}$) and Urbanization (Urb_{ct}) as key components, which captures important exogenous factors like technical and social issues. Urbanization captures the effect of demography on energy use. Changes in the economic structure of each country are captured by the share of value added from the service. Thus, Eq. (1) can be rewritten in log-log functional form as:

$$lnED_{ct} = \alpha + \beta_P lnP_{ct} + \beta_Y lnY_{ct} + \beta_S lnServ_{ct} + \beta_U lnUrb_{ct} + v_{ct} - u_{ct} \tag{2}$$

where, v_{ct} and u_{ct} are independent error terms which are not related to explanatory variables. v_{ct} is a symmetric disturbance with a normal distribution and u_{ct} represents underlying energy efficiency, modeled as a half-normal, one-sided, non-negative random disturbance (Aigner et al., 1977).

It is common practice in SFA models to estimate the underlying amount of energy inefficiency as a function of explanatory variables. Instead of the two-stage method, where inefficiency indices are predicted first and then regressed on environmental factors, we follow a one-stage approach. This method, recommended by Battese and Coelli (1995), allows us to explain inefficiency effects u_{ct} concurrently with a set of environmental factors. In this study, we concentrate on energy policies. Accordingly, we express the inefficiency equation as a function of energy policy in Eq. (3).

$$u_{ct} = g(\gamma, EP_{ct}) \tag{3}$$

where, γ is a constant term that captures the baseline level of inefficiency when the effect of energy policies is zero and EP_{ct} is the aggregate measure of energy policies, encompassing various policy types and their overall effect.

To address the issue of endogeneity in the frontier, we follow the approach of Karakaplan and Kutlu (2017) and Adom et al. (2023). Recognizing the data quality challenges in the income data of developing economies, where informal economies are prevalent, we acknowledge the risk of inaccuracies in national income reporting. This could lead to biases in the income elasticity of the frontier equation. To address this, we use life expectancy at birth as an instrumental variable for real GDP per capita in the frontier equation. Higher life expectancy can impact income in various ways [see Adom et al., 2023 for details]. To validate life expectancy as an instrumental variable, we employ a pseudo-regression method. This involves conducting a regression with total energy consumption, economic growth (i.e., GDP), and urbanization, economic structure (i.e., service sector), energy price, and life expectancy, while setting the life expectancy coefficient to zero. Non-rejection of the null hypothesis indicates that the exclusion restriction is satisfied.

Furthermore, it is essential to determine the suitability of using a stochastic frontier function and the statistical significance of inefficiency among the sampled countries before applying an SFA estimator. To evaluate this, we use the Coelli (1995) skewness test on the residuals obtained from the Ordinary Least Squares (OLS) method. According to Schmidt and Lin (1984), in a production-type SFA, the OLS residuals should exhibit negative skewness, whereas in a cost-type SFA, the distribution should be positively skewed.

3.3. Data Processing

This section outlines the data utilized in our empirical analysis, which examines 23 countries in the Asia-Pacific (APAC) region over the period from 2000 to 2017 (refer to Table A1 for the list of countries).[2] Our data processing involves two main equations: the demand frontier equation and the inefficiency equation. The demand frontier equation models total energy consumption as the dependent variable, with energy price, income, and other relevant factors serving as control variables. In the inefficiency equation, the dependent variable is the energy inefficiency estimates derived from the demand frontier equation. The independent variables in this equation is the aggregate energy policies.

3.3.1. Demand frontier equation

1. Dependent variable

- Total energy consumption

To estimate the energy demand frontier, we utilized total energy consumption as our dependent variable. This data was sourced from the US Energy Information Administration (EIA) and subsequently transformed into the natural logarithm of Quadrillion Btu (British thermal units).

2. Independent/Control variables

- Energy price

Energy prices shape global energy consumption, production and investments. According to demand theory, higher energy prices typically reduce demand due to increased focus on efficiency. Therefore, we expect energy price to reduce energy demand. However, without specific energy price data for our sampled countries, we adjusted crude oil prices based on each country's consumer price index, following Doytch and Narayan (2016) and Sun et al. (2021) using the BP Statistical Review data.

- Gross domestic product (GDP)

There is a strong connection between economic growth and energy use. But, researchers disagree on how economic growth affects energy efficiency. It can lead to technological advances and improved efficiency, but also increased consumption and production. Thus, economic growth may impact energy efficiency positively or negatively. To explore this, we use data from the – World Development Indicators (WDI) of the World Bank.

- Share of Service

To assess the impact of economic structure on energy efficiency, we hypothesize that a shift towards a less energy-intensive production structure will reduce energy demand and improve efficiency. We measure this by the service sector's share of GDP, expecting countries with larger service sectors to consume less energy than those dominated by industry. Thus, we anticipate a negative relationship between the service sector and energy demand. Data for this variable are sourced from the WDI.

- Urbanization

The effect of urbanization on energy demand is unclear, with potential for both positive and negative impacts. In this study, we expect a positive relationship between urban growth and energy demand. Rapid urbanization tends to increase energy consumption, as meeting the growing demands often requires expanding or creating new facilities, leading to higher energy intensity. These data are sourced from the WDI.

3.3.2. Inefficiency equation

1. Dependent variable

- Efficiency Inefficiency

Here, our dependent variable is energy inefficiency, which is derived from the energy demand frontier equation. This estimation allows us to quantify the degree of inefficiency in energy use relative to the optimal energy demand.

2. Independent variables/variable of interest

- Energy policy

For this study, energy policy data were sourced from Chen et al. (2022), utilizing the Asia Pacific Energy Portal policy database. These policies were categorized into three main types: Laws, Regulations, and Strategies. Laws, identified as acts or legislative measures, provide the legal framework for energy policy, establishing binding requirements and standards. Regulations, identified as rules or guidelines, offer detailed instructions on implementing these laws, including specific compliance mechanisms and enforcement measures. Strategies, identified as strategic plans or policies, outline long-term goals and approaches to achieve energy efficiency and sustainability. Policies not falling into these categories were grouped under 'others,' encompassing all other forms of energy policies. We hypothesize that the implementation of these energy policies will improve energy efficiency, given their role in providing a structured approach to managing energy consumption and promoting sustainable practices. Summary of the definition of the variables and sources are presented in Table 1. Table A2 in the Appendix presents the correlation matrix of the variables.

