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A Dynamic Analysis of the Environmental Impacts and Energy Consumption in the Industrial Sector on Iran's Economic Growth

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Highlights

- **This study examines the dynamic relationship between industrial energy consumption, CO_2 emissions, and economic growth in Iran over the period 1996–2051.**
- **Industrial energy consumption exerts a positive effect on Iran's per capita GDP, whereas CO_2 emissions have a negative impact.**
- **Scenario-based simulations suggest that carbon taxation and renewable energy subsidies can foster economic growth.**

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Abstract

The industrial sector is the largest consumer of fossil energy and a fundamental pillar of economic development. Due to the critical role of energy usage and CO_2 emissions in shaping both economic outcomes and environmental quality, this study investigates their connection with economic growth in Iran's industrial sector.

First, key trends and components of the industrial sector are analyzed. Then, using data from the Central Bank of Iran and the national energy balance sheet, the study applies an autoregressive distributed lag (ARDL) model to estimate the variables influencing economic growth. In the second phase, a dynamic modeling framework is utilized to project system behavior from 1996 to 2051. The innovation of this study lies in its dynamic modeling approach, which enables the simulation of future trends and the examination of variable interactions under different policy scenarios and potential economic shocks. The findings indicate a statistically significant negative effect of industrial CO_2 emissions on economic growth (-0.025852) and a positive impact of industrial energy consumption (0.209015). Based on these results, carbon taxation policies and subsidies for renewable energy in industrial processes are recommended to support economic growth while promoting sustainable development.

1. Introduction

The growing dependence of societies on energy and the substitution of machines for human labor have made energy one of the key drivers of economic growth (Motaffaker Azad & Mozaffari, 2017). In fact, energy and the economy have become deeply intertwined (Alaayedi et al., 2024). Accordingly, the reliable and timely supply of energy provides a solid foundation for the production of

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goods and services, thereby fostering economic growth and prosperity, which, in turn, can enhance individual and societal well-being (Mowlaee & Intezar, 2019).

Increased prosperity and economic growth significantly affect environmental quality. This relationship has prompted changes in environmental policies, as evidence shows that economic growth and rising per capita income are often accompanied by increased environmental pollution (Zabihi et al., 2024). Empirical evidence further confirms a positive and significant relationship between economic growth and energy consumption (Shahbaz et al., 2018). In fact, carbon emissions resulting from fossil fuel consumption are an inevitable consequence of economic development (Zabihi et al., 2024). As the most prominent greenhouse gas, CO_2 has been a major contributor to global warming in recent decades. Between 1990 and 2000, net greenhouse gas emissions increased by approximately 35%, and without serious intervention, this figure is projected to rise by 52% by 2050 (Ahani et al., 2024), gradually raising global temperatures (Abdollahi & Sadeghi, 2024).

In addition to environmental degradation, the abundance of fossil fuel resources in the Middle East has led to higher energy intensity in the region compared to the global average. The low cost of fossil fuels has encouraged industries to increase their consumption (Fathabadi, 2023). Iran, as a key country in this region, has particularly high energy intensity. Based on exchange rate calculations, Iran's primary and final energy intensity is 3.3 times the global average; based on purchasing power parity, it is 1.9 times the global average. In 2021, Iran's energy intensity, based on primary energy supply and final energy consumption, was 0.15 and 0.10 barrels of crude oil equivalent per million Rials, respectively, reflecting a 5.6% decrease and a 0.7% increase compared to the previous year (Energy Balance Sheet, 2021).

Given these considerations, and the fact that the industrial sector serves both as the foundation of economic development (Ibekwe et al., 2024) and as the largest global energy consumer (IEA, 2023), special attention must be paid to energy consumption in this sector. Compared to global figures, Iran's industrial sector reports a per capita final energy consumption approximately 1.6 times higher. According to the latest official statistics from 2021, pollutant emissions from this sector include 136,387 tons of CO_2, 131,000 tons of SO_2, and 222,000 tons of NO_2, highlighting its significant contribution to environmental pollution (Energy Balance Sheet, 2021).

Accordingly, this study first analyzes the four main industrial sub-sectors in Iran, then reviews the relevant literature, and finally, in the methodology section, investigates the variables affecting economic growth, CO_2 emissions, and energy consumption in the industrial sector. It also presents a dynamic model to provide a comprehensive analysis of the interrelationships within this domain.

2.Theoretical Background

Steel, copper, petrochemical, and cement industries are among the largest energy consumers in the industrial sector. Among these, the steel industry has a strong connection to economic growth and plays a crucial role in advancing countries toward higher stages of industrialization (Huh, Kwang-Suk, 2011). Steel is also one of the most widely used materials globally and has maintained its significance in industry since the beginning of the Industrial Revolution (Mele & Magazzino, 2020).

In 2021, the global market value of the iron and steel sector reached $1.51 trillion, making it one of the most influential industries worldwide. This sector directly employs more than 6 million people (IEA, Circular Steel Industry Report, 2024). However, its heavy dependence on fossil fuels remains the primary driver of high CO_2 emissions. In 2022, about 1.4 tons of CO_2 were emitted per ton of steel produced, making the iron and steel industry responsible for nearly 8% of global CO_2 emissions related to energy and industrial activities (IEA, G7 Decarbonization Report, 2024).

Due to the long lifespan of steel products, a growing portion of steel production now comes from scrap recycling currently about 30%. This figure is expected to reach around 50% by 2050. Since traditional steel production still relies heavily on fossil fuels, transitioning to recycled steel produced with renewable energy can help pave the way toward green steel (IEA, Circular Steel Industry Report, 2024). Today, green steel is already used in vehicles, ships, trains, wind turbines, solar panels, electrical equipment, and other renewable energy technologies (Ebrahim Bai Salami Mojtabi, 2024).

