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A System Dynamics Approach to Renewable Power Generation and Emission Control in Iran

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ABSTRACT

This study presents a system dynamics model to analyse how renewable electricity can reduce carbon emissions in Iran. It investigates the effects of population growth and the substitution of fossil fuels with renewable energy. Four population scenarios are considered: decreasing, moderate, stable, and high fertility. The results show that a high-fertility scenario (2.6) leads to a sharp increase in carbon emissions by 2051, underscoring the importance of demographic trends in energy planning. The study also tests three levels of renewable electricity substitution: high, medium, and low. Higher substitution levels lead to greater emission reductions. The simulation results provide both absolute and relative production values, indicating the amount of additional renewable electricity required to replace fossil-fuel-based generation. This model helps policymakers understand the long-term impact of energy and population policies on emissions. It also demonstrates how dynamic modelling can capture complex feedback mechanisms between population and energy systems. The approach offers a flexible tool for testing future scenarios and supporting strategic decision-making. Future work can improve the model by including economic analysis, carbon absorption capacity, and detailed investment scenarios.

Keywords

Renewable Electricity, Carbon Emissions, System Dynamics Modelling, Population Scenarios, Energy Transition.

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1. Introduction

Policymaking regarding demographic change affects other sectors, such as energy and the environment. Carbon footprints and greenhouse gas emissions, which are major global concerns, along with their root causes, need to be addressed in future planning (Sahari et al., 2024). At the same time, renewable sources such as solar and wind energy offer clean alternatives. Replacing fossil fuels with renewable energy sources helps reduce carbon dioxide emissions and contributes to efforts to combat climate change (Karlilar Pata and Balcilar, 2024).

However, limited research has used dynamic modelling to integrate population growth with electricity-mix optimisation in the context of Iran or similar developing countries. Most existing studies focus on the technical or economic feasibility of renewables, but few examine long-term policy impacts using system dynamics under population- and demand-growth scenarios.

Demographic transition is a fundamental and pervasive process experienced by countries worldwide. When demographic change is not aligned with economic and social transformation, or when appropriate policies are not adopted, countries may face challenges that, if unresolved, can result in serious socio-economic consequences (Yang, Rosenberg and Li, 2020; Nasrolahi Vosta, 2017).

Among energy carriers, electricity is a vital resource for the world economy. It reflects and influences a country's economic status and level of welfare, as indicated by measures such as production and consumption. Electricity demand in Iran has steadily increased along with national development. This demand stems from industrial, domestic, and public consumers. Meeting this demand typically requires establishing new power plants (Rostami, 2018).

Global energy-related CO_2 emissions rose by 1.1% in 2023, increasing by approximately 410 million tonnes to a record 37.4 Gt. Fossil fuel combustion, particularly from coal, accounted for over 65% of that increase. Meanwhile, renewables made significant gains, supplying 30% of global electricity in 2023, a record high, even as growth in solar and wind additions largely supplemented rather than replaced fossil generation. China and India continued to drive the emissions surge, while advanced economies saw emissions decline by 4.5%, largely due to increased clean power, coal-to-gas fuel shifts, and favourable weather conditions (International Energy Agency, 2025).

In 2022, Iran emitted approximately 696 million tonnes of CO2, representing about 2.0% of global energy-related carbon emissions. A sectoral breakdown shows that power generation contributes around 24%, households/buildings about 28%, and the transport sector roughly 20–21%, with the remaining emissions arising from industrial processes and other uses

(International Energy Agency, 2024). Between 2009 and 2022, CO_2 emissions rose sharply due to high consumption of natural gas, fuel oil, and gas oil in thermal power plants, highlighting Iran's continued reliance on fossil fuels. Meanwhile, electricity generation from renewable sources, primarily solar and wind, remained extremely limited, accounting for less than 1% of electricity output in 2022 (U.S. Energy Information Administration, 2023). This stark contrast underscores the urgent need to scale up clean energy infrastructure to reduce emissions and align with global sustainability goals.

Rising carbon emissions are accelerating climate change, contributing to ice melt, sea-level rise, and more extreme weather. In 2015, 195 countries, including Iran, joined the Paris Agreement and committed to reducing emissions and supporting a sustainable economy. The goal is to limit global warming to well below 2°C, while pursuing efforts to limit it to 1.5°C. The IPCC projects continued growth in global energy demand, while developing countries face the challenge of reducing fossil-fuel use even as energy prices rise (Unfccc, 2015).

A core strategy for combating global warming in the 21st century is to increase energy production while simultaneously reducing greenhouse gas emissions. Renewable energy sources, particularly solar and wind, are now central to this transformation. Despite some economic and technical constraints in large-scale deployment, renewable technologies have become increasingly viable and competitive. Their development is crucial for energy security, environmental protection, and long-term sustainability (Soylu et al., 2024).

With electricity demand rising from both industrial and domestic consumers, Iran must expand its energy capacity. A study (Fakhari et al., 2020) examined 25 cities to identify optimal locations for power plant deployment using models such as Z-number DEA and Fuzzy DEA, considering factors such as pollution, land cost, natural hazards, economic feasibility, and access to infrastructure. Prioritising renewable energy development within these frameworks can enhance electricity generation and distribution while minimising environmental impacts.

As population and electricity demand rise, continued reliance on fossil-based generation will increase greenhouse gas emissions and exacerbate environmental problems. This path also contradicts global efforts to reduce carbon emissions. This study aims to design an electricity production portfolio that meets population growth while increasing the share of low-carbon sources, especially renewables. The central research questions are explored through the development of a system dynamics model:

• How will carbon emissions from electricity generation in Iran evolve in the future, given the country's population growth?

• Given demographic trends and Iran's commitment to reduce carbon emissions, what role can renewable energy sources play in meeting the country's future low-carbon electricity needs?

Forecasts indicate that population growth and rising electricity demand will substantially increase greenhouse gas emissions if fossil-based generation continues. This poses risks to environmental stability and undermines Iran's commitments under international climate agreements. Accordingly, this research examines renewable energy sources as strategic options for meeting national energy needs while reducing emissions.

As shown in Figure 1, this research examines the dynamic interconnections between population growth, electricity generation, and carbon dioxide emissions. A system dynamics simulation model was used to explore these interrelated components over time.

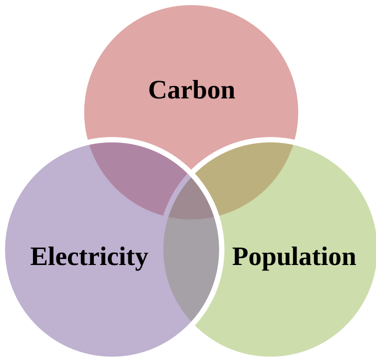

Figure 1 Interconnection of research aspects

Strategic planning and policy formulation on population growth must prioritise the energy and environmental sectors. As global warming and greenhouse gas emissions intensify, decision-makers are increasingly focused on CO_2 reduction strategies. Electrical energy is indispensable for households and industries, yet it remains one of the main sources of greenhouse gases, particularly CO_2 (International Energy Agency, 2024). Consequently, it is vital to investigate the relationships between population dynamics, carbon emissions, and electricity generation systems to develop sustainable and resilient energy strategies.

2. Literature review

Sahari et al., (2024) studied how social and psychological factors affect individual carbon footprints in Finland. They found that age, income, education, and awareness influence personal emissions. This indicates that reducing carbon emissions requires both technological innovation

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and behavioural change. For countries such as Iran, considering population changes and human behaviour can inform the design of better energy policies. This supports the study's focus on linking population growth to renewable energy and emissions reduction.

Lu et al., (2013)conducted research in Taiwan across four carbon-emitting sectors: electricity, industry, residential-commercial, and transportation. They considered two strategies—"Energy Saving Measures and Carbon Reduction" and "Low-Carbon Infrastructure"—to achieve national carbon reduction targets. The electricity sector's strategy emphasised the integration of renewable energy sources, particularly solar and wind, alongside clean coal technologies. Their findings show Taiwan is on track to meet GHG reduction goals aligned with UN IPCC targets by 2030.

Similarly, Karlilar Pata and Balcilar (2024) analysed how renewable energy reduces fossil fuel use in OECD countries. They showed that increasing the share of renewables significantly reduces carbon emissions. Their findings highlight the importance of clean energy transitions for meeting climate goals.

Zhan et al.(2024) emphasised the role of urban development in mitigating emissions through increased energy efficiency, cleaner infrastructure, and smart city design. It employed various modelling techniques to forecast carbon efficiency and assess urban and regional development scenarios for carbon neutrality, providing practical guidance for policymakers.

Li, Raza and Cucculelli (2024) used the Logarithmic Mean Divisia Index (LMDI) method to analyse factors influencing CO_2 emissions in China. By decomposing these drivers—such as energy intensity, industrial activity, and energy mix—they showed that transitioning towards renewable energy sources can support economic growth while reducing carbon intensity.

Zhang et al. (2024) applied a system dynamics (SD) approach to examine emission scenarios in China's construction sector. This study found that, under integrated policy and renewable energy investment strategies, carbon emissions can be significantly curtailed by 2030.

Soylu et al. (2024) evaluated the effects of renewable energy policies in Turkey using a synthetic control method. Their study demonstrated how targeted action plans can effectively increase renewable energy adoption and reduce carbon emissions. This research highlights the importance of policy-driven transitions to clean energy, offering insights relevant to Iran's efforts to expand renewable electricity generation and meet its emission-reduction goals.

Zuo et al. (2024) explored how machine learning techniques can support emission reduction in fossil-fuel plants. These tools can optimise operational efficiency and monitor emissions in real time, which is especially valuable during the transition to cleaner energy sources, including renewables.

Trappey et al.(2012) used SD modelling to analyze the relationship between carbon taxation, electricity costs, and solar cell deployment in Taiwan. Their simulation results provide valuable insights for shaping solar incentives and carbon tax policies to support environmental and economic goals.

Mohamed et al.(2024) investigated the impact of renewable energy on environmental quality in Malaysia (1985–2020) using the ARDL method. Their findings confirm that renewables—particularly in electricity generation—significantly reduce both carbon emissions and ecological footprints. The study supports the Environmental Kuznets Curve (EKC) hypothesis, indicating that sustainable development policies should prioritise the deployment of clean energy.

Rokhmawati et al.(2024) similarly highlights that although increased electricity intensity can raise emissions, renewables can mitigate this effect, making them a crucial component of strategic environmental planning.

A system dynamics study of wind energy development in China (2012–2032) Li and Ren(2017) analyzed long-term growth scenarios. It emphasised the importance of updating transmission infrastructure and reducing over-dependence on subsidies. The research showed that investment in innovation and grid modernisation is essential to sustainably scale wind energy.

While previous research has addressed carbon reduction, renewable energy, and energy policies, certain gaps persist. Long-term feedback-based policy models for countries like Iran are scarce. This study addresses these gaps by developing a dynamic model tailored to Iran. It investigates the impact of renewable electricity on emissions, electricity balance, and sustainable policy-making.