4. Results and discussion

This section is organized as follows: We begin by discussing the preliminary test results that justify the use of the SFA model. Next, we examine how aggregate energy policy affects energy efficiency using both exogenous and endogenous SFA models. Within this exploration, we discuss the determinants at the frontier and the expected energy efficiency as a result of this analysis. Following this, we analyze the impact of different types of energy policies on energy efficiency. The results are subsequently subjected to a series of robustness tests. Finally, we estimate the potential energy savings that could be realized through

[2] The selection of countries and years are based on data availability.

Table 1
Data, source and descriptive statistics.

Variable	Definition	Source
lnED	Log of total energy usage in Btu	The US EIA
lnP	Log of deflated crude oil to the country's consumer price index.	BP Statistics of World Review and PWT.
lnY	Log of GDP per capita in constant 2011 prices	WDI
lnServ	Log of service value added as a percentage of GDP	WDI
lnUrb	Log of urban population measured as percentage of total population	WDI
lnEnergy_Policies	Log of aggregate energy policies	APEPPD
lnEnergy_Laws	Log of energy laws	APEPPD
lnEnergy_Reg	Log of energy regulations	APEPPD
lnEnergy_Strategies	Log of energy strategies or plans	APEPPD
lnEnergy_Others	Log of other energy policies	APEPPD

Note: WDI – World Development Indicators of the World Bank; APEPPD – Asia Pacific Energy Portal Policy database; PWT – Penn World Tables.

enhanced energy policy implementation.

4.1. *Results from preliminary tests*

Before utilizing the SFA model, we conducted preliminary tests to ensure its appropriateness. We tested the statistical significance of inefficiency within the sampled countries using the Coelli (1995) skewness test on the residuals generated by the conventional least squares method. Our findings revealed a skewness score of −0.215 and an estimated statistic of −2.736. Based on the Schmidt and Lin (1984), skewness interpretation criteria, we rejected the null hypothesis of no skewness in favor of the alternative hypothesis. This indicates that the SFA model is of the production type, with the residual distribution exhibiting negative skewness.

4.2. *The relationship between aggregate energy policy and energy inefficiency*

In this section, we use the translog production function to assess the influence of aggregate energy policies on energy inefficiency. The translog function was selected for its ability to capture complex relationships, including nonlinearity, structural regime shifts, and variable interactions (Christensen et al., 1973).[3] The results are presented in Table 2, where Column 1 represents the baseline result under the assumption of exogeneity in the frontier. Column 2 (the final model) incorporates life expectancy at birth to address potential endogeneity concerns related to the income variable in the frontier equation. The endogeneity test indicated the need to correct for the endogeneity of the income variable. The F-test results in the pseudo-regression (see Table 2, bottom) support the validity of the exclusion constraints and confirm the relevance of life expectancy at birth in the frontier equation.

4.2.1. *Frontier equation*

In the frontier equation, higher income and urbanization levels show a positive correlation with energy inefficiency, indicating that increased income and urbanization are associated with greater energy consumption or inefficiency. This finding aligns with previous studies by Filippini and Hunt (2011), Filippini and Zhang (2016) and Sun et al. (2021). Although the squared of income is statistically insignificant, the squared term of urbanization reveals a turning point where increased urbanization can reduce inefficiency. Similarly, the squared terms of price and service are statistically significant, consistent with research by Marin and Palma (2017) and Adom et al. (2023). The interaction between income and price, as well as income and service, is negative and statistically insignificant. However, the interaction between income and urbanization reveals that higher income leads to greater inefficiency in more urbanized areas. Additionally, the interactions between price and service, and price and urbanization, are both positive and significant, while the relationship between service and urbanization is negative but statistically insignificant.

Table 2
Effects of aggregate energy policies on energy inefficiency.

	(1)		(2)	
Variables	EX		EN	
Frontier Equation Dependent variable: ln (Energy)				
Constant	2.327***	(0.204)	2.300***	(0.166)
lnGDP	0.197***	(0.0553)	0.483***	(0.106)
lnP	−0.0848***	(0.0326)	−0.288***	(0.0762)
lnServ	−0.455	(0.294)	−0.585*	(0.350)
lnUrban	0.862***	(0.102)	0.863***	(0.102)
$lnGDP^2$	−0.0404	(0.0411)	0.0770	(0.0587)
lnP^2	−0.0140	(0.0569)	−0.0909	(0.0742)
$lnServ^2$	−0.201	(0.456)	0.0688	(0.554)
$lnUrban^2$	−0.0997***	(0.0296)	−0.0997***	(0.0362)
lnGDP*lnP	0.0148	(0.0583)	−0.0429	(0.0687)
lnGDP*lnServ	0.157	(0.194)	−0.326	(0.269)
lnGDP*lnUrban	0.0282	(0.0426)	0.206***	(0.0707)
lnP*lnServ	0.134	(0.231)	0.536*	(0.294)
lnP*lnUrban	0.00391	(0.0249)	−0.100**	(0.0439)
lnServ*lnUrban	−0.0465	(0.171)	−0.297	(0.298)
Inefficiency Equation Dependent variable: Energy inefficiency				
Constant	1.171***	(0.349)	1.122***	(0.338)
lnEnergy Policies	−0.151***	(0.0310)	−0.158***	(0.0300)
eta1 (GDP)			−0.309**	(0.101)
eta Endogeneity Test			X2 = 9.36	p = 002
F-test exclusion restriction			0.2889	
LL	64.81		−159.75	
Mean EE	0.38		0.39	
Median EE	0.312		0.318	
Observations	414		414	

Note: The frontier equation presents the factors that drives energy consumption. The inefficiency equation examines factors that influences inefficiency in energy consumption, and energy inefficiency is the dependent variable. Table 3 makes the assumption that there is no endogeneity present in the frontier equations. The bottom section of the table shows results on the instrument validity test and average estimate of energy efficiency (EE). Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.2.2. *Inefficiency equation*

The second section of Table 2 presents the impact of aggregate energy policies on energy inefficiency. The relationship between aggregate energy policies and energy inefficiency is consistent in both exogenous (baseline) and endogenous (final) regression models. In the exogenous model, the energy policies coefficient is −0.151, indicating that more stringent energy policies reduce energy inefficiency. This negative relationship is validated in the endogenous model, with an energy policy coefficient of −0.158, supporting the hypothesis that greater energy stringency leads to less energy inefficiency. This finding aligns with Azhgaliyeva et al. (2020), who found that energy policies reduce energy intensity in 44 non-OECD countries, but contradicts Bertoldi (2022), who argued that energy policies alone are insufficient to improve energy efficiency in OECD countries.