Primary inputs in steel production include raw materials such as iron ore and coal, as well as energy carriers like electricity and gas. In Iran, the availability of coal mines and the relatively low cost of energy due to heavy government subsidies offer a comparative advantage in steel production. The steel industry supports various sectors such as automotive, household appliances, and metal industries. However, because of its high energy consumption, it is classified as one of Iran's energy-intensive industries (Khatib et al., 2009).

The mispricing of energy carriers stemming from the absence of real price signals has contributed to Iran's high energy intensity and inefficient energy use (Emami Meybodi et al., 2018). In many countries, steel prices have traditionally been tied to coal prices. On average, energy accounts for about 35% of steel production costs globally. In Iran, this figure is estimated at 26.5%, as reported by the Ministry of Industry, Mine, and Trade. Although intended to be a temporary measure, this pricing model has persisted and created serious challenges for the coal industry. Experts argue that coal prices should reflect a rational proportion of steel billet prices, which is not currently the case. This mispricing imposes financial burdens on the economy and leads to increased greenhouse gas emissions and air pollution (Emami Meybodi et al., 2018; Iran Energy Balance Sheet, 2021).

Another key pillar of the global economy is the petrochemical industry. This sector plays an essential role in industrialization, transportation, and trade by providing critical energy resources. Due to its central contribution to economic growth, it has always been a focus of development efforts (Anaba et al., 2024).

Petrochemical products and chemicals are integral to everyday life and are used across a wide range of industries, technologies, and household goods. Plastic production as one of the largest branches of the petrochemical sector has nearly doubled since the early 21st century, reaching about 400 million tons by the end of 2022. It is projected that by 2050, global plastic production will exceed 986 million tons annually. Despite this growth, reuse and recycling of petrochemical products remain limited and insufficient. Meanwhile, the sector's energy intensity continues to rise by 0.5% to 1% per year (IEA, G7 Decarbonization Report, 2024).

The entire lifecycle of petrochemicals from exploration and extraction to refining and distribution carries significant environmental impacts. These include greenhouse gas emissions, water and air pollution, ecosystem degradation, and biodiversity loss (Anaba et al., 2024). Living near oil refineries has even been linked to increased risks of premature birth and congenital abnormalities (Ashish et al., 2024). Table 1 presents CO_2 emissions from oil industries in major oil-producing countries during 2022 and 2023, with Iran ranking third after Russia and Saudi Arabia.

Table1. Annual emissions (CO_2) from oil, measured in tons

Rank	Country	2022	2023
1	Saudi Arabia	442617440	459965400
2	Russia	386742080	390756600
3	Iran	231812960	225849940
4	Turkey	125124910	131863570
5	Iraq	87077970	91909900
6	United Arab Emirates	84125780	85995720
7	Venezuela	40048720	52036080
8	Kuwait	35500948	34953630
9	Bahrain	3150616	3133812

Source: *https://ourworldindata.org/*

Despite environmental concerns, the petrochemical industry remains a crucial sector, generating thousands of direct and indirect employment opportunities. It contributes to the pharmaceutical, food, and packaging industries, playing a vital role in technological advancements across industrial, medical, and agricultural fields (Rashidinia et al., 2025).

In Iran, policymakers and members of parliament widely regard the petrochemical sector as a key driver of job creation, largely due to its comparative advantages. Recent data indicate that petrochemical exports based on oil feedstock amounted to 21.2 million tons, valued at approximately $7.1 billion (Najafpour et al., 2024).

Additionally, Iran possesses one of the largest compressed natural gas (CNG) fleets globally and has made significant investments in expanding its natural gas distribution network, which now reaches over 90% of households (Azadi et al., 2021). However, despite this expansion, available statistics from

2021 show that final consumption of natural gas declined by 2.7% (equivalent to 4.2 billion cubic meters) compared to the previous year, while total energy sector consumption including residential, commercial, industrial, transport, agricultural, and petrochemical uses rose by 6.7% (5.9 billion cubic meters).

Among natural gas consumers, the industrial sector (including petrochemical units) accounted for 41.2% of total use, followed by the residential sector at 37.2%. Additionally, natural gas and diesel fuel were the two primary contributors to greenhouse gas emissions in Iran's industrial sector in 2021 (Iran Energy Balance Sheet, 2021).

Another essential industry often referred to as the "barometer of the economy" is the copper sector. Copper ranks as the third most widely used metal after steel and aluminum (Bejastani et al., 2021) and occurs naturally in rocks, soil, and various environmental sources (Mirzaei et al., 2021). Global copper supply from mining is projected to reach approximately 25 million tons by 2026. The top three producer's combined share of total global mine output is expected to increase from 47% to 55% by 2040, with Chile remaining the world's largest copper supplier, accounting for nearly one-quarter of global output (IEA, 2024). Copper plays a critical role in national economic modernization, supporting industrial and technological development. With the continued expansion of renewable energy industries, copper's importance is steadily increasing (Li et al., 2021). In 2020, Iran ranked fourth in copper production across Asia, following China, Kazakhstan, and Indonesia.