3. Research Methodology

This is an applied analytical study based on system dynamics modelling. This study does not involve any experimental or observational interaction with human subjects. Expert input used in model design was based on previously published literature and informal consultation, rather than formal human-subject research. The steps of this research are shown in Figure 2.

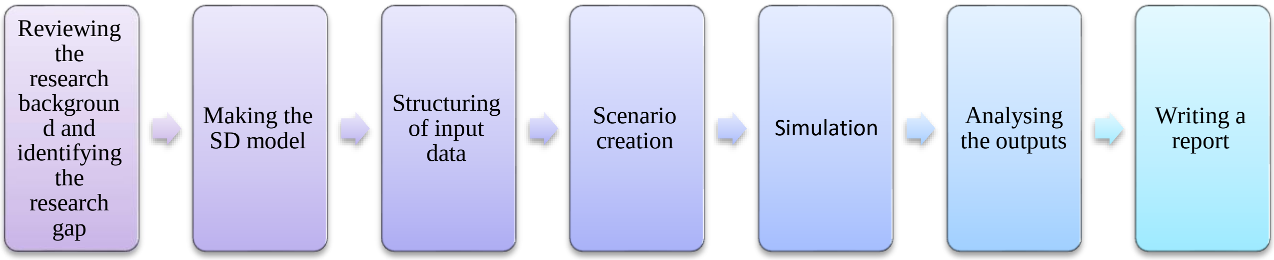

Figure 2 Steps of the research

The research methodology is outlined as follows:

1. **Initial Step:** The process starts with a literature review. A demographic model is built based on Iran's population growth. Key variables are identified using academic sources and national data. This step also highlights research gaps in energy transition and sustainable electricity.
2. **Step Two:** The electricity generation system is modeled dynamically to capture non-linear links between resource supply, renewables, price changes, and delays. The SD model comprises three subsystems: population growth, electricity production (focused on renewable energy), and carbon emissions. Modelling and simulation are done in Vensim, which supports feedback loops and delays. The model covers the capacities of power plants, primarily solar and wind, and their carbon emissions. It simulates interactions among population, electricity demand, and emissions.
3. **Step Three:** Population, electricity, and emission data were collected from credible national sources, including the Statistical Center of Iran and the Ministry of Energy. Only official datasets relevant to Iran's context were used. Due to format differences, data preprocessing and time-series conversion were done in Microsoft Excel. All simulations and policy analyses were carried out in Vensim.
4. **Step Four:** Upon completing the modelling and preparing structured input data, a range of policy and population-based scenarios is developed. These scenarios are designed using theoretical frameworks and prior research on renewable energy expansion and population growth.
5. **Step Five:** The complete SD model, including all integrated data and scenarios, is then simulated to analyze how different strategies for renewable energy development could affect carbon emissions under varying demographic conditions.
6. **Step Six:** After simulation, the outputs are evaluated to determine the most effective policies for supporting renewable energy expansion and reducing greenhouse gas emissions. The results offer insights into potential interventions and policy options for energy planners and environmental policymakers.
7. **Step Seven:** Finally, a detailed report is prepared to summarise the research process, methodologies, model structure, simulation outcomes, and policy recommendations.

3.1. Model Assumptions

To increase transparency and ensure replicability, this subsection explicitly outlines the main assumptions adopted in the development of the system dynamics model. These assumptions reflect necessary simplifications and define the boundaries within which the results should be interpreted.

3.1.1. Boundary of the System and External Emissions

Emissions from non-power sectors (including industry, transportation, buildings, and agriculture) are treated as exogenous and constant throughout the simulation period. This assumption enables the model to isolate and examine the dynamics of the power sector transition. However, it implies that total economy-wide emissions may differ if other sectors experience structural or technological changes.

3.1.2. Electricity Consumption Structure and Linear Coefficients

Electricity demand in the residential, industrial, and commercial sectors is modeled using linear consumption coefficients, assumed to remain constant over time. This simplification is adopted due to the lack of detailed long-term historical intensity data that would allow modelling time-varying or nonlinear consumption patterns. As a result, the model does not capture potential shifts in consumer behavior, technological improvements, or structural changes in energy use.

Previous system dynamics studies have frequently employed linear demand approximations when the primary purpose is to capture long-term feedback behavior rather than short-term demand fluctuations. Furthermore, historical electricity consumption data in Iran exhibit an approximately linear increasing trend over the study period, supporting the use of this simplification.

3.1.3. No Autonomous Improvement in Energy Efficiency

The model does not impose any autonomous improvements in energy efficiency (e.g., reductions in energy intensity per capita or per unit of output) unless explicitly defined within a scenario. This approach isolates the effect of renewable energy expansion on emissions and capacity requirements. Nevertheless, it may lead to conservative estimations of future electricity needs and associated emissions.

3.1.4. Constant Carbon Conversion Factor for Fossil Generation

The carbon emission factor for fossil-fuel-based electricity generation is assumed constant over time. The model does not incorporate potential changes in the fuel mix (e.g., coal-to-gas switching), fuel quality, or combustion technology. Thus, emission estimates are sensitive to this fixed parameter.

3.1.5. Renewable Generation and Capacity Expansion Simplifications

Renewable electricity generation is calculated using installed capacity and growth rates. Seasonal variability, intermittency, curtailment, transmission constraints, and storage requirements are not explicitly modeled. This assumption may lead to overly optimistic estimates of the required renewable capacity to meet future demand.

3.1.6. Economic and Policy Variables Not Endogenised

Economic factors (e.g., capital costs, subsidies, carbon pricing) are not modeled endogenously. The renewable expansion trajectory is scenario-driven rather than cost-optimised. Therefore, results should be interpreted as technical-physical projections rather than economic forecasts.

3.1.7. Numerical Method and Validation

The model uses the Euler integration method with a fixed time step. While this approach is computationally efficient, it may introduce numerical approximation errors for rapidly changing variables. Model behavior has been validated against historical population and emissions data, but further validation using higher-order integration methods is recommended for future work.

4. System Dynamics Modelling and Results

System complexity is often defined by the number of variables and decision-making components. For example, optimising power production in a national energy system involves numerous interconnected elements. However, many challenges in policy-making arise not from technical complexity but from dynamic complexity—the interaction of system variables over time. Such complexity can exist even in relatively simple systems due to feedback loops, delays, non-linearity, historical dependencies, policy resistance, and adaptability.

System Dynamics (SD), introduced by Jay Forrester at MIT, provides a framework for analysing such systems. Unlike traditional operational research models that are often static and linear, SD focuses on feedback-driven behavior over time. It has been used extensively in social, environmental, and energy systems due to its capacity to model continuous change and system-wide feedback (Sterman, 2018; Lane, 2007; Lane and Sterman, 2011). Figure 3 illustrates the iterative and nonlinear nature of SD modelling, in which learning and refinement occur continuously.

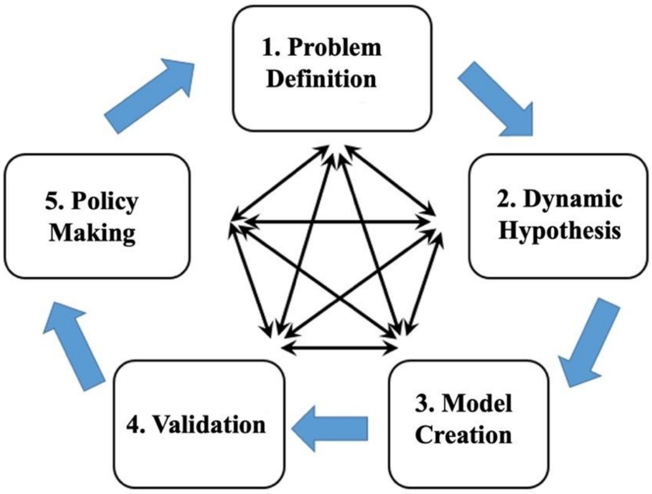

Figure 3. The steps of the SD modelling (Sterman, 2000)

4.1. Variables and Model Boundary

To define the system, relevant variables were selected based on literature in carbon footprint modelling and expert consultation in the electricity and energy policy sectors. These variables were grouped as endogenous (internal system variables), exogenous (external inputs), and excluded (irrelevant or non-modeled variables)(Table1) (Hosseini et al., 2012).

Table 1. Model Boundary Chart

Excluded Variable	**Exogenous Variable**	**Endogenous Variable**
Population growth policies Electricity exports Global warming Global policies and commitments Internal obligations	Birth Rate Death Rate Fractional Birth Rate Average Lifetime slope for Commercial and public slope for Household slope for Industrial consumption slope for fossil power plants CO_2 production rate from industrial sector CO_2 production rate from household, commercial, public sector CO_2 production rate from transportation sector CO_2 production rate from agriculture sector CO_2 Production Rate of power plants Convert coefficient	Population Commercial and Public Consumption household consumption Industrial consumption Electricity Generation Rate Electricity consumption rate Electricity In Net Generation by Fossil power plants Generation by Nuclear power plants Generation by Hydro power plants Generation by renewable energy sources CO_2 Production Rate CO_2 emissions CO_2 Emission Limit CO_2 Emission Gap Slope for fossil power plants Slope for renewable power plants

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4.2. *Dynamic Hypothesis*

A dynamic hypothesis represents the conceptual structure of feedback loops driving system behavior over time. It shows how population growth, electricity demand, and carbon emissions interact in a reinforcing or balancing manner (Homer, 2019). In this study, population growth increases electricity consumption, first in the residential sector, then in the industrial and commercial sectors, over time. To meet this demand, electricity production must increase. Traditionally, this increase has come from fossil-fuel power plants, which are directly correlated with CO_2 emissions.

However, this research proposes that replacing fossil-generated electricity with renewable energy can help keep CO_2 emissions within allowable limits. Unlike fossil fuels, renewable energy sources such as solar, wind, and hydropower produce electricity with negligible direct CO_2 emissions. Their integration into the national grid reduces both environmental impact and reliance on fossil fuels.

The dynamic structure of the model captures the following feedback loops:

- Reinforcing Loop: Population growth → More energy demand → More fossil energy → More emissions
- Balancing Loop: Policy intervention → Increase in renewable generation → Reduction in fossil energy → Decrease in emissions

According to the dynamic assumptions and background of the research, the Subsystems diagram is shown in Figure 4.