Our research highlights the substantial efficiency improvements that

[3] The translog production function may be inappropriate in light of (i) multicollinearity issues and (ii) the possibility of misidentifying the actual technology. To address these concerns, we first calculated VIFs (refer to Table A3). No substantial multicollinearity issues were identified, indicating that the variables are reasonably independent of one another. Furthermore, to ensure that we have correctly identified the true technology, we also employ the Cobb-Douglas function in the robustness check section.

can be achieved through well-designed and effectively implemented energy policies in the APAC region. This region has experienced significant economic progress in recent decades, increasing energy usage and raising environmental concerns (Baloch et al., 2021). Previous research suggests that robust energy policies are essential for achieving the 1.5 °C target (IPCC, 2018), and improving energy efficiency could help cut emissions by up to 50% to meet the Paris Agreement targets (IEA, 2019). Over the past 20 years, the APAC region has adopted numerous energy policies, with countries like India, Vietnam, the Philippines, and Thailand implementing about 232, 200, 193, and 101 energy policies, respectively (Chen et al., 2022). This commitment demonstrates the region's dedication to balancing economic growth with environmental protection.

4.2.3. *Energy efficiency*

Building on the estimates above, we extended our approach to compute energy efficiency using both exogenous and endogenous models. The results, depicted in Fig. 3, illustrate the trend in energy efficiency performance, with the endogenous model represented in blue and the exogenous model in red. The graph reveals that energy efficiency derived from the endogenous model is marginally higher than that from the exogenous model, with average energy efficiencies of 0.39 and 0.38, respectively. Over the examined period, energy efficiency has shown noticeable improvement, yet the average efficiency level remains below the optimal threshold of one. Economically, these findings suggest that while progress in energy efficiency has been made, significant potential for improvement remains. The slightly higher efficiency in the endogenous model may suggest that directly accounting for policy impacts within the efficiency equation captures their influence more effectively than the exogenous model. Our results are consistent with Zhang and Chen (2022), who reported an overall energy efficiency of 0.384, with higher efficiency in China and Japan and lower efficiency in Brunei and Cambodia. Similarly, Adetutu et al. (2016) found that countries in the APAC region generally exhibit low levels of energy efficiency. The consistency of our results with previous studies strengthens the validity of our approach, reinforcing the notion that while energy efficiency is improving in the APAC region, significant challenges remain. Thus, there is the need for continued policy focus and innovation to bridge the gap towards optimal energy efficiency levels.

The region's energy efficiency challenges can be attributed to a delayed focus on efficiency during the energy transition phase. According to Yang et al. (2020), in APAC, the ongoing energy transition has prioritized energy access over efficiency. Moreover, the policy framework for promoting energy efficiency remains inadequate. Despite recent policy advancements, only a handful of economies—such as India, China, Vietnam, the Philippines, and Thailand—have developed mature policies and regulatory systems to support energy efficiency.

In general, our analysis indicates that achieving an optimal energy efficiency rating of one could potentially result in energy savings of approximately 61%. This substantial figure highlights the significant opportunity for future improvements in energy efficiency within the region. Enhanced policy measures and a greater focus on efficiency could drive substantial gains, contributing to both economic growth and environmental sustainability.

4.3. *The relationship between energy policy types and energy efficiency*

Thus far, our focus has been on evaluating the effects of aggregate energy policies. However, these policies can take various forms, such as laws, regulations, plans, and other forms, each with its own criteria, methods of execution, and governance structures (Chen et al., 2022). Their impact on energy efficiency can vary significantly. For instance, laws impose strict standards, regulations use compliance mechanisms, and strategies promote collaboration. As a result, there are differences in the effectiveness of these policies and their effects on energy efficiency. To gain deeper insights, we will examine these categorized policies to understand the precise impact of each type on energy efficiency in the region.

Table 3 presents the endogenous model, illustrating the effect of various policy categories on energy efficiency. The use of endogenous SFA is supported by the results of the eta endogeneity test, presented at the bottom of Table 3. Income estimation using life expectancy at birth remains a suitable instrument in the frontier equation. Similar to Table 2, the regression outcomes for the frontier equation indicate a positive and statistically significant relationship between income, urban characteristics and energy consumption. This implies that as urbanization and income increase, so does energy consumption. Furthermore, a statistically significant inverse relationship is observed between energy consumption and service costs. The examination of squared and interaction terms reveals discrepancies across results for model (1), (2), (3)

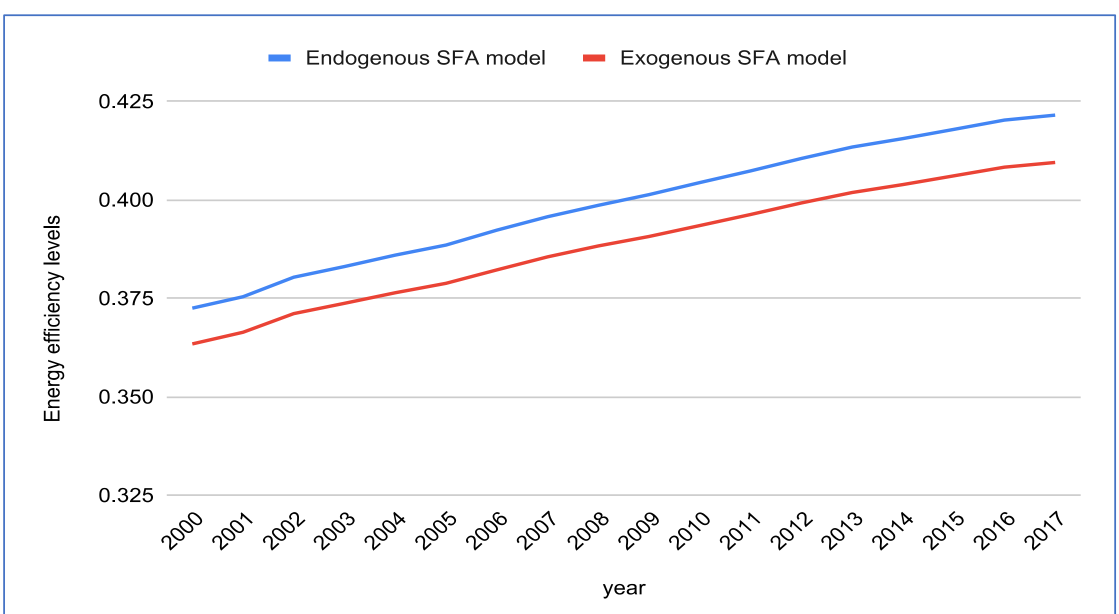

Fig. 3. Plot of the average annual energy efficiency (2000–2017).