Table2. Copper mine production in metric tons, 2020

Rank in Asia	countries	metric tons, 2020
1	China	1723100
2	Kazakhstan	551800
3	Indonesia	505377
4	Iran	313500
5	Mongolia	303000
6	Burma	185000
7	Uzbekistan	140000
8	Saudi Arabia	92915
9	Laos	88163
10	Armenia	82600

Source: https://www.usgs.gov/

The role of copper in economic development is undeniable. Due to its strong correlation with industrial production growth, copper can play a crucial and meaningful role in Iran's economy and become one of the country's major sources of foreign currency income (Razini & Rasti, 2015). The National Iranian Copper Industries Company, one of the largest copper producers in Iran and the Middle East, ranks 15th worldwide in copper production. Approximately 98% of Iran's copper reserves are located in the provinces of Kerman and East Azerbaijan, while the remaining provinces hold only 2%. Specifically, the copper reserves of East Azerbaijan and Kerman provinces are estimated at 1,631 million tons and 729 million tons, respectively (Copper Status Report in Iran, 2019).

Cement consumption is also directly linked to economic growth and is considered an important indicator of a country's economic development (Effnu et al., 2020). However, it is important to note that cement production inherently generates CO_2 emissions, which are difficult to reduce (Marmier, 2023).

Iran ranks 11th in global cement production. Based on the licenses issued for cement factories and recent national policies, Iran's nominal cement production capacity is projected to reach around 100 million tons by 2025. The most significant challenge facing the industry is overcapacity, caused by the issuance of excessive permits for cement plants beyond national demand. Additionally, the lack of sufficient economic justification for exports and government price control policies are major issues. These factors have created uncertainty regarding the future of the cement industry. Despite sector growth, excess production, and price regulations, the country has experienced periods of cement shortages and price volatility (Parliament Research Center, 2021).

In the first five months of 2024, cement consumption increased by 7.1% to 26.241 million tons in Iran. During the nine months of 2023, 10.5 million tons of cement were exported to 25 countries, including Iraq, Kuwait, Afghanistan, Pakistan, and Syria. According to the Russian Cement Association, Iran's share of Russia's cement imports rose to 16.7% in 2023 from 6.5% in 2021 (International Cement Review, 2022).

The cement industry is the main consumer of electricity and natural gas in Iran. Producing one ton of clinker requires 66 kilowatt-hours of electricity and 830 kilocalories of fuel per kilogram. Additionally, producing one ton of cement consumes 110 kilowatt-hours of electricity. In 2021, the cement industry consumed approximately 7 billion kilowatt-hours of electricity and 7 billion cubic meters of natural gas, accounting for about 3.5% of total natural gas consumption and 2.5% of the country's electricity use (Parliament Research Center, 2021).

Since fossil fuels are used in nearly all stages of cement production, the industry contributes to approximately 7% of global anthropogenic greenhouse gas emissions (Sambataro et al., 2024). As shown in Figure 1, producing one ton of cement emits on average 0.5 to 0.6 tons of CO_2 (Guo et al., 2024). Based on this, CO_2 emissions from cement production in Iran are estimated to be between 13.12 and 15.47 million tons annually.

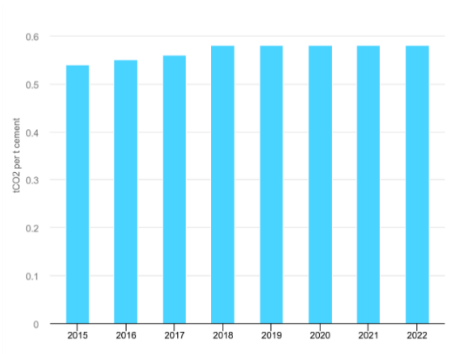

Figure 1. Global Emission Intensity of the Cement Industry
Source: *IEA,2023*.

In conclusion, given the high level of carbon emissions in the cement industry compared to other sectors, it is essential for this industry to take decisive steps toward becoming a green and sustainable sector.

3.Research Background

Given the growing importance of environmental considerations in economic development, and the critical roles played by industry, investment, and trade sectors in fostering economic growth, this section surveys earlier studies regarding the connection between energy consumption and economic growth, as well as the factors affecting industrial growth. This review not only establishes the framework for the current study but also highlights gaps in existing research.

3.1. Economic Growth and Energy Consumption

The connection between energy consumption and economic growth continues to be a contentious issue within economic research. Although numerous studies have addressed this topic, a definitive conclusion remains elusive, largely due to differences in analytical approaches and the temporal scopes considered (Fallahi et al., 2022). Generally, four hypotheses explain the interplay between energy consumption and economic growth. The first, the growth hypothesis, posits a unidirectional causal relationship from energy consumption to economic growth. The second, known as the conservation hypothesis, suggests a one-way causal link from economic growth to energy consumption, meaning economic growth drives energy demand. The third, the neutrality hypothesis, indicates no causal relationship, implying that neither energy conservation policies nor increased energy consumption significantly affect economic growth. Finally, the feedback hypothesis posits a bidirectional causal relationship between energy consumption and economic growth (Haghnejad & Farahati, 2020).

Numerous studies have examined these hypotheses. For example, Nademi & Dalvandi (2023), Esfahani et al. (2022), and Farahati & Salimi (2022) found that long-term energy consumption positively and significantly influences economic growth. Conversely, some research shows asymmetric relationships; for instance, Savari et al. (2020) found that positive energy consumption shocks reduce economic growth in both the short and long term. Similarly, Fallahi et al. (2022) reported that energy consumption stimulates economic growth in the short run, but no significant relationship exists in the long run.

Studies such as Ghoodarzirad (2010) demonstrate that the production effect plays the most significant role in changes in industrial energy consumption, followed by energy intensity and structural effects. Additionally, Sadeghi et al. (2011), using Granger causality tests from 1995 to 2007, found a unidirectional causal relationship from energy consumption to industrial output, highlighting the determining role of energy consumption on industrial production value.