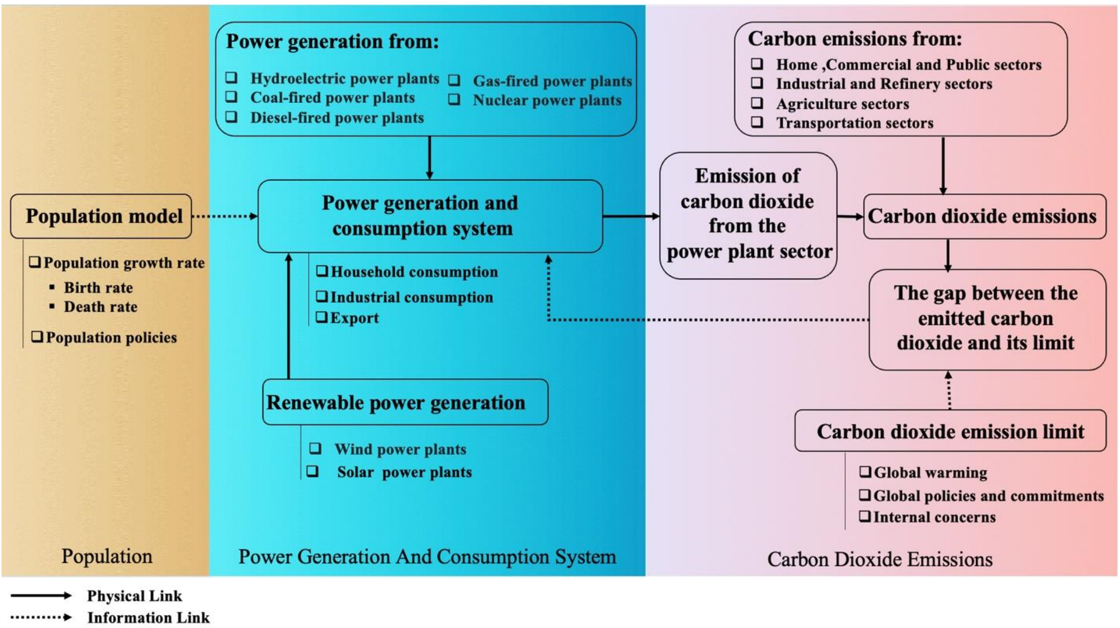

Figure 4. Subsystems Diagram

4.3. Causal Relations, Feedback Loops, CLD, and SFD

Figure 5 and Figure 6 present the Causal Loop Diagram (CLD) and Stock and Flow Diagram (SFD) of the dynamic system model, respectively, which consists of three main subsystems: population, electricity generation, and carbon emissions.

To improve the clarity of the CLD, all feedback loops were identified and labeled according to standard system-dynamics notation, where reinforcing loops are denoted as R1, R2, … and balancing loops as B1, B2, …. Below, each loop is explicitly described using an arrow-based causal sequence to illustrate how variables influence one another within each feedback mechanism.

4.3.1. Population Feedback Loop: Birth–Population (Reinforcing Loop R1)

The first loop is a reinforcing (positive) feedback loop that governs the dynamics of population growth. An increase in population leads to a higher birth rate, which subsequently results in further population growth. This positive cycle generates a self-reinforcing mechanism that, in the absence of limiting factors, can produce exponential growth patterns.

Loop pathway:

Population (+) → Birth Rate (+) → Population

This loop represents a classic reinforcing structure described in the system dynamics literature, in which initial increases in the stock accumulate through positive feedback and generate accelerating growth behavior.

4.3.2. Population Feedback Loop: Death–Population (Balancing Loop B1)

The second loop is a balancing (negative) feedback structure that moderates population growth. As the population increases, the death rate also rises, which exerts a downward force on the population level. This mechanism counteracts the reinforcing effect of the birth loop and prevents unbounded growth.

Loop pathway:

Population (+) → Death Rate (+) → Population (–)

This negative feedback structure contributes to system stability and convergence toward equilibrium. Balancing loops typically generate goal-seeking or stabilising behavior (Sterman, 2000) and are essential for maintaining long-term population stability.

4.3.3. Electricity Supply Loop: Electricity Generation–Electricity in Net (Balancing Loop B2)

This balancing loop represents the supply-side adjustment mechanism within the electricity system. A reduction in electricity available in the network increases the electricity generation rate as the system responds to the emerging supply shortfall. The resulting increase in electricity generation subsequently raises the level of electricity available in the network, thereby reducing the initial shortage. This negative feedback structure represents a goal-seeking mechanism through which electricity supply adjusts to changes in grid availability.

Loop pathway:

Electricity in Net (–) → Electricity Generation Rate (+) → Electricity in Net (+)

Because the loop contains one negative causal relationship, its overall polarity is negative, classifying it as a balancing loop. The loop therefore acts to counteract deviations in electricity availability and contributes to stabilising the supply-demand balance within the energy system.

4.3.4. CO_2 Emission Control Loop: Production–Emissions–Gap–Fossil Generation (Balancing Loop B3)

This feedback loop captures the relationship between CO_2 production, cumulative emissions, the emission gap, and fossil-fuel-based electricity generation. Increases in CO_2 production increase total CO_2 emissions, thereby widening the emission gap relative to the allowable limit. A larger emission gap then influences fossil fuel power generation—typically leading to reductions in fossil-fuel output—and ultimately decreases CO_2 emissions. This creates a balancing feedback loop.

Loop pathway:

CO_2 Production Rate (+) → CO_2 Emissions (+) → CO_2 Emission Gap (+) → Generation by Fossil Power Plants (–) → CO_2 Production Rate (+)

Such loops are central to emission-control and environmental-policy models. As the deviation from the emission limit increases, regulatory or economic pressures typically reduce fossil-fuel generation, thereby constraining CO_2 production.

Fertility and mortality are core demographic variables shaping population dynamics. Fertility, representing actual reproductive behavior, directly influences population growth in the absence of migration. Mortality, influenced by age and gender, also plays a key role in determining population size and structure. Governmental policies to increase population

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typically include economic incentives (e.g., monthly allowances, free nutrition packages, and insurance coverage for mothers and children) and measures to reduce the cost of childbearing.

Figure 6 illustrates the interactions between these variables in the SFD. An increase in the birth rate raises the total population, thereby increasing household electricity consumption. This surge in demand initially requires short-term adjustments in power plant output, and in the long term, leads to the construction of new power generation units. Population growth also necessitates expanded infrastructure and increases electricity demand across industrial, commercial, and public sectors, albeit with a time delay.