Table 3
Endogenous SFA.

	Model (1)	Model (2)	Model (3)	Model (4)
Variables	Energy Laws	Energy Regulations	Energy Plans	Others energy Policies
Frontier Equation Dependent variable: ln(Energy)				
Constant	2.348***	1.544***	2.802***	2.504***
	(0.199)	(0.0727)	(0.216)	(0.203)
lnGDP	0.617***	0.364***	0.803***	0.502***
	(0.119)	(0.0589)	(0.142)	(0.101)
lnP	−0.362***	−0.149***	−0.457***	−0.325***
	(0.0880)	(0.0428)	(0.109)	(0.0742)
lnServ	−1.046***	−0.270	−1.057**	−0.494
	(0.388)	(0.308)	(0.455)	(0.348)
lnUrban	0.847***	0.858***	0.845***	0.962***
	(0.138)	(0.0553)	(0.0712)	(0.101)
$lnGDP^2$	0.0708	−0.187***	0.0847	0.0819
	(0.0765)	(0.0507)	(0.0986)	(0.0596)
lnP^2	−0.181*	−0.275***	−0.367***	−0.0782
	(0.103)	(0.0830)	(0.141)	(0.0811)
$lnServ^2$	−0.519	0.272	0.391	0.00805
	(0.669)	(0.658)	(0.834)	(0.566)
$lnUrban^2$	−0.0549	−0.0183	−0.144***	−0.0793***
	(0.0589)	(0.0232)	(0.0354)	(0.0304)
lnGDP*lnP	−0.0384	0.215***	0.00327	−0.0434
	(0.0888)	(0.0754)	(0.112)	(0.0734)
lnGDP*lnServ	−0.161	0.709**	−0.680	−0.365
	(0.336)	(0.333)	(0.478)	(0.289)
lnGDP*lnUrban	0.253***	0.0460	0.477***	0.213***
	(0.0907)	(0.0507)	(0.103)	(0.0709)
lnP*lnServ	0.626*	−0.341	0.434	0.544
	(0.366)	(0.364)	(0.559)	(0.331)
lnP*lnUrban	−0.163***	−0.0517	−0.214***	−0.128***
	(0.0587)	(0.0322)	(0.0690)	(0.0472)
lnServ*lnUrban	−0.643**	−0.184	−0.738**	−0.206
	(0.312)	(0.285)	(0.316)	(0.215)
Inefficiency Equation Dependent variable: Energy inefficiency				
Constant	0.910***	−0.588	1.126***	1.112***
	(0.333)	(0.399)	(0.350)	(0.344)
lnEnergy_Laws	−0.0960**			
	(0.0435)			
lnEnergy_Regulations		0.0366		
		(0.100)		
lnEnergy_Strategies			−0.0867***	
			(0.0281)	
lnEnergy_Others				−0.135***
				(0.0294)
eta1_lnGDP	−0.0960**	−0.254***	−0.661***	−0.381***
	(0.0435)	(0.0758)	(0.145)	(0.0982)
eta Endogeneity Test	16.61***	11.23***	20.76***	15.09***
F-test exclusion restriction	0.2889	0.2889	0.2889	0.2889
LL	−174.11	−3.76	−134.35	−144.59
Mean EE	0.3307	0.625	0.324	0.3583
Median EE	0.2802	0.6101	0.2229	0.3042
Observations	397	217	310	388

Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

and (4).

Now, focusing on the main topic of the inquiry: for energy laws, we find a statistically significant negative coefficient of −0.096. This implies a decrease of 0.096 in energy inefficiency for each incremental increase in the implementation of energy legislation, emphasizing the critical role of energy laws in improving energy efficiency in the APAC region. This finding is consistent with Huhta (2022), who asserts that the enforcement of energy legislation is essential to enhancing energy efficiency and transitioning to alternative energy sources. On the other hand, the results for energy regulations reveal a coefficient of 0.0366 and is statistical insignificant. This suggests that regulatory measures do not significantly reduce energy inefficiency. This result may stem from the inadequate regulatory framework and the dynamic nature of the energy market in APAC. These findings align with the 2020 RISE report and Drago and Gatto (2022), which show that low-income countries often lack the necessary rules and regulations to maintain and improve energy efficiency. This suggests that the regional regulatory framework needs to be updated, and regulatory agencies and involved parties must become more proactive and transparent (Brown et al., 2006).

For energy strategies, the coefficient is negative and statistically significant, indicating that a 1 % increase in energy strategies improves energy efficiency by 0.0867%. Our results are in line with Townshend et al. (2013), who show that strategies or policies have a stronger effect on energy intensities than regulations. This is why several countries, especially in Southeast Asia, have pursued medium and long-term energy transition plans and strategies (ADB, 2013; Eskander et al., 2021). Finally, other energy policies yield a statistically significant negative coefficient of −0.135, indicating a strong positive relationship between energy efficiency and the implementation of other energy policies not explicitly categorized as laws, regulations, or strategies. This finding highlights the potential impact of various energy policy efforts on improving energy efficiency.

In summary, our analysis reveals that the enforcement of energy laws and the implementation of strategic plans is associated with a reduction in technical inefficiency in energy consumption. However, regulations show no discernible impact on energy efficiency. Additionally, the presence of other diverse energy policies significantly contributes to reducing energy inefficiencies. These findings highlight the importance of adopting comprehensive and well-crafted energy policies that incorporate a variety of policy instruments particularly laws and strategic plans. Such measures are crucial not only for improving energy efficiency but also for fostering sustainable economic growth across the Asia-Pacific region.

4.4. Robustness checks

The findings from the preceding section highlight the significant role of energy policies in addressing energy inefficiency across the APAC region. In this section, we conduct a series of robustness tests to substantiate these findings. These tests involve employing alternative measures of energy efficiency, examining the effects of energy policies over different timeframes, and switching from a translog functional form to a Cobb-Douglas (CD) specification.

4.4.1. Changing the production function

The choice of production functional form has a direct bearing on the energy efficiency estimate. Up to this point, we have favored the translog production function for its flexibility since it may be seen as a second Taylor approximation to any unknown functional form (Coelli, 1995). However, understanding the true technological framework is crucial. If the underlying technology indeed follows a Cobb-Douglas (CD) form, coefficient estimates in the translog model may be biased. As part of our robustness checks, we re-estimated the model using the CD production function to address this concern.