Previous research generally indicates a one-way causal link from industrial production to energy consumption within the industrial sector, suggesting that industrial output changes drive energy consumption patterns (Mozaffari & Motefakker Azad, 2016). Consistent with these findings, Kamalian et al. (2024) emphasize that improving energy efficiency can significantly reduce carbon emissions while sustaining economic growth. Overall, these studies reveal that optimizing energy consumption in industrial processes not only enhances productivity and economic growth but also plays a critical role in mitigating environmental impacts.

3.2. The Role of Foreign Investment and Trade in Industrial Growth

All economic growth theories and models emphasize the role of capital in economic development. Therefore, attracting sufficient capital to finance economic projects remains a primary concern for policymakers (Mohammadinode et al., 2020). Foreign direct investment (FDI) significantly contributes to economic development by creating employment opportunities, expanding production capacity, enhancing workforce skills, and integrating domestic economies into the global market (Dowlatzadeh et al., 2024).

Recent empirical studies indicate that FDI exerts asymmetric effects on macroeconomic indicators. In other words, the impacts of increases in FDI differ from those of decreases, affecting variables such as production and growth differently (Samiee Nasab et al., 2025). For example, Nemati & Jabalameli (2023) found a positive and significant effect of investment on economic growth. However, Mohammadinode et al. (2020) identified a nonlinear relationship between FDI and economic growth in Iran, with inflation fluctuations impacting agriculture, industry, and services differently. Daliri (2021) further found that FDI's impact on growth depends on the host country's income level, with middle- and high-income countries experiencing greater benefits.

Exports of industrial goods and FDI in the industrial sector both play crucial roles in GDP growth (Li Bing et al., 2020). For instance, Abbasi et al. (2021)

documented that the industrial sector's value-added positively affects economic growth in both the short and long term in Pakistan (1972–2018). Similarly, findings by Suhail Wasiq et al. (2024) indicate that increases in traditional goods exports and investment significantly boost economic growth. These results align with other studies (Alaayedi et al., 2024; Shahbaz & Lean, 2012; Mukhtarov et al., 2017; Shahbaz et al., 2020), all of which highlight the positive role of energy consumption on economic growth.

Collectively, these findings suggest that revitalizing the industrial sector through export development, foreign investment attraction, improved energy consumption, and enhanced industrial value-added can serve as an effective strategy to promote economic growth in developing countries. Nonetheless, environmental considerations must be integrated into policymaking alongside growth objectives.

3.3. Environmental Impacts of Economic Growth with Emphasis on Industry

One of the central hypotheses in studying the environmental impacts of economic growth is the Environmental Kuznets Curve (EKC) hypothesis (Esfahani et al., 2022). The Environmental Kuznets Curve (EKC) hypothesis suggests a nonlinear and inverted U-shaped link between economic growth and environmental pollution. According to this theory, pollution levels tend to rise during the initial phases of economic development, but begin to decrease once the economy surpasses a specific income level.(Khalili et al., 2025). Numerous studies support the EKC hypothesis (Khalili et al., 2025; Aminzadeh, 2022; Jafari Samimi et al., 2024; Amadeh et al., 2024), while others, such as Voumik et al. (2023) and Zhang & Liu (2019), reject it. Despite differing views, most agree on the critical need to control CO_2 emissions and prioritize environmental sustainability.

For instance, Chikezie Ekwueme. (2023) show that in the long term, renewable energy use and economic growth significantly reduce CO_2 emissions, whereas short-term economic growth increases carbon emissions. They recommend stringent environmental policies in Asian countries to encourage industries to adopt cleaner resources. Behera et al. (2024) provide complementary findings aligned with this study.

Rapid industrialization remains a major barrier to transitioning toward sustainable, low-carbon systems. In East and South Asia, increased demand for production, transportation, and energy-intensive services has substantially raised carbon footprints (Bahman et al., 2023). Therefore, identifying and controlling major environmental degradation factors in industries, and implementing policies such as replacing fossil fuels with renewables, are crucial (da Silveira Cachola et al., 2023). For example, Wu et al. (2019) identify China (5,700 tons CO_2/year), India (1,300 tons), Russia (807 tons), Japan (564 tons), and South Korea (403 tons) as the countries with the highest carbon sequestration potential in the region. Studies such as Wu et al. (2019) and Shen et al. (2018) advocate policies including shifting industrial structure from energy-intensive to less energy-consuming sectors, reforming ownership structures, enhancing technological innovation, and strengthening government roles to control greenhouse gas emissions and reduce environmental degradation, which can guide policymakers.

In summary, existing literature underscores the importance of optimizing energy consumption, promoting sustainable industrial development, and concurrently addressing environmental concerns. However, a comprehensive understanding of the interplay among industrial structure, energy policies, and environmental variables in developing countries especially in Asia is still ignored. Given Iran's significant economic position in the region, the present study aims to examine these factors within a coherent and dynamic framework.

4.Empirical Model

Based on theoretical foundations and previous studies, the conceptual model of this research is illustrated in Figure 2. This model delineates the mechanism through which variables influencing economic growth (per capita GDP) operate. In this context, CO_2 emissions and energy consumption in the industrial sector are considered essential factors influencing economic growth through both direct and indirect channels. The conceptual framework forms the theoretical foundation for constructing the empirical model and illustrates the directional relations between the variables.

Additionally, the model incorporates the roles of variables such as population, technology, labor force, and environmental and energy policies. Accordingly, the research methodology has been designed based on the points outlined above and the conceptual model has been presented.