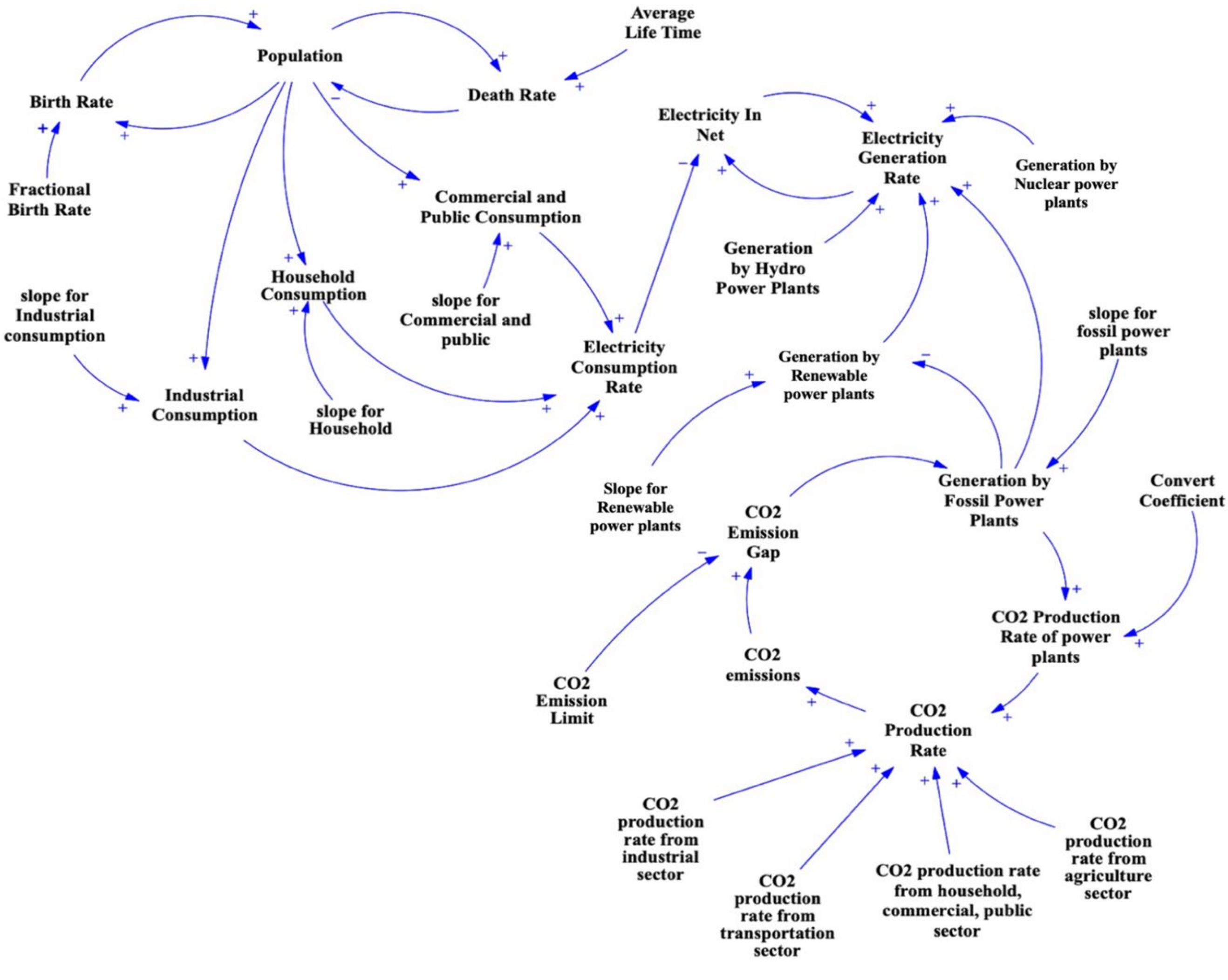

Figure 5. *Casual loop diagram*

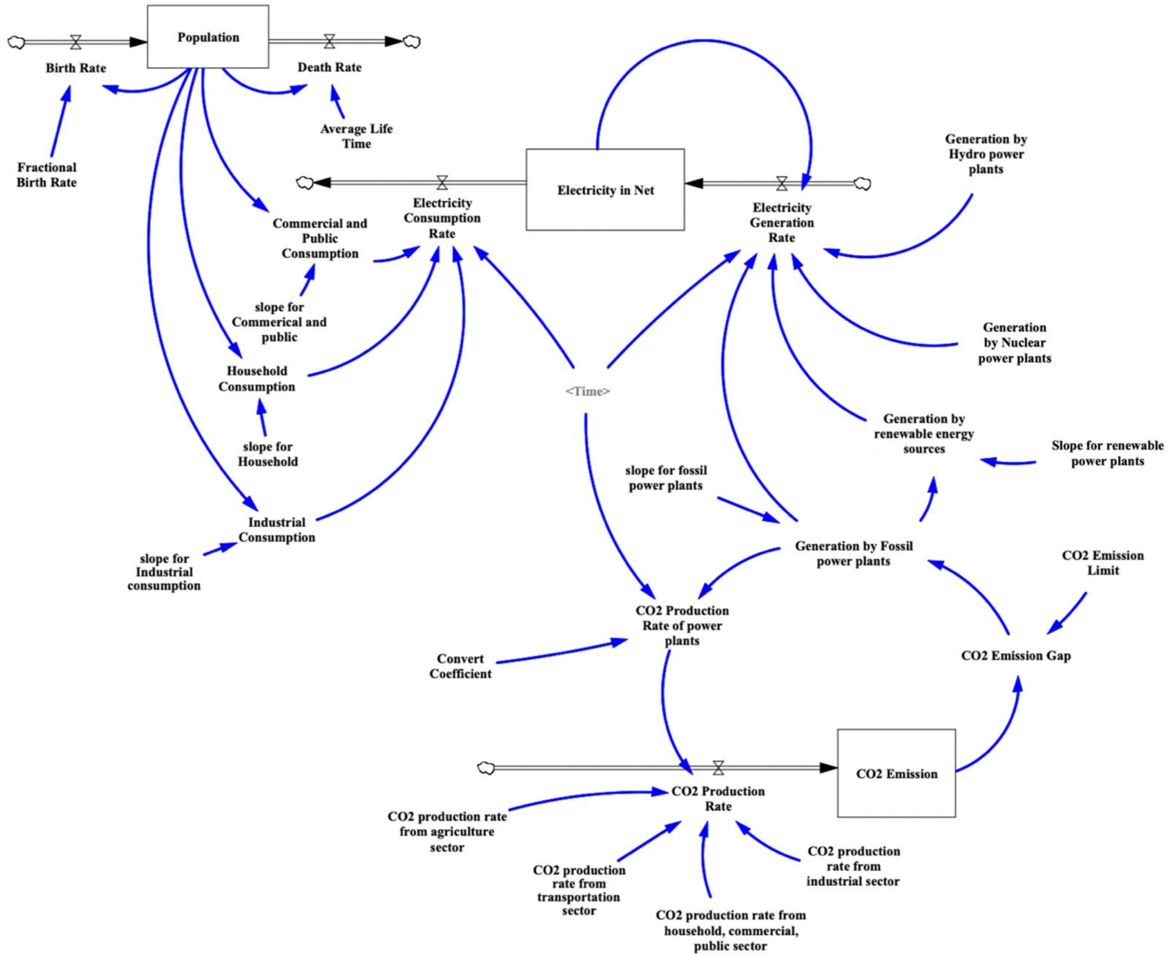

Figure 6. *Stock and flow diagram*

Figure 7 depicts the SFD of the carbon-emission subsystem, which exhibits goal-seeking behavior by adjusting fossil-fuel electricity generation to align actual CO_2 emissions with a predefined allowable threshold.

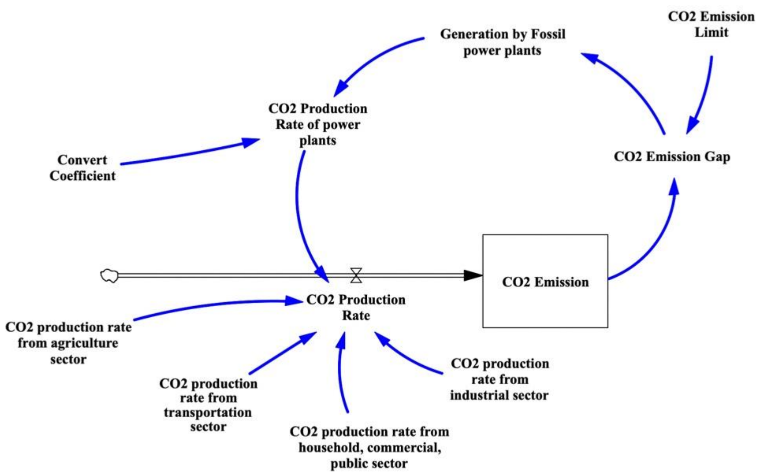

Figure 7. SFD of the carbon emission subsystem

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4.4. Model Validation

To ensure the model realistically represents the actual system, the aim is to minimise the difference between the simulated output and historical data by adjusting parameters within defined upper and lower bounds. For instance, electricity production from renewable sources such as solar and wind is modeled based on nominal capacities but may vary due to seasonal changes, weather fluctuations, and system intermittency. These variations are captured by allowing parameter values to fluctuate within an acceptable tolerance range.

The model uses the Euler method for numerical integration because of its simplicity and compatibility with the Vensim simulation structure. More complex methods like the fourth-order Runge-Kutta are avoided as they may be highly sensitive to initial condition errors.

Model validation involves structure tests, unit consistency, extreme conditions, sensitivity analysis**,** and behavior reproduction. Point-to-point comparisons are used to match model output with historical data. Historical data on population, electricity generation from renewable sources, and carbon dioxide emissions are obtained from credible databases and independently validated across relevant subsystems.

4.4.1. Unit Consistency Check

A critical step in verifying the structural soundness of a system dynamics model is ensuring dimensional consistency across all equations. To this end, the built-in "Unit Check" feature of the Vensim PLE software was employed. This automated tool rigorously examines all model equations to verify that the units on both sides of each equation are consistent and that operations between variables are dimensionally valid (e.g., preventing the addition of variables with incompatible units, such as 'Person' and 'MW').

Table 2 shows the variables of the research, the units, and the relationships of the variables in the research.

Table 2. Relationships between variables and units

Variable	**Unit**	**Equation**
Average Life Time	1/year	constant
Birth Rate	person/year	Fractional Birth Rate * Population
CO_2 Emission	Kton	INTEG (CO_2 Production Rate, 0)
CO_2 Emission Gap	Kton	CO_2 Emission - CO_2 Emission Limit
CO_2 Emission Limit	Kton	Constant
CO_2 Production Rate	Kton/year	CO_2 production rate from agriculture sector + CO_2 production rate from household, commercial, public sector + CO_2 production rate from industrial sector + CO_2 production rate from transportation sector + CO_2 Production rate from power plants

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Variable	Unit	Equation
CO_2 production rate from agriculture sector	Kton/year	Constant
CO_2 production rate from household, commercial, public sector	Kton/year	Constant
CO_2 production rate from industrial sector	Kton/year	Constant
CO_2 production rate from transportation sector	Kton/year	Constant
CO_2 Production Rate from power plants	Kton/year	(Generation by Fossil power plants * Convert Coefficient) / Time
Commercial and Public Consumption	MW	Population * slope for Commercial and public
Convert Coefficient	Kton/MW	Constant
Death Rate	person/year	Population * Average Life Time
Electricity Consumption Rate	MW/year	(Commercial and Public Consumption + Household Consumption + Industrial Consumption) / Time
Electricity Generation Rate	MW/year	(Generation by Fossil power plants + Generation by Hydro power plants + Generation by Nuclear power plants + Generation by renewable energy sources) / Time + Electricity in Net / Time
Electricity in Net	MW	INTEG (Electricity Generation Rate-Electricity Consumption Rate, 0)
Fractional Birth Rate	1/year	Constant
Generation by Fossil power plants	MW	slope for fossil power plants * CO_2 Emission Gap
Generation by Hydro power plants	MW	Constant
Generation by Nuclear power plants	MW	Constant
Generation by renewable energy sources	MW	slope for renewable power plants * Generation by Fossil power plants
Household Consumption	MW	Population*slope for Household
Industrial Consumption	MW	Population*slope for Industrial consumption
Population	person	INTEG (Birth Rate-Death Rate,0)
slope for Commercial and public	MW/person	Constant
slope for fossil power plants	MW/person	Constant
slope for Household	MW/person	Constant
slope for Industrial consumption	MW/person	Constant
slope for renewable power plants	dmnl	Constant

The check was performed on the final integrated model, which encompasses the population, electricity generation, and carbon emission subsystems. The test passed successfully, confirming that all model equations are dimensionally consistent. No unit errors or warnings were generated. This ensures the mathematical integrity of the model and confirms that the simulated behaviors result from the model's causal structure rather than from hidden dimensional errors.

4.4.1. *Extreme Condition*

To validate the structural robustness and behavioral plausibility of the developed system dynamics model, a series of Extreme Conditions Tests was conducted. These tests simulate the model's behavior under implausible or extreme assumptions to ensure that it responds logically and stably.

Three extreme scenarios were simulated from the base year (2016) to the horizon (2051). The scenarios were developed using a theory-driven and policy-oriented approach. Population scenarios were derived from fertility projections reported by national demographic studies and previous research on Iran's demographic transition. Renewable energy scenarios were designed based on alternative levels of renewable substitution in electricity generation and represent plausible policy pathways rather than predictive forecasts :

- Scenario 1: Zero Fertility Rate

Test: If no children were born, how would the system behave?

- Scenario 2: 100% Renewable Substitution

Test: If it were possible to completely replace fossil fuel generation with renewables, how much would carbon emissions be reduced?

- Scenario 3: Zero Electricity Demand Growth

Test: If electricity demand across all sectors remained constant (no growth), how would carbon emissions change?

4.4.2. *Model Assumptions for the Test*

Other parameters (such as mortality rate, generation from nuclear and hydro power plants) were held constant at their base values. Base data are extracted from 2016 (the start of the simulation).

Table 3. Output results of the extreme conditions test

Year	Scenario	Population (person)	Renewable Electricity Generation (MW)	CO_2 Emissions from Power Plants (Kton)	Model Behavior Explanation and Analysis
Base (2016)	Business as Usual	80,038,167	256.4	171,687	Reference value for comparison.
2051	1. Zero Fertility Rate	~58,200,000	256.4	~135,000	The model behaves logically and stably under extreme conditions, correctly simulating a decline in population, electricity demand, and CO_2 emissions when fertility is zero, without generating any unrealistic negative values.

Year	Scenario	Population (person)	Renewable Electricity Generation (MW)	CO_2 Emissions from Power Plants (Kton)	Model Behavior Explanation and Analysis
2051	2. 100% Renewable Substitution	80,038,167	~117,000 (equal to base fossil generation)	~0	The model correctly simulates the targeted outcome, showing near-zero power-sector emissions under a 100% renewable transition, thereby validating its core policy feedback mechanism.
2051	3. Zero Electricity Demand Growth	80,038,167	256.4	171,687	The model maintains a stable equilibrium, confirming that population-driven demand growth is the primary driver of emissions increases in the simulation.

The model demonstrated stable, reasonable, and theoretically sound behavior across all tested extreme scenarios (Table3). It successfully avoided generating physically impossible values (such as negative population or power generation) and maintained its causal relationships even under boundary-pushing conditions. These results strongly confirm the reliability and structural integrity of the developed system dynamics model for policy analysis and long-term scenario simulation.