Table 4 presents the results from this alternative specification. The findings corroborate our earlier observations. Specifically, they indicate a substantial relationship between adherence to energy laws and policies and reduced energy inefficiency (coefficients: −0.135 and − 0.0720, respectively). The relationship with energy regulations shows a positive direction, but statistically insignificant coefficient. However, increased implementation of energy plans is associated with lower inefficiencies (coefficient: −0.0750). Furthermore, “other” types of energy policies also contribute significantly to reducing inefficiency (coefficient: −0.121).

Table 4
Results from CD Production function.

Variables	(1) Energy Policies	(2) Energy Laws	(3) Energy Regulations	(4) Energy Plans	(5) Energy Others
Frontier Equation					
Dependent variable: Energy					
Constant	2.452***	2.496***	1.525***	2.524***	2.502***
	(0.126)	(0.154)	(0.0745)	(0.198)	(0.143)
lnGDP	0.326***	0.446***	0.434***	0.526***	0.368***
	(0.0571)	(0.0491)	(0.0512)	(0.0649)	(0.0587)
lnP	−0.209***	−0.232***	−0.137***	−0.264***	−0.244***
	(0.0445)	(0.0417)	(0.0339)	(0.0553)	(0.0471)
lnServ	−0.260**	−0.272**	−0.389**	−0.434***	−0.275**
	(0.111)	(0.132)	(0.165)	(0.156)	(0.119)
lnUrban	0.995***	0.948***	0.915***	0.977***	1.005***
	(0.0552)	(0.0790)	(0.0229)	(0.0852)	(0.0622)
Inefficiency Equation					
Dependent variable: Energy inefficiency					
Constant	1.317***	1.067***	−0.580	0.975***	1.212***
	(0.315)	(0.314)	(0.401)	(0.329)	(0.312)
lnEnergy_Policies	−0.135***				
	(0.0242)				
lnEnergy_Laws		−0.0720**			
		(0.0360)			
lnEnergy_Reg			0.0424		
			(0.123)		
lnEnergy_Strategies				−0.0750***	
				(0.0274)	
lnEnergy_Other					−0.121***
					(0.0227)
eta1_lnGDP	−0.213***	−0.341***	−0.190***	−0.368***	−0.270***
	(0.0625)	(0.0648)	(0.0615)	(0.0756)	(0.0646)
eta Endogeneity Test	11.65***	27.61***	9.57***	23.76***	17.42***
F-test exclusion restriction	0.2889	0.2889	0.2889	0.2889	0.2889
LL	−325.32	−326.95	−78.01	−266.96	−313.95
Mean EE	0.3143	0.2813	0.5900	0.2781	0.3115
Median EE	0.2462	0.2083	0.5594	0.2373	0.2446
Observations	414	397	217	310	388

Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.4.2. Decomposing the effects of energy policy across different time-horizons

Next, we explore the relationship between energy policies and energy inefficiency across different time horizons (Table 5). The first results, represented in the first column, indicate that over a two-year average, a 1% increase in energy policies correlates with a 0.159% decrease in energy inefficiency. This suggests that energy policies exert an immediate and noticeable impact on reducing inefficiencies within a shorter timeframe.

Moving to the second column, a statistically significant negative coefficient observed over a four-year average further reinforces the notion that decreasing energy inefficiency is associated with sustained improvements in energy policies. This suggests a longer-lasting influence and emphasizes the possible medium-term cumulative impact of energy policies (Azhgaliyeva et al., 2020).

In the third column, extending our analysis to a six-year average reveals a negative coefficient, albeit not statistically significant. This longer timeframe introduces complexities such as evolving policy landscapes, external influences, and cumulative effects, making it challenging to pinpoint a precise and consistent relationship. In summary, our findings indicate that energy policies can lead to significant reductions in inefficiency over both short and medium-term periods.

4.4.3. Using energy intensity as an alternative measure for energy efficiency

So far, our analysis has focused on energy inefficiency as the dependent variable. To bolster the robustness of our findings, we now introduce an alternative measure—specifically, energy intensity. This serves to validate our results and offers additional insights into the impact of aggregate energy policies. Energy intensity allows us to quantitatively assess the effectiveness of these policies by calculating the percentage change in average energy efficiency, comparing scenarios with and without these policies.

Table 6 presents the results. Like in (Chen et al., 2022) the findings in column (1) reveal a significant negative coefficient indicating a strong relationship between aggregate energy policies and energy intensity. This suggests that higher emphasis on energy policies correlates with reduced energy intensity. However, interpreting the effects of specific policy categories—laws, regulations, and plans—on energy intensity is challenging due to statistically insignificant coefficients observed for these policy types. However, coefficients associated with "other" energy policies demonstrate a statistically significant negative relationship with energy intensity.

Utilizing the estimated impact of aggregate energy policies from the first column, we computed the counterfactual effect based on our regression results. Fig. 4 illustrates the comparison of energy intensity levels in the APAC region with and without energy policies. The blue bar represents energy intensity levels with policies in place, while the red bar represents levels without policies. Over time, energy intensity decreases in both scenarios, yet significantly more so—by at least 14%—when energy policies are implemented (as indicated by the blue bar). This reduction highlights the effectiveness of energy policies in the APAC region.

4.4.4. Using energy efficiency measures that address both short- and long-term inefficiencies

Furthermore, our calculation of energy efficiency may be biased due to the inability to distinguish between transient (short-run) and persistent (long-run) inefficiencies, as well as accounting for unobserved

Table 5
Endogenous SFA results for varying time span.