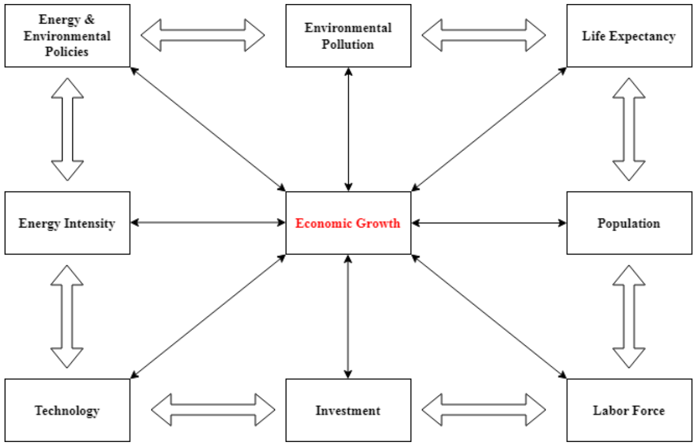

Figure 2. Conceptual model examined in the present study
Source: *research findings*

4.1. Research Methodology

In this study, using available data from the Energy Balance Sheet (2021) and the Central Bank, the relationship between energy consumption in the industrial sector and carbon dioxide emissions on economic growth is analyzed employing two methods: ARDL and dynamic systems. The data utilized, spanning the period from 1996 to 2020, were logarithmically transformed for analysis.

After conducting unit root tests for the variables (Table 3), the ARDL approach was selected as the estimation method. The primary reason for choosing the ARDL model lies in its suitability for variables integrated at levels I(0) and I(1). One of the primary strengths of the ARDL framework lies in its ability to model both short-run and long-run relationships among the variables under investigation.

Therefore, in addition to examining the effect of industrial energy consumption on per capita GDP, this study also investigates the impact of variables such as population, labor force, capital stock, CO_2 emissions from the industrial sector, and trade openness, which is indexed by the sum of exports and imports divided by GDP.

Table 3. Stationarity test of variables

Variable	Variable Symbol	Stationarity
GDP per capita	LGDPPC	I (1)
Population	LP	I (0)
Labor Force	LL	I (1)
Total Industrial Sector Energy Consumption	LTES	I (1)
Sum of Exports and Imports Divided by GDP	LXMG	I (1)
CO2	LCO2	I (1)
capital stock	LK	I (1)

Source: *research findings*

Therefore, based on the aforementioned points, per capita gross domestic product (GDP) is considered as follows:

$$GDPPC_{it} = \beta_0 + \beta_1 LTES_{it} + \beta_2 LCO2_{it} + \beta_3 LP_{it} + \beta_4 LL_{it} + \beta_5 LXMG_{it} + \beta_6 LK_{it} \quad (1)$$

Table 4 presents the results of the model estimation. As shown, all variables except LXMG and LL are statistically significant at the 5% and 10% levels. The R-squared value indicates that approximately 99% of the variation in per capita GDP is explained by the variables included in the model.

The long-run relationship indicates that, except for the labor variable, all other variables are statistically significant. Furthermore, stability and robustness tests confirm that the model exhibits appropriate stability and reliability. The autocorrelation test shows that the model does not suffer from autocorrelation, meaning that the errors in one period are not correlated with those in the subsequent period, thus satisfying the assumption of error independence.

Additionally, the ARCH test for heteroscedasticity suggests that the error variance is constant, indicating no heteroscedasticity issues in the model.

Table 4. Research findings

short-run relationship				
Variable	Coefficient	Std. Error	t-Statistic	Prob.*
LGDPPC (-1)	0/594604	0/075511	7/874384	0/0002
LGDPPC (-2)	-0/789569	0/089316	-8/840162	0/0001
LGDPPC(-3)	0/516010	0/101438	5/086949	0/0023
LP	9/360773	2/980612	3/140554	0/0201
LTES	0/209015	0/039012	5/357733	0/0017
LTES(-1)	-0/149054	0/016439	-9/066953	0/0001
LTES(-2)	0/144730	0/044725	3/235977	0/0178
LK	-0/450783	0/104533	-4/312342	0/0050
LK(-1)	1/464841	0/124112	11/80257	0/0000
LK(-2)	-1/449787	0/101046	-14/34776	0/0000
LL	0/161480	0/074338	2/172244	0/0728
LCO2	-0/025852	0/006954	-3/717593	0/0099
LCO2(-1)	-0/048783	0/003983	-12/24896	0/0000
LXMG	0/023569	0/029681	0/794086	0/4574
C	-92/68421	32/67254	-2/836762	0/0297
@TREND	-0/110974	0/041389	-2/681217	0/0365
R-squared		0/994020		
Adjusted R-squared		0.979069		
F-statistic		66.48494		
Prob(F-statistic)		0.000021		
long-run relationship				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
LP	13/78703	2/417954	5/701942	0/0013
LTES	0/301479	0/050056	6/022802	0/0009
LK	-0/641765	0/251538	-2/551368	0/0434
LL	0/237837	0/152517	1/559411	0/1699
LCO2	-0/109926	0/036299	-3/028340	0/0231
@TREND	-0/163448	0/034611	-4/722455	0/0032
EC = LGDPPC - (13/7870*LP + 0/3015*LTES -0/6418*LK + 0/2378*LL -0/1099 *CO2 - 0/1634*@TREND)				
F-Bounds Test				
Test Statistic	Value	Signif	I(0)	I(1)
			Asymptotic: n=1000	
F-statistic	4.446407	10%	2.49	3.38
k	5	5%	2.81	3.76
		2.5%	3.11	4.13
Actual Sample Size	22		Finite Sample: n=30	
		10%	2.907	4.01
Variable	Coefficient	Std. Error	t-Statistic	Prob.
CointEq(-1)*	-0/678955	0/086054	-7/889848	0/0002
Autocorrelation test	Prob. F(2,4)		0/1480	
Breusch–Pagan test for Heteroscedasticity	Prob. F(15,6)		0/9079	

ARCH for Heteroscedasticity test	Prob. F(1,19)	0/5290

Source: *research findings*

The coefficient of LTES (0.209015) indicates that a 1% increase in energy consumption in the industrial sector leads to approximately a 0.21% increase in per capita GDP, highlighting its significant role in the short run.