4.4.3. Sensitivity Analysis

To assess the model's robustness and identify the parameters with the greatest influence on the system's long-term behavior, a sensitivity analysis was conducted. This analysis quantifies how variations in key input parameters affect the primary output variables: cumulative CO_2 emissions (2016-2051) and renewable electricity generation capacity in 2051. The analysis focuses on three critical parameters: the Total Fertility Rate (TFR), the Renewable Substitution Coefficient, and the growth rate of Industrial Electricity Demand. Each parameter was varied by ±20% from its base value under a moderate policy scenario, with all other parameters held constant.The results of the sensitivity analysis are summarised in Table 4.

Table 4. Results of the Sensitivity Analysis on Key Model Parameters

Parameter (Base Value)	Variation	Cumulative CO_2 Emissions (2016-2051) [Kton]	% Change from Base	Renewable Gen. in 2051 [MW]	% Change from Base	Analysis & Policy Implication
Base Scenario	--	~8,450,000	--	~12,500	--	Reference point for comparison.
Total Fertility Rate (TFR=2.1)	+20% (TFR=2.52)	~9,850,000	+16.6%	~12,500	0%	High Sensitivity in Emissions. A higher population drastically increases cumulative emissions. The lack of change

Parameter (Base Value)	Variation	Cumulative CO_2 Emissions (2016-2051) [Kton]	% Change from Base	Renewable Gen. in 2051 [MW]	% Change from Base	Analysis & Policy Implication
						in renewable generation indicates that the model's policy response is insufficient to offset the surge in demand. Implication: Population policy is a critical, indirect driver of emissions.
	-20% (TFR=1.68)	~7,150,000	-15.4%	~12,500	0%	High Sensitivity in Emissions. A lower population significantly reduces the emission burden by lowering overall demand.
Renewable Substitution Coefficient	+20%	~7,900,000	-6.5%	~15,000	+20%	Moderate Sensitivity. A higher substitution rate directly increases renewable capacity and reduces emissions. Implication: Investing in renewable technology is an effective direct strategy for decarbonisation.
	-20%	~9,050,000	+7.1%	~10,000	-20%	Moderate Sensitivity. A lower substitution rate impedes the growth of renewable energy, resulting in higher emissions.
Industrial Demand Growth Slope	+20%	~8,850,000	+4.7%	~12,500	0%	Low-Moderate Sensitivity. Faster growth in industrial demand increases emissions, as the additional demand is primarily met by fossil fuels. Implication: Industrial energy efficiency is a valuable complementary measure.
	-20%	~8,100,000	-4.1%	~12,500	0%	Low-Moderate Sensitivity. Slower industrial growth helps reduce emissions.

The analysis leads to three main conclusions:

- The Total Fertility Rate is the most influential parameter, underscoring the profound long-term impact of demographic trends on Iran's emissions.
- The Renewable Substitution Coefficient is the most effective direct policy lever, showing a direct and proportional response in emission reduction.
- The growth rate of Industrial Electricity Demand has a measurable, though smaller, impact, highlighting the role of demand-side management.

Therefore, a holistic strategy that integrates demographic planning, aggressive promotion of renewable energy, and industrial energy efficiency is essential.

4.4.4. Reproduction Test for Population

According to the published statistics (Fathi, 2025), The country's population has increased from 1990 to 2023. Figure 8 shows the model results for the population variable, as well as the actual values of Iran's population. The difference between real and simulated values is presented as a percentage.

The Mean Absolute Percentage Error (MAPE) for the simulation compared to historical population data is approximately 3.07%. This indicates that, on average, the model's predictions deviate from the actual population values by just over 3 percent each year. Given the large population size, ranging from approximately 55 million to nearly 90 million over the study period, a MAPE of 3.07% indicates relatively high accuracy in capturing population trends. Such a low percentage error suggests that the model reliably approximates the historical data and can be trusted for forecasting purposes within a reasonable margin of error.

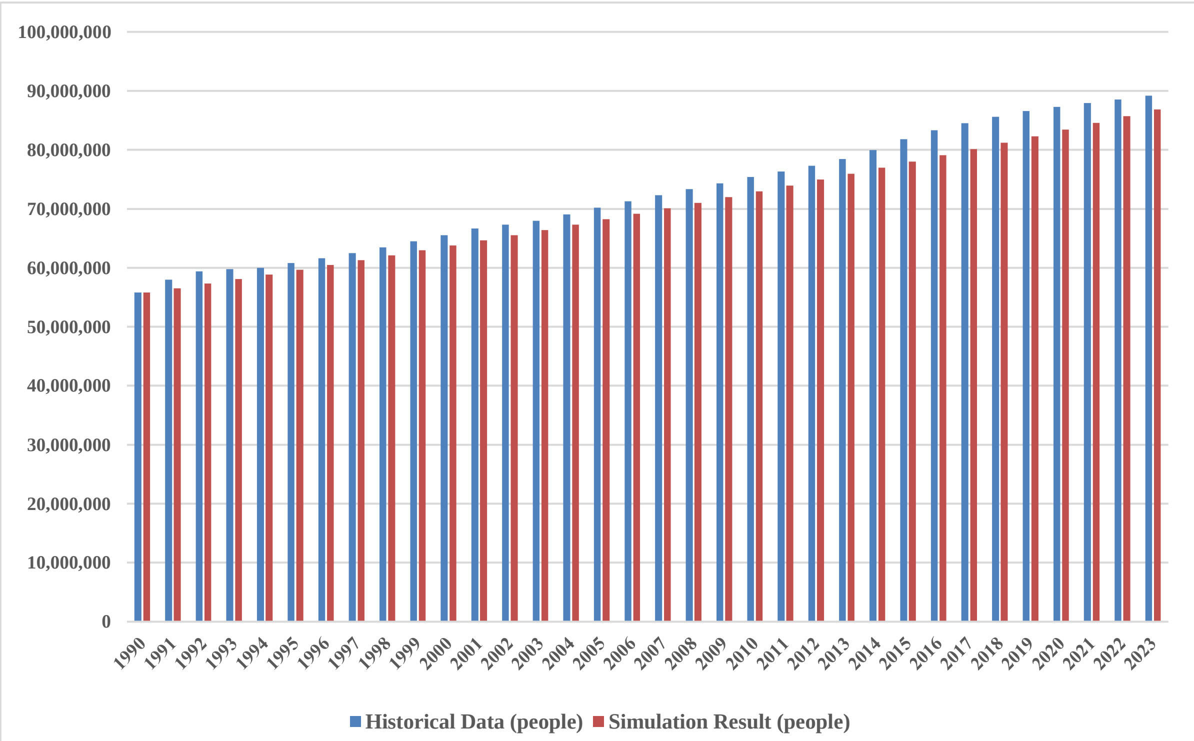

Figure 8. Iran's population simulation result and actual values

4.4.5. Reproduction Test for Power Generation

According to the energy balance sheet published by the Ministry of Energy in 2017, the production of electricity in various power plants in Iran over a ten-year period is described in the Table 5 (Vice President of Electricity and Energy Affairs of the Ministry of Energy, 2022), (The Atomic Energy Organization of Iran (AEOI), 2017). Because heating, gas, combined-cycle, and diesel power plants all emit carbon dioxide, they are grouped together as fossil power plants. In the SD model, the variable for electricity production by fossil power plants represents the total output of these plants.

Table 5. Iran's nominal electricity generation capacity by type of power plant

Year	Fossil Power Plant (MW)	Hydro Power Plant (MW)	Nuclear Power Plant (MW)	Renewable Power Plant (MW)	Total (MW)
2007	41928.1	7422.3	0	74	49424.4
2008	45209.2	7672.5	0	89.9	52971.6
2009	48708.7	7704.7	0	90.4	56503.8
2010	52871.6	8487.8	0	100	61459.4
2011	55350.8	8746.2	1020	105	65222
2012	58014.9	9746.1	1020	113.1	68894.1
2013	58832.4	10266.4	1020	117.1	70235.9
2014	61173.8	10789.3	1020	165.7	73148.7
2015	61631.8	11354.3	1020	179.3	74185.2
2016	63627.8	11579.8	1020	256.4	76484

Following Figures (9-10-11-12) compare actual data with simulation results.Figure10 shows a nearly linear trend in renewable electricity production, with a noticeable shift in slope after 2013. Due to the Bushehr nuclear plant's activation in 2011, a step function was added to the model, as shown in Figure11.