	(1)	(2)	(3)
Variables	2-year average	4-year average	6-year average
Frontier Equation			
Dependent variable: Energy			
Constant	2.206***	2.124***	2.079***
	(0.109)	(0.148)	(0.182)
lnGDP	0.541***	0.541**	0.888***
	(0.137)	(0.251)	(0.331)
lnP	−0.347***	−0.445	−0.894*
	(0.122)	(0.305)	(0.484)
lnServ	−0.498	−0.124	−0.319
	(0.482)	(0.831)	(1.008)
lnUrban	0.814***	0.813***	0.954***
	(0.0599)	(0.105)	(0.126)
$lnGDP^2$	0.0627	0.0840	0.0538
	(0.0838)	(0.146)	(0.185)
lnP^2	−0.166	−0.318	−0.742
	(0.133)	(0.293)	(0.650)
$lnServ^2$	0.206	1.413	1.553
	(0.839)	(1.580)	(2.206)
$lnUrban^2$	−0.110***	−0.0954**	−0.0436
	(0.0263)	(0.0443)	(0.0517)
lnGDP*lnP	−0.00881	−0.0715	0.0385
	(0.104)	(0.221)	(0.285)
lnGDP*lnServ	−0.342	0.376	−0.186
	(0.435)	(0.719)	(1.311)
lnGDP*lnUrban	0.228**	0.157	0.307
	(0.0908)	(0.172)	(0.229)
lnP*lnServ	0.637	0.199	1.788
	(0.497)	(0.956)	(1.795)
lnP*lnUrban	−0.112	−0.0733	−0.255
	(0.0689)	(0.141)	(0.235)
lnServ*lnUrban	−0.252	−0.147	0.000543
	(0.391)	(0.642)	(0.565)
Inefficiency Equation			
Dependent variable: Energy inefficiency			
Constant	1.009***	0.924**	0.329
	(0.349)	(0.410)	(0.629)
lnEnergy_Policies	−0.159***	−0.170**	−0.119
	(0.0428)	(0.0769)	(0.128)
eta1_lnGDP	−0.337**	−0.319	−0.586*
	(0.144)	(0.227)	(0.319)
eta Endogeneity Test	5.47**	1.97	
F-test exclusion restriction	0.2889	0.2889	0.2889
LL	−96.79	−37.64	−42.77
Mean EE	0.4246	0.4324	0.4977
Median EE	0.3287	0.3475	0.4058
Observations	207	92	69

Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

heterogeneity. To address this limitation, we employ a methodology proposed by Kumbhakar et al. (2014) that separate unobserved heterogeneities while distinguishing transitory from persistent inefficiency.

The results presented in Table 7A reveal a relatively low overall energy efficiency level estimated at 0.349 for the APAC region which is close to what was estimated earlier. Interestingly, the energy efficiency estimate from the endogenous SFA model shows a strong association of about 61% with persistent inefficiency, while demonstrating a weaker correlation with transient inefficiency. This suggests that, similar to many emerging regions, energy efficiency in the region is primarily influenced by persistent inefficiencies (Adom, 2019).

To ensure the robustness of our findings, we use total energy efficiency, encompassing both transient and persistent components to investigate the impact of aggregate energy policies. As depicted in Table 7B, our findings indicate a robust and positive relationship between aggregate energy policies and total energy efficiency, implying that increased emphasis on energy policies corresponds to higher energy efficiency. However, specific policy types—laws, regulations, and strategies—appear to lack discernible effects on overall energy efficiency.

4.5. Energy conservation potential

From Table 2, the primary findings of our study indicate that aggregate energy policies contribute to improving energy efficiency by an average increase of 0.158%. Given the increasing importance of energy conservation, we went ahead to quantify the potential energy savings achievable through more comprehensive energy policy implementation. Thus, we explore the potential for energy conservation by estimating the energy savings that could result from optimizing the level of energy policies.

To illustrate this, we follow Xu et al. (2022) and first compute the actual energy efficiency in each country for every year, represented by EE_{ct}, where "c" represents each country and "t" represents each year. Then, we compute the average regional energy efficiency for each year ($EE_{regiont}$) using the formula (Xu et al., 2022): $EE_{regiont} = \frac{\sum_c (EE_{ct} * E_{ct})}{\sum_c E_{ct}}$.

Second, we assume a scenario where every country optimizes its energy policies for maximum effectiveness (i.e. optimal energy policy degree), leading to enhanced energy efficiency across all countries in the years. We went on to compute the counterfactual optimal energy efficiency using the optimal adoption of energy policy. This is denoted by $EE_{ct}^{counter}$. We calculate the optimal regional energy efficiency with the counterfactual optimal energy efficiency, using the formula (Xu et al., 2022): $EE_{regiont}^{counter} = \frac{\sum_c (EE_{ct}^{counter} * E_{ct})}{\sum_c E_{ct}}$, where, E_{ct} is the energy consumption of country "c" in year "t". Finally, we compute the potential energy conservation when we optimize the adoption of energy policy using the formula (Xu et al., 2022): $Ene_{conservationt} = \left(EE_{regionnt}^{counter} - EE_{regiont}\right) * E_{regiont}$.

Fig. 5 illustrates our findings. The red bar depicts potential conservation assuming all countries achieve optimal energy efficiency of 1. The blue bar represents potential energy conservation achieved by optimizing energy policies. The potential energy savings resulting from optimizing energy policies increased from 0.9 quadrillion Btu in 2000 to 2.2 quadrillion Btu in 2017, averaging 0.15 quadrillion Btu annually. These results suggest that implementing energy policies represents a feasible strategy for enhancing energy efficiency and promoting conservation in the APAC.

5. Conclusion

The APAC region has witnessed substantial economic growth over the past three decades, lifting millions out of poverty. Establishing an affordable and sustainable energy system is critical to sustaining this development, particularly given the region's increasing energy demands. Energy efficiency stands out as a key strategy to alleviate this pressure. In response, various energy-related policies and programs—including laws, regulations, and strategic action plans—have been implemented. However, understanding their impact on energy efficiency remains crucial. This study employs the endogenous Stochastic Frontier Analysis (SFA) model to examine how different types of energy policies—such as laws, strategies, regulations, and other forms—affect energy efficiency. The outcomes are as follows:

First, aggregate energy policies contribute to an average improvement in energy efficiency by 0.158%. This highlights the significance of effectively implementing a mix of energy policies to achieve energy efficiency goals, combat energy poverty, and advance Sustainable Development Goal 7.3.

Second, a comprehensive analysis of various energy policies show that a 1% increase in laws correlates with a 0.096% decrease in inefficiency, while strategies and "other" policy types show reductions of 0.0867% and 0.135%, respectively. However, regulations demonstrate minimal influence on energy efficiency.

Table 6
Using energy intensity as dependent variable.