Therefore, based on the findings from the first part of the empirical model, it can be concluded that there is a positive relationship between industrial energy consumption and per capita GDP.

According to the short-run results presented in the above table, the first lag of per capita GDP (0.594604) is positive and significant, indicating a reinforcing effect of the previous period's GDP. The significance of the third lag further reflects the dynamic nature of this variable. Consistent with these findings, the significance of the CO_2 emissions variable emphasizes the negative economic consequences of carbon emissions, while its first lag demonstrates a persistent effect of CO2 emissions in reducing output.

In the present study, all relationships among the variables are significant except for the variable LL. A noteworthy point among the long-run coefficients is the negative sign of investment (LK), suggesting that the effect of investment on output may decline after a certain period, which can be attributed to decreasing productivity.

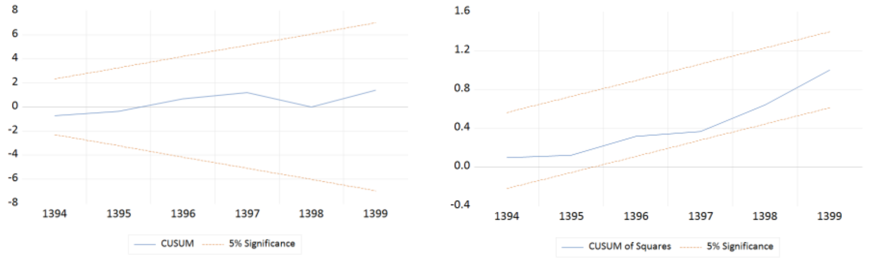

Figure 3. Stability and Sustainability Test
Source: *research findings*

In the second part of the empirical model, the system dynamics methodology was employed using Vensim software. Based on the results from the first part, the model was estimated, and various scenarios were designed and thoroughly analyzed. The main advantage of using system dynamics, compared to previous studies, lies in its ability to simulate the future behavior of the system and to examine interactions among variables under different scenarios and potential shocks. This capability helps clarify the trajectory of changes and provides a deeper understanding of the system's internal structure.

Overall, system dynamics is a method aimed at enhancing learning in complex systems. The foundations of this method lie in the principles of nonlinear dynamic systems and are shaped by control feedback theories originating from disciplines such as engineering, physics, and mathematics. Additionally, it incorporates perspectives from fields like cognitive and social psychology, economics, and other branches of the social sciences (Sterman, 2000).

Economic, social, and environmental phenomena are understood to interact dynamically and complexly with feedback loops under real-world conditions (Rusiawan et al., 2015). System dynamics arise solely from the interaction of positive (reinforcing) and negative (balancing) feedback loops. Positive loops amplify changes within the system (as illustrated in Figure 4), while negative loops counteract and resist change (as shown in Figure 5) (Sterman, 2000).

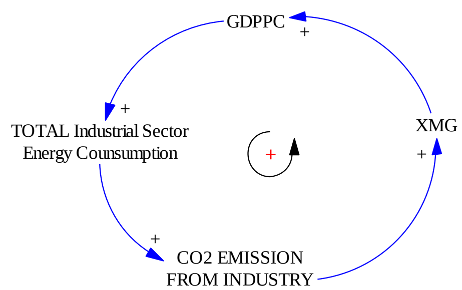

Figure 4. An example of a positive feedback loop in the study
Source: *research findings*

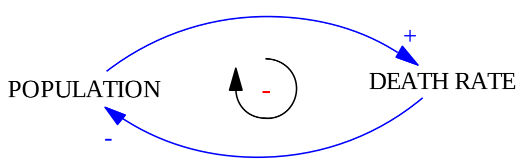

Figure 5. An example of a negative feedback loop in the study
Source: *research findings*

The main skill in system dynamics modeling lies in identifying and analyzing feedback processes. These processes, along with flow structures, time delays, and nonlinear characteristics, collectively shape the dynamic behavior of the system (Sterman, 2000).

Building on this foundation, the system dynamics method has been applied in the second part of the empirical model in this study. This approach is particularly effective in representing feedback loops and interactions among variables, while also enabling the prediction of system behavior over long-term horizons. Therefore, this section aims to leverage this method to more accurately capture the interactive relationships and feedback mechanisms among the variables under investigation.

Figure 6 illustrates the causal loops related to the variables studied in this research. These loops depict the positive and negative relationships among variables and demonstrate how each variable influences others within the system.

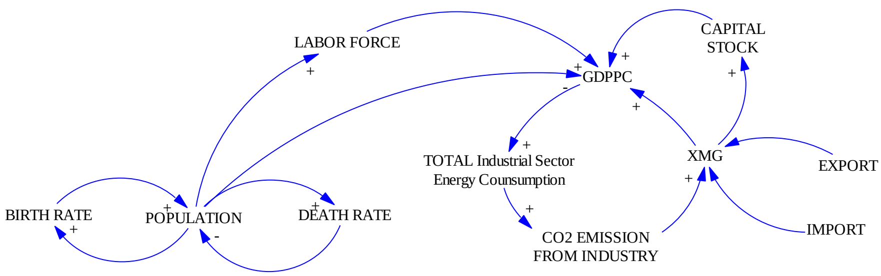

Figure 6. Causal Loop Diagram in the study
Source: *research findings*

As shown in Figure 6, the variables of capital stock, carbon dioxide emissions, and population play key roles in the study. The interactions among these variables can lead to changes in per capita GDP. Therefore, based on the points discussed above and using the causal loop diagram alongside the regression equation estimated in the previous section, the stock-flow diagram for this model has been developed and is presented in the figure below.