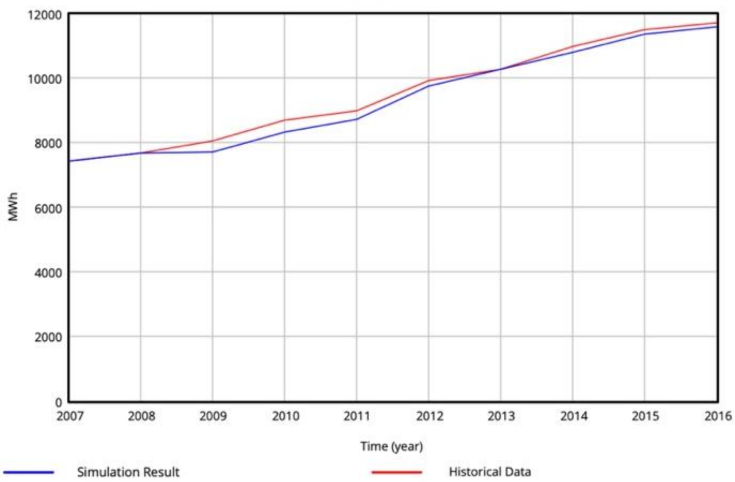

Figure 9. *Generation by hydro power plants*

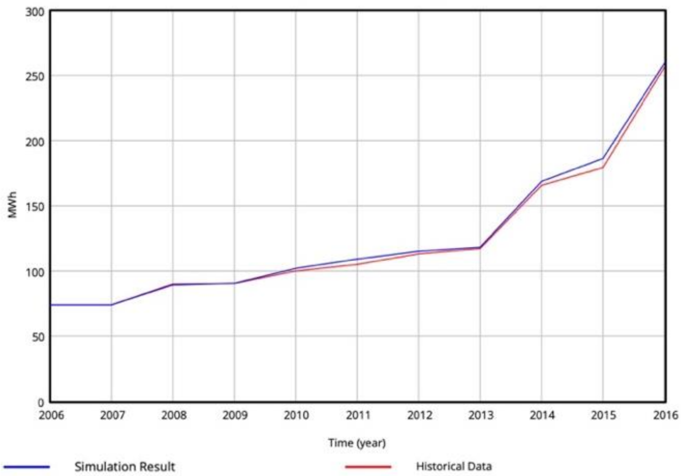

Figure 10. Generation by renewable power plants

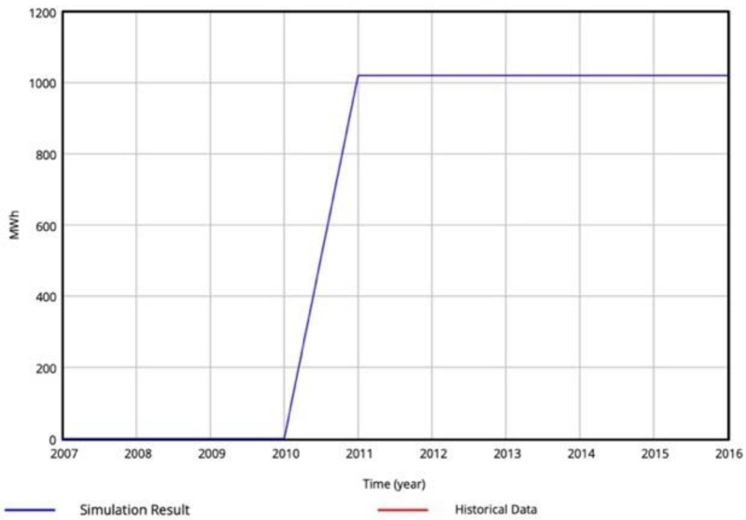

Figure 11. *Generation by nuclear power plants*

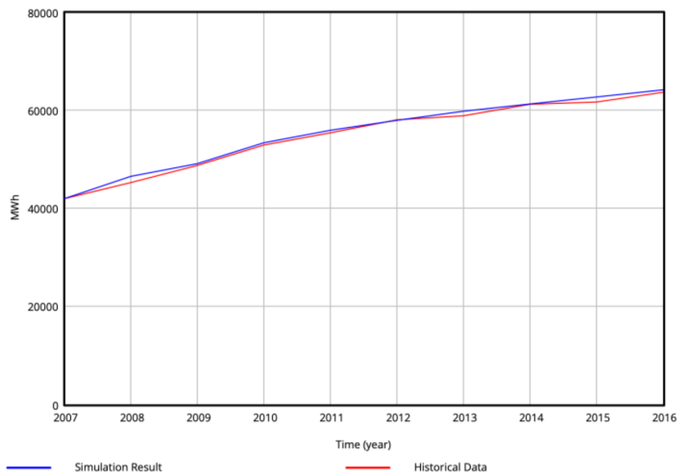

Figure 12. Generation by fossil power plants

4.4.6. Reproduction Test for Emission

Figure 13 shows the actual values and the simulation results related to the total carbon emission in fossil power plants. The calculated Mean Absolute Percentage Error (MAPE) is 2.92%, indicating high accuracy of the simulation model. This low error rate suggests that the model closely follows the historical trends in the data. Emissions from other power plants have been omitted.

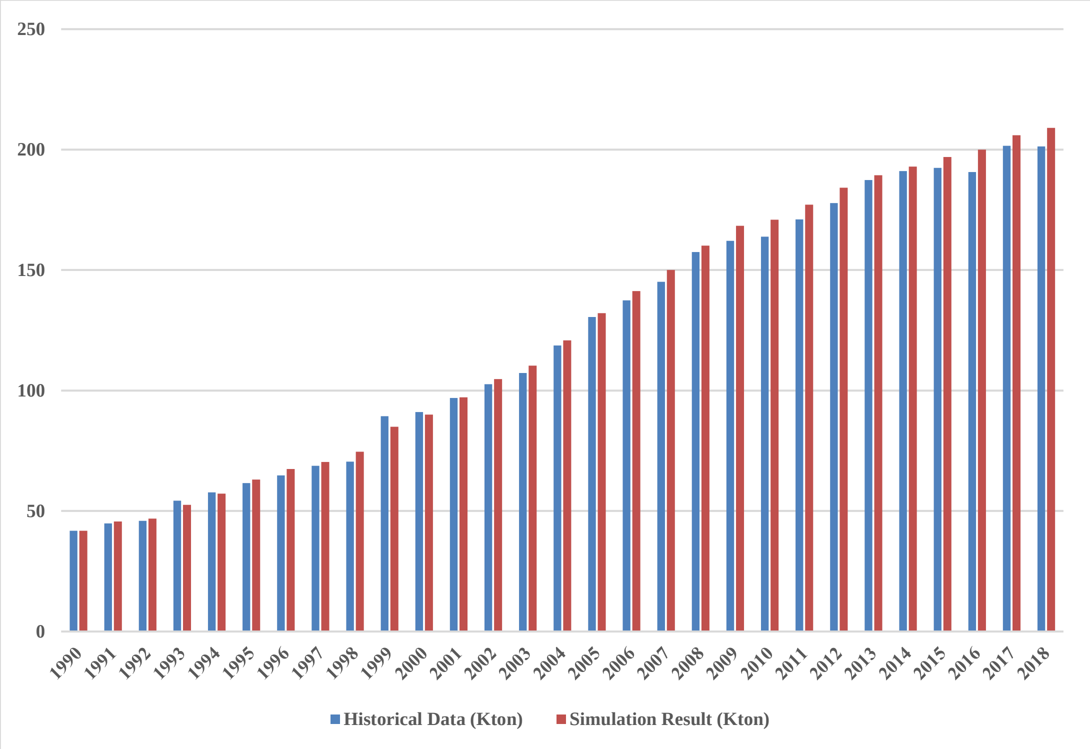

Figure 13. Compare of simulation results and real values in carbon emission

4.5. Policymaking and Results

After validation, policies should be analyzed. The policy levers should encompass the conditions of the underlying goals, along with incentives to achieve the desired outcomes. A combination of applicable policies and scenarios determines the policy matrix. Policy structure diagrams highlight the information that the modeler assumes decision-makers use to control the system's flow rate. The following sections present the diagrams of the policy structure for each area.

4.5.1. The Emission Trends Scenarios

In response to the first research question on emission trends associated with population change, this study will examine carbon emissions from electricity generation in Iran through 2050. The scenarios are defined based on three approaches: increasing, stabilising, and reducing the fertility rate. The dynamic system model is implemented accordingly. To account for the declining fertility rate, four scenarios are proposed based on the rate of decline. Figure 14 provides a detailed overview of these scenarios.

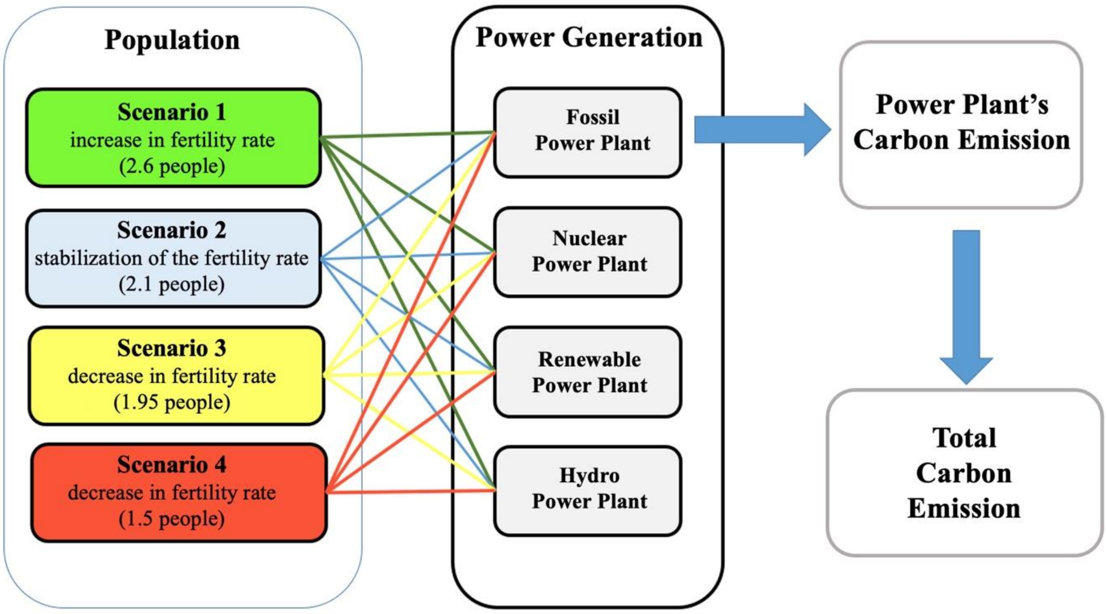

Figure 14. structure of population scenarios

4.5.1.1. First scenario: Increase in fertility rate (2.6 people)

In this scenario, assuming a total fertility rate of 2.6, the population, electricity generation, and CO_2 emissions are simulated for 2016–2051, as shown in Table 6 and Figure 15. These results reflect power plant sector outputs, excluding emission control mechanisms and feedback loops.

Table 6. Population, electricity generation, and carbon dioxide with a fertility rate of 2.6

Year	Population (person)	Power Generation (MW)				Carbon Emission (Kton)
		Fossil	Nuclear	Renewable	Hydro	
2016	80038167	63627.8	1020	256.4	11579.8	171687
2021	84258125	71076.7	1020	338.3	14219.8	191683
2026	88742989	78732.4	1020	420.2	16791.3	212471
2031	93466394	86388.2	1020	502.1	19362.8	232989
2036	98441254	94043.9	1020	584.0	21934.4	245461
2041	103681720	101699.7	1020	666.0	24505.9	258432
2046	109199280	109355.4	1020	747.9	27077.4	272166
2051	114875458	117011.1	1020	829.8	29648.9	286312

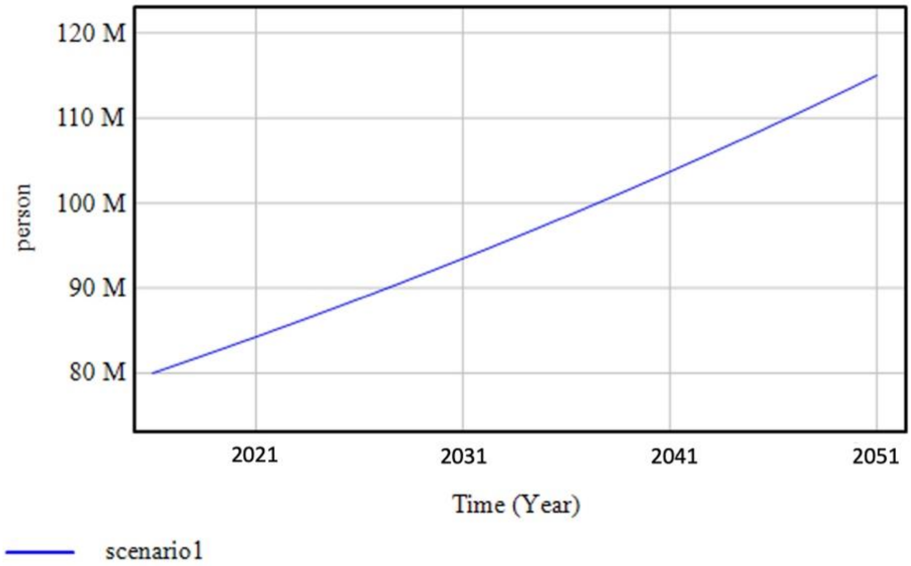

Figure 15. Population predict

4.5.1.2. Second scenario: Stabilisation of the fertility rate (2.1 people)

In this scenario, with the population stabilisation forecast, the total fertility rate is estimated at 2.12 children per household. Table 7 and Figure 16 show the simulation results for the population, electricity production, and carbon dioxide emissions in the period from 2016 to 2051.