	(1)	(2)	(3)	(4)	(5)
Dependent Variable: Energy intensity					
lnEnergy_Policies	−0.0572***				
	(0.0206)				
lnEnergy_Laws		0.00611			
		(0.0233)			
lnEnergy_Reg			0.00888		
			(0.0306)		
lnEnergy_Plan				−0.0314	
				(0.0291)	
lnEnergy_Other					−0.0480***
					(0.0151)
lnGDP	0.0360	0.0342	−0.157***	0.0291	0.0457*
	(0.0230)	(0.0232)	(0.0236)	(0.0255)	(0.0233)
lnP	−0.201***	−0.234***	−0.112***	−0.208***	−0.239***
	(0.0444)	(0.0404)	(0.0372)	(0.0443)	(0.0449)
lnServ	−1.382***	−1.268***	−0.654***	−1.050***	−1.254***
	(0.146)	(0.135)	(0.145)	(0.160)	(0.150)
lnUrban	−0.0132	−0.0270***	−0.0859***	−0.0357***	−0.0229**
	(0.00989)	(0.0103)	(0.0133)	(0.0101)	(0.00899)
Constant	1.860***	1.634***	1.527***	1.661***	1.800***
	(0.0821)	(0.0504)	(0.0689)	(0.0595)	(0.0524)
Observations	414	397	217	310	388
R-squared	0.424	0.397	0.456	0.344	0.408

Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

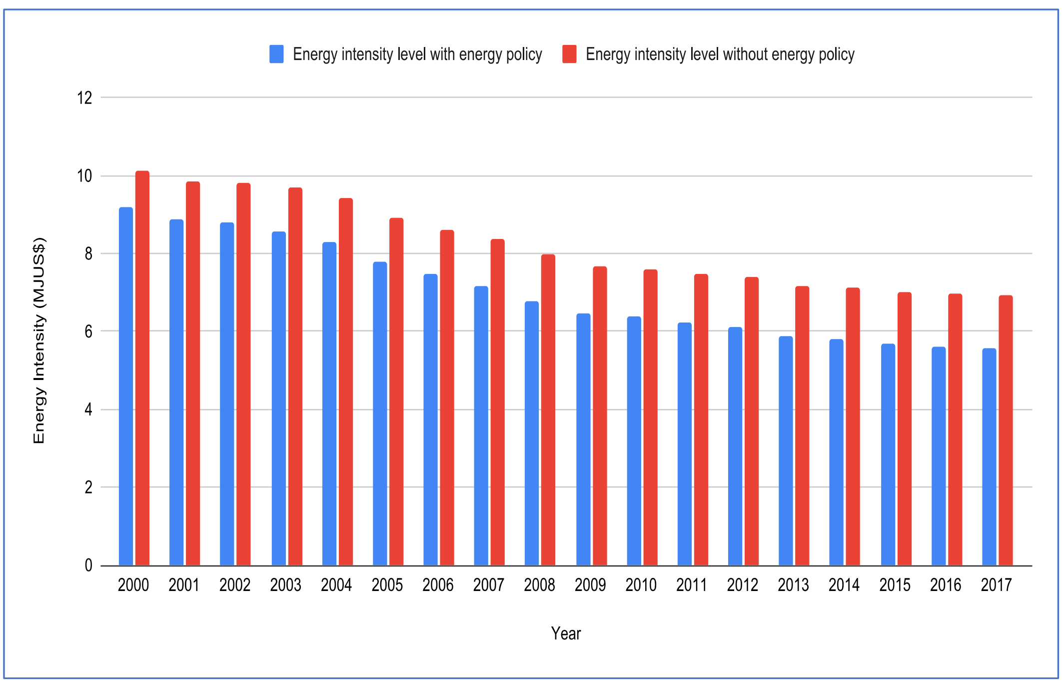

Fig. 4. Level of energy intensity of APAC countries with and without energy policy.

Table 7A
Energy efficiency estimates.

Energy efficiency (EE)	Obs	Mean	Std. Dev.	Min	Min	Max
Transient EE	414	0.999	4.06e-06	0.999	0.999	0.999
Persistent EE	414	0.35	0.183	0.038	0.038	0.675
Overall EE	414	0.349	0.183	0.037	0.037	0.674

Third, the study observes a consistent upward trajectory in energy efficiency from 2000 to 2017, with average levels stabilizing between 0.38 and 0.39. Despite the relatively modest averages, this steady increase in efficiency over the years signifies a positive trend towards more efficient energy use in the future in the region. Ultimately, the analysis indicates that by optimizing energy policies, APAC could achieve average energy savings of 0.15 quadrillion British thermal units (Btu) annually between 2000 and 2017.

Based on the findings presented, actionable policy recommendations to enhance energy efficiency in the APAC region can be synthesized into integrated policies: to begin, policymakers should prioritize the implementation and enforcement of stringent energy efficiency standards and regulations across all sectors. This entails establishing clear benchmarks for energy performance in buildings, appliances, and industrial processes, alongside rigorous compliance monitoring. Additionally, promoting comprehensive energy plans that incentivize industries and businesses to adopt energy-efficient technologies and practices is crucial. Governments can support this effort through subsidies, tax

Table 7B
Using log of total energy efficiency as dependent variable.

	(1)	(2)	(3)	(4)	(5)
Dependent variable: Total Energy efficiency					
lnEnergy_Policies	1.75e-06**				
	(6.89e-07)				
lnEnergy_Law		7.15e-07			
		(6.45e-07)			
lnEnergy_Reg			1.69e-06**		
			(7.97e-07)		
lnEnergy_Plans				1.80e-07	
				(6.73e-07)	
lnEnergy_Other					9.71e-07
					(6.04e-07)
Constant	−1.261***	−1.288***	−1.541***	−1.295***	−1.277***
	(1.47e-06)	(1.15e-06)	(1.49e-06)	(1.71e-06)	(1.16e-06)
Observations	414	397	217	310	388
R-squared	0.029	0.023	0.080	0.030	0.021
Number of id	23	23	17	23	23

Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

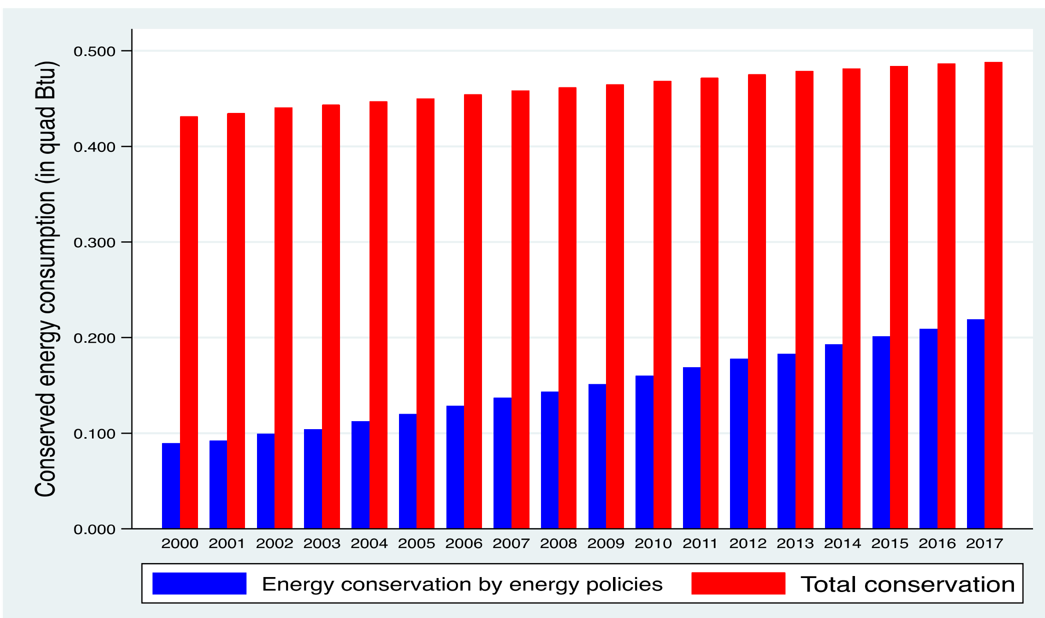

Fig. 5. Energy conservation potential by enhanced energy efficiency and energy policy (in quad btu).

incentives, or grants aimed at investments in energy-saving technologies and renewable energy sources. Also, educational campaigns aimed at raising public awareness about the benefits of energy efficiency can drive behavioral changes and widespread adoption of energy-saving practices, such as efficient lighting and appliance usage. Integrating energy efficiency considerations into urban planning and development strategies can mitigate energy demand growth in rapidly urbanizing areas. This includes designing energy-efficient infrastructure, promoting mixed land-use developments, and prioritizing sustainable public transportation options. Lastly, establishing robust monitoring and evaluation frameworks is critical to assess the impact of energy efficiency policies and programs accurately. Regular reviews and data-driven assessments will provide insights into policy effectiveness, identify areas for improvement, and ensure accountability in achieving energy efficiency targets.

This study examined the influence of aggregate energy policies on energy consumption efficiency. To enhance this analysis, future research could examine efficiency at a more micro level, focusing on how specific entities, such as firms or households, respond to energy policies. Additionally, investigating different energy types could provide a more better understanding of policy impacts. Expanding the data coverage to include more countries and a longer time frame would yield richer, more comprehensive results. Furthermore, future studies could also consider country-specific analyses to offer valuable insights into the varied effects of energy policies across different national contexts.

CRediT authorship contribution statement

Bless Kofi Edziah: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Eric Evans Osei Opoku:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Formal analysis.

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Appendix A. Appendix

Table A1
List of APAC countries considered in this study.

	Countries		Countries
1	Azerbaijan	13	Mongolia
2	Bangladesh	14	Nepal
3	Bhutan	15	Pakistan
4	Cambodia	16	Philippines
5	Fiji	17	Sri Lanka
6	Georgia	18	Tajikistan
7	India	19	Thailand
8	Iran, Islamic Rep.	20	Turkey
9	Kazakhstan	21	Turkmenistan
10	Lao PDR	22	Uzbekistan
11	Malaysia	23	Vietnam
12	Maldives		

Table A2
Correlation matrix.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
(1) lnEne	1.000														
(2) lnGDP	0.229*	1.000													
(3) lnEP	−0.003	0.574*	1.000												
(4) lnServ	−0.045	0.304*	0.284*	1.000											
(5) lnUrban	0.907*	−0.017	−0.011	0.033	1.000										
(6) lnGDP_2	−0.156*	−0.697*	−0.455*	−0.234*	0.015	1.000									
(7) lnEP_2	−0.028	−0.362*	−0.634*	−0.172*	−0.049	0.519*	1.000								
(8) lnServ_2	−0.215*	0.154*	0.036	−0.439*	−0.347*	−0.051	0.025	1.000							
(9) lnUrban_2	−0.751*	0.061	0.070	0.154*	−0.819*	−0.092	−0.005	0.309*	1.000						
(10) lnGDP_lnEP	−0.099*	−0.515*	−0.579*	−0.207*	−0.048	0.783*	0.795*	0.047	0.008	1.000					
(11) lnGDP_lnServ	−0.241*	−0.308*	−0.253*	−0.148*	−0.262*	0.524*	0.429*	0.030	0.246*	0.552*	1.000				
(12) lnGDP_lnUrban	−0.368*	−0.629*	−0.424*	−0.400*	−0.275*	0.566*	0.314*	−0.119*	0.008	0.440*	0.420*	1.000			
(13) lnEP_lnServ	−0.148*	−0.203*	−0.248*	−0.204*	−0.213*	0.405*	0.533*	0.172*	0.191*	0.528*	0.721*	0.236*	1.000		
(14) lnEP_lnUrban	−0.105*	−0.405*	−0.667*	−0.342*	−0.126*	0.379*	0.412*	−0.007	0.025	0.430*	0.260*	0.676*	0.244*	1.000	
(15) lnServ_lnUrban	0.192*	−0.286*	−0.258*	−0.853*	0.151*	0.203*	0.117*	0.145*	−0.353*	0.144*	0.024	0.494*	0.105*	0.410*	1.000

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A3
VIF test assesses multicollinearity.

Variable	VIF	1/VIF
lnGDP	4.14	0.241447
lnP	3.90	0.256587
lnServ	7.58	0.131919
lnUrban	5.97	0.167635
0.5*lnGDP^2	4.68	0.213759
0.5*lnP^2	3.93	0.254734
0.5*lnServ^2	2.32	0.430516
0.5*lnUrban^2	5.01	0.199480
0.5*lnGDP*lnP	6.04	0.165696
0.5*lnGDP*lnServ	3.47	0.288505
0.5*lnGDP*lnUrban	7.42	0.134819
0.5*lnP*lnServ	2.92	0.342946
0.5*lnP*lnUrban	3.89	0.257096
0.5*lnServ*lnUrban	7.65	0.130723
Average VIF	**4.92**	

The table shows VIF test results for multicollinearity. All VIF values for the regressors in the frontier equation are below 10, indicating no multicollinearity.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2024.107831.

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