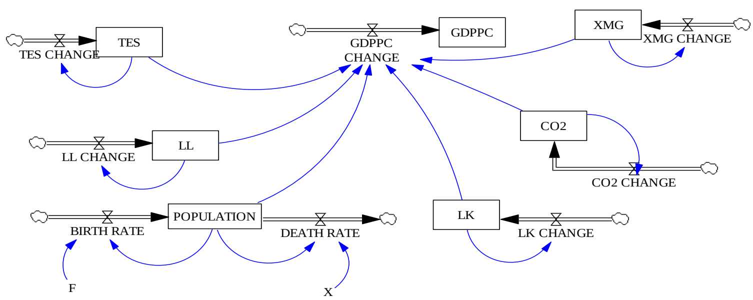

Figure 7. Stock-Flow Diagram in this study
Source: *research findings*

Next, using available data from the Energy Balance Sheet and information published by the Central Bank, the model is implemented. Based on the outputs of the baseline scenario, various alternative scenarios are then developed.

4.2. Scenario Development

Under "Scenario 1," two policies are evaluated: the implementation of a carbon tax and the provision of subsidies for renewable energy. These measures aim to encourage the adoption of clean and renewable energy within the industrial sector and are expected to positively impact per capita GDP. For the year 1404 (2025–2026), this scenario assumes a 5% increase in industrial energy consumption alongside a 2.5% reduction in carbon emissions. The outcomes of these policies are illustrated in Figure 8.

It is anticipated that this scenario will have a positive effect on per capita GDP. Specifically, these policies not only have the potential to boost per capita GDP but also contribute to environmental protection by increasing the share of renewable and clean energy within the industrial energy mix. Overall, the approach supports economic growth while advancing the objectives of sustainable development.

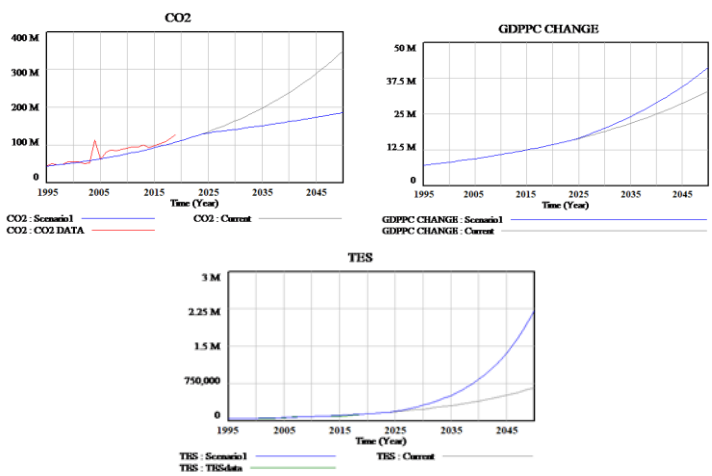

Figure 8. Model Results Following Scenario Implementation

Source: *research findings*

4.3. Model Validation

To validate the model, the common approach of comparing actual data with the model's output through behavior reproduction were employed (see Figure 9). The comparison between observed data and the model's estimated trends indicates that the model achieves an acceptable level of accuracy. Additionally, the results reveal that carbon dioxide emissions and industrial energy consumption are growing at a faster rate than the other variables analyzed in this study. To validate the model, the common method of comparing actual data with the model's output through behavior reproduction was employed (Figure 9). As shown, by comparing the real data with the model's estimated trends, it can be concluded that the model demonstrates an acceptable level of accuracy. Furthermore, the results indicate that the two variables carbon dioxide emissions and industrial energy consumption are increasing at a faster growth rate compared to the other variables examined in this study.