Table 7. Population, electricity generation, and carbon dioxide, with a fertility rate of 2.1

Year	Population (person)	Power Generation (MW)				Carbon Emission from Power Plant (Kton)
		Fossil	Nuclear	Renewable	Hydro	
2016	80038167	63627.8	1020	256.4	11579.8	171687
2021	84974052	67586.4	1020	272.3	12274.5	181988
2026	89236244	70976.2	1020	285.9	12888.2	191087
2031	92821360	73827.6	1020	297.3	13403.7	198730
2036	96009001	76363.2	1020	307.4	13805.8	204691
2041	99013613	78757.5	1020	317	14219.9	210831
2046	101781474	80959.2	1020	325.8	14504.2	215047
2051	104017588	82737.5	1020	333.8	14794.2	219562

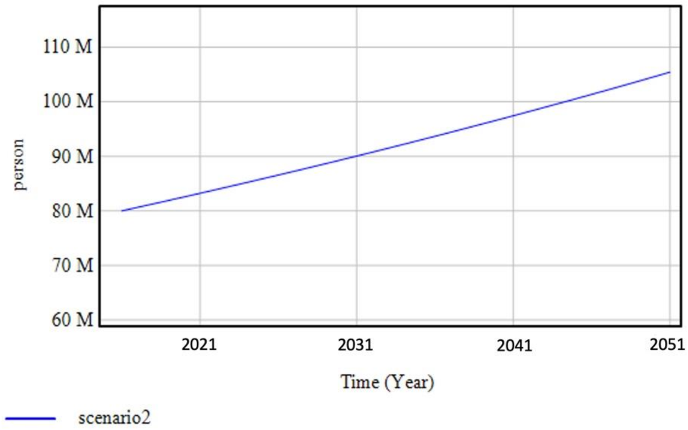

Figure 16. Population predict

4.5.2. Third scenario: decrease in fertility rate (1.95 people)

In this scenario, the population is assumed to decline, with a total fertility rate of 1.95 children per household. Table 8 shows the simulation results for population values, electricity production, and carbon dioxide emissions. Figure 17 shows the population from 2016 to 2051.

Table 8. Population, electricity generation, and carbon dioxide with a fertility rate of 1.95

Year	Population (person)	Power Generation (MW)				Carbon Emission from Power Plant (Kton)
		Fossil	Nuclear	Renewable	Hydro	
2016	80038167	63627.8	1020	256.4	11579.8	171687
2021	84912293	67507.6	1020	271.7	12274.5	181988
2026	89022406	70747.9	1020	284.7	12836.6	190723
2031	92338906	73365.5	1020	295.2	13339.5	197779
2036	95103985	75566.4	1020	304	13739.6	203712
2041	97590896	77531.1	1020	311.9	14096.8	209008
2046	99788488	79236.7	1020	318.7	14406.9	213606
2051	101392320	80504.4	1020	323.7	14637.4	217023

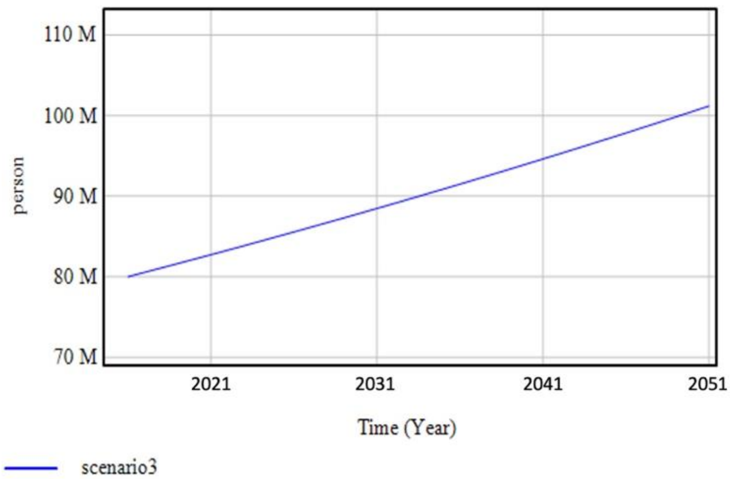

Figure 17. *Population predict*

4.5.2.1. *Fourth scenario: decrease in fertility rate (1.5 people)*

In scenario 4, the population trend is modeled with a sharper decrease in the total fertility rate of 1.5 children per household. Table 9 shows the simulation results for population values, electricity production, and carbon dioxide emissions, and Figure 18 shows the population from 2016 to 2051.

Table 9. Population, electricity generation, and carbon dioxide with a fertility rate of 1.5

Year	Population (person)	Power Generation (MW)				Carbon Emission from Power Plant (Kton)
		Fossil	Nuclear	Renewable	Hydro	
2016	80038167	63627.8	1020	256.4	11579.8	171687
2021	84785344	67404.2	1020	271.7	12274.5	181988
2026	88541099	70393.5	1020	283.6	12814.5	189995
2031	91141301	72460.6	1020	291.8	13186.1	195504
2036	93003091	73939.3	1020	297.6	13449.8	199414
2041	94428050	75072.1	1020	302	13651.5	202405
2046	95304218	75771.7	1020	304.7	13774.3	204226
2051	95317646	75779.6	1020	304.7	13775.6	204246

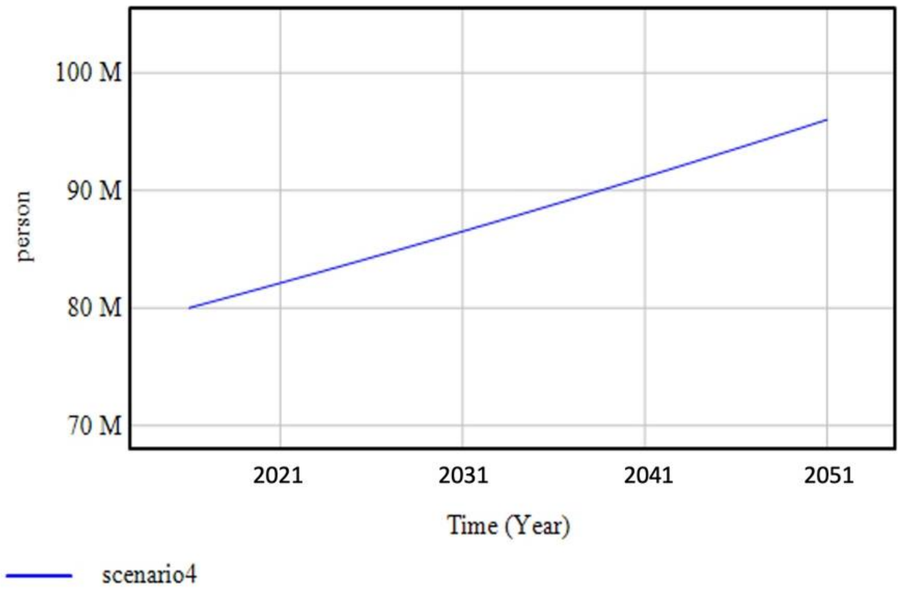

Figure 18. Population predict

After examining the population scenarios using the model and the electricity production values, the carbon dioxide emissions from power plant production were calculated for each of the four scenarios, based on population growth. Table 10 and Figure19 show the values of carbon dioxide production for four scenarios from 2016 to 2051.

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Table 10. Emissions for all scenarios

Year	Emission with fertility rate 2.6 people (Kton)	Emission with fertility rate 2.1 people (Kton)	Emission with fertility rate 1.95 people (Kton)	Emission with fertility rate 1. 5 people (Kton)
2016	171687	171687	171687	171687
2021	191683	181988	181988	181988
2026	212471	191087	190723	189995
2031	232989	198730	197779	195504
2036	245461	204691	203712	199414
2041	258432	210831	209008	202405
2046	272166	215047	213606	204226
2051	286312	219562	217023	204246

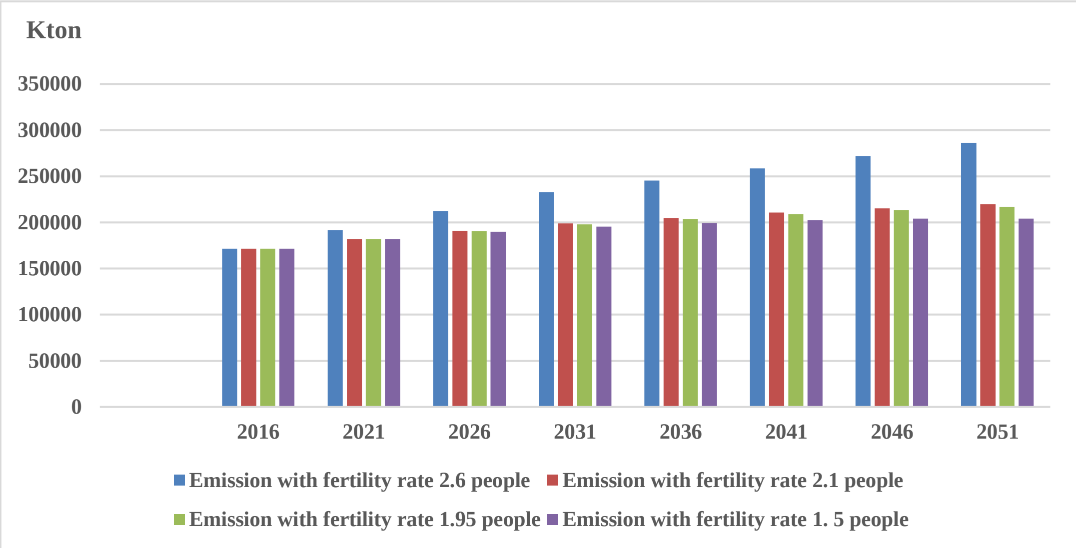

Figure 19. Carbon dioxide produced for different fertility rates

As illustrated in Figure 19 the population growth projected under Scenario 1 results in a significant rise in carbon dioxide emissions. In the absence of emission-control measures in the electricity generation sector, emissions are projected to increase by approximately 70% by 2051 relative to 2016 levels. Such an upward trajectory would surpass acceptable environmental thresholds, particularly in light of global efforts to reduce carbon emissions across all sectors. It is also noteworthy that, within the simulation framework, emissions from non-electricity sectors are assumed constant, and the graph depicts only emissions attributable to power plants.

4.5.3. The Renewable Energy Replacement Scenarios

The second policy focus of this study addresses the role of renewable electricity generation in response to demographic shifts. Given global carbon reduction commitments, Iran must also adjust its energy strategy. To capture this, the system dynamics model incorporates a feedback loop linking carbon-emission gaps to electricity production, thereby encouraging a shift from

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fossil fuels to renewables. The model explores scenarios based on varying rates of renewable adoption and demographic trajectories, particularly under two fertility assumptions: increasing vs. stabilised. Figure 20 illustrates the structure of this policy framework.

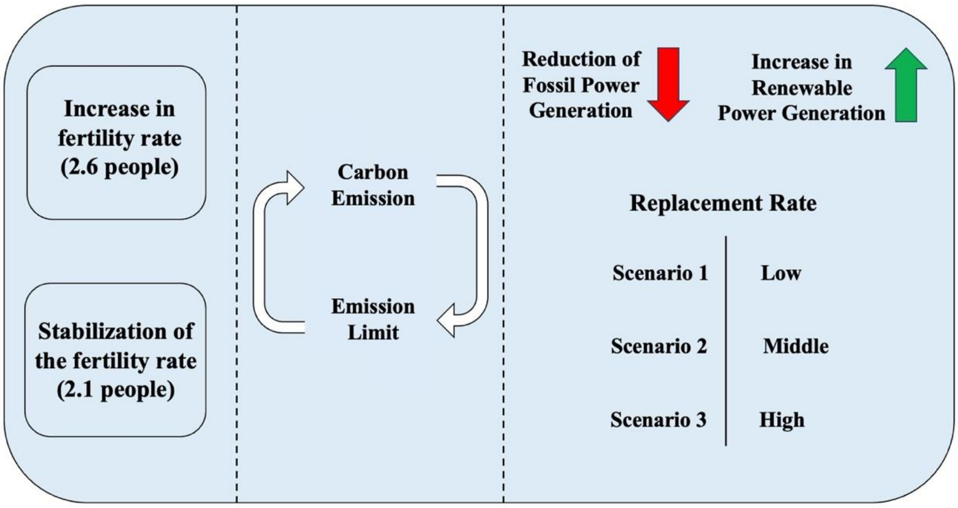

Figure 20. Structure of replacement policies

Three levels — high, medium, and low — have been established to evaluate the substitution coefficient of renewable electricity across different population scenarios. This approach accounts for the current capacity and growth rates of renewable energy sources, yielding three distinct trends in renewable electricity generation and the corresponding reduction in fossil-fuel-based power generation. Expanding solar and wind farms, alongside enhancing grid integration and energy storage systems, are two effective solutions.

4.5.3.1. First State (fertility rate 2.6)

In the first case, with a fertility rate of 2.6 and three substitution levels, the simulated renewable electricity generation is shown in Figure 21 The different levels are as follows :

- First scenario (high replacement rate): According to the amount of carbon emissions in this statistical scenario, the amount of carbon dioxide production in 2051 will be 286 Kton. Considering the high replacement rate, the amount of carbon dioxide emission for this scenario is considered to be 200 Kton.
- Second scenario (average replacement rate): In this scenario, the average replacement rate of carbon dioxide emissions is considered to be 220 Kton.
- Third scenario (low replacement rate): Due to the small amount of substitution, the emission limit for carbon is considered to be 240 Kton.

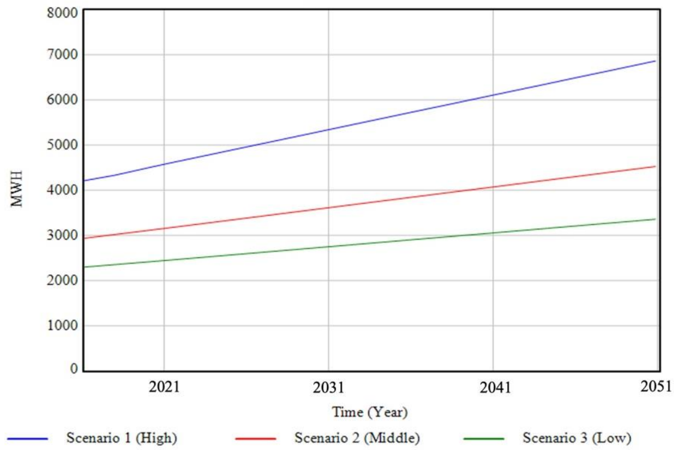

Figure 21. Renewable power generation in three scenarios according to the fertility rate of 2.6 people

4.5.3.2. Second State (fertility rate 2.1)

In the second scenario, with a fertility rate of 2.1 and three substitution levels, the simulation results for renewable electricity generation are depicted in Figure 22 The different levels are as follows:

- First scenario (high replacement rate): Due to the high replacement rate, the limit of carbon dioxide emissions for this scenario is considered to be 190 Kton.
- Second scenario (average replacement rate): In this scenario, the average replacement rate of the carbon dioxide emission limit of 200 Kton is considered.
- Third scenario (low replacement rate): Considering the small amount of replacement rate, the emission limit for carbon is considered to be 210 Kton.

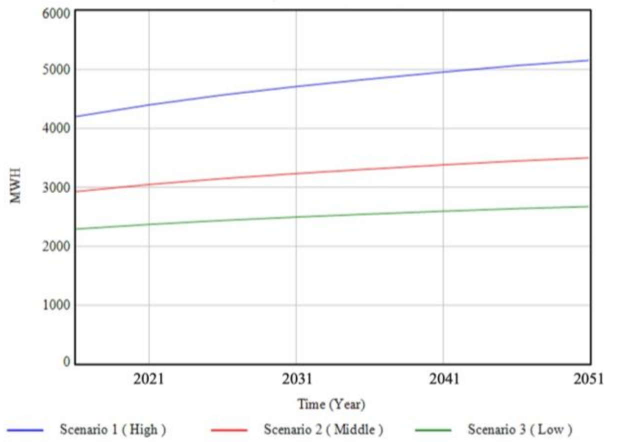

Figure 22. Renewable power generation in three scenarios according to the fertility rate of 2.1 people

The notable aspect of the output diagrams from the renewable electricity generation simulation is the production rate. The values presented in these two graphs represent the absolute production levels, not relative ones. Given that several renewable energy facilities (such as solar and wind farms) are already operational with an approximate combined capacity of 1100 megawatts, it is essential to subtract this existing capacity from the figures in the chart to determine the additional electricity required from new renewable power plants. This additional amount corresponds to the reduction in the share of electricity generated from fossil fuels.

Table 11 shows the simulation results for renewable energy development scenarios and their associated population states. In this table, the relative amount of production is given.

Table 11. Simulation results of the scenarios related to the second question

Year	First State (fertility rate 2.6)			Second State (fertility rate 2.1)		
	First scenario (high replacement rate) (MW)	**Second scenario (average replacement rate) (MW)**	**Third scenario (low replacement rate) (MW)**	**First scenario (high replacement rate) (MW)**	**Second scenario (average replacement rate) (MW)**	**Third scenario (low replacement rate) (MW)**
2016	3181.39	1908.834	1272.556	3181.39	1908.834	1272.556
2021	3553.835	2132.301	1421.534	3379.32	2027.592	1351.728
2026	3936.62	2361.972	1574.648	3548.81	2129.286	1419.524
2031	4319.41	2591.646	1727.764	3691.38	2214.828	1476.552
2036	4702.195	2821.317	1880.878	3818.16	2290.896	1527.264
2041	5084.985	3050.991	2033.994	3937.875	2362.725	1575.15
2046	5467.77	3280.662	2187.108	4047.96	2428.776	1619.184
2051	5850.555	3510.333	2340.222	4136.875	2482.125	1654.75

As shown in Figure 23, under high substitution scenarios, Iran must significantly expand its renewable electricity capacity in the coming decades. For example, in the high substitution case with a fertility rate of 2.6, renewable electricity generation is projected to increase by approximately 585% by 2051. This is nearly six times the current installed capacity, underscoring the critical need for strategic investments in solar, wind, and related infrastructure.

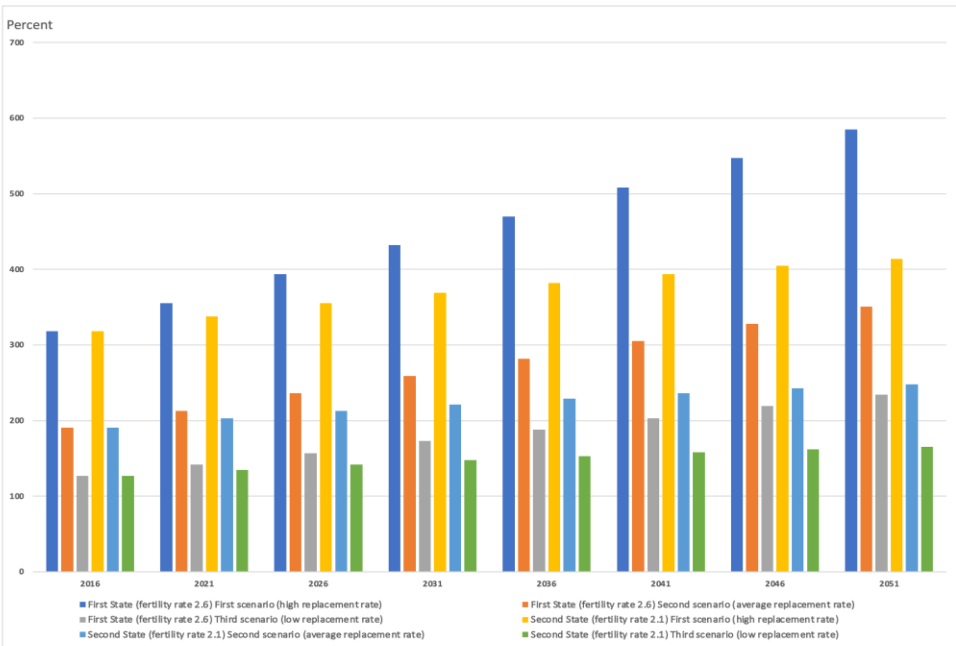

Figure 23. percentage of renewable power plant replacement in different scenarios

5. Discussion

This study developed a system dynamics model to assess how renewable electricity can replace fossil-fuel-based generation in Iran, accounting for demographic changes and varying fertility scenarios. The results indicate that under a high-fertility scenario (TFR=2.6), electricity demand will rise sharply by 2051, necessitating an approximately 585% increase in renewable electricity generation to meet energy needs without increasing carbon emissions. This expansion equals nearly six times the current installed capacity and aligns with findings by Karlilar Pata and Balcilar(2024), who confirmed the crucial role of renewables in reducing fossil fuel dependence in OECD countries.

The model highlights strong interdependencies between population growth, energy demand, and emissions. Without renewable energy expansion, the electricity deficit is met primarily by fossil fuels, leading to substantial increases in CO_2 emissions. Conversely, robust