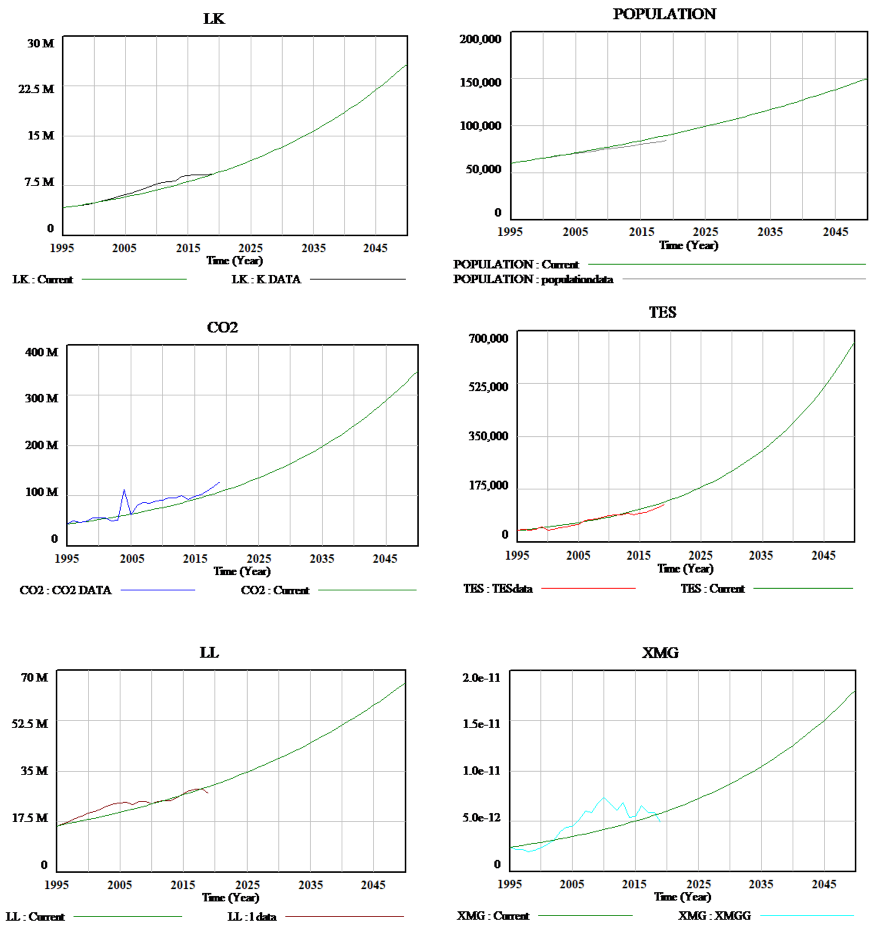

Figure 9. Research Results in the Baseline Scenario without Policy Implementation
Source: *research findings*

5.Conclusion and Policy Recommendations

Industrial enterprises are the largest consumers of fossil fuels, and their energy consumption is typically accompanied by negative impacts on environmental quality, contributing significantly to greenhouse gas emissions. In light of the significant influence of energy use within the industrial sector on economic performance, the study explores how industrial energy consumption and CO_2 emissions are associated with Iran's economic development.

Using the conceptual framework alongside energy balance data and Central Bank statistics from 1996 to 2020, this study first conducted unit root tests and then applied the ARDL model to estimate the variables affecting economic growth. Subsequently, the results from the first part of the empirical model were employed in the second part, where a dynamic systems modeling approach was developed and applied to simulate the period from 1996 to 2051.

The study examined the impact of industrial energy consumption and carbon dioxide emissions on Iran's per capita GDP, alongside the effects of variables such as population, trade-to-GDP ratio, labor force, and capital stock. Based on the findings and analysis, the following key points are highlighted:

- The results indicate that carbon dioxide emissions and industrial energy consumption exert negative and positive effects, respectively, on Iran's per capita GDP.
- Scenario analysis involving policies such as carbon taxation and subsidies for renewable energy use over the period 1996 to 2051 demonstrated that these policies positively influence per capita GDP and, as expected, promote economic growth.
- The findings reveal that while carbon dioxide emissions negatively affect economic growth, industrial energy consumption positively contributes to growth in Iran. Considering that fossil fuels are the primary energy source in Iran's industrial sector, there is an urgent need to focus on energy transition within this sector.
- Moreover, the results align with previous studies including Chikezie Ekwueme et al. (2023), Abbasi et al. (2021), Li Bing (2020), Alaayedi et al. (2024), Jafari et al. (2014), Zabihi et al. (2024), Kamalian et al. (2024), and Motafakker Azad & Mozaffari (2017). The novelty of the present study lies in the dynamic investigation of the relationship between industrial energy consumption and carbon dioxide emissions on economic growth in Iran, providing a clear outlook on energy consumption patterns and carbon emissions in the industrial sector. Additionally, this study's examination of four major industrial subsectors offers a detailed picture of this vital sector, which can inform industry stakeholders, policymakers, and energy regulators.

5.1. Research Limitations

- Lack of publication of new official data.
- Inability to extend the research period.
- Exclusion of external shocks such as economic crises, COVID-19 pandemic impacts, and economic sanctions.

Due to the absence of updated official data and reliance on outdated datasets, the results of this study may diverge from the current real economic conditions. Moreover, restricting the analysis to a limited time frame might reduce the predictive power of the model and confine the findings to the characteristics of that particular period. Additionally, excluding the effects of external shocks such as crises, the COVID-19 pandemic, and sanctions may lead to overlooking important economic realities. Therefore, future studies could incorporate dummy variables, structural modeling methods that consider shocks, and periodic analyses dividing the timeline into pre- and post-crisis intervals to better account for these influences.

5.2. Recommendations

- Extend the study period as new official data become available.
- Incorporate feedback loops affecting economic growth and the impact factors on industrial carbon dioxide emissions into the model.
- Analyze the effects of external factors such as international sanctions on the industrial sector and per capita GDP.

5.3. Policy Recommendations

- Implement a tiered carbon tax policy as a priority, especially targeting energy-intensive industries such as steel and cement, with revenues directed to support renewable energy initiatives.
- Given the positive effect of renewable energy on GDP, subsidy policies for renewable and clean energy use in the industrial sector should be prioritized by policymakers. This approach not only promotes sustainable economic growth but also facilitates the transition from fossil fuels to renewable energy. Enterprises using clean energy would benefit from tax discounts and low-interest loans.
- Develop and enforce stringent regulations on carbon dioxide emissions from the industrial sector. This could begin with mandatory use of filters or modern pollution control technologies in highly polluting industries, with standards becoming progressively stricter over the study period.
- Promote research and development in technologies that improve energy intensity in the industrial sector and reduce carbon dioxide emissions, including funding university projects on smart technologies and environmental emission control systems. Such efforts are essential for energy conservation and environmental protection in line with global initiatives.

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Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data used in the study were taken from https://www.worldbank.org/ & https://cbi.ir/ & https://pep.moe.gov.ir/.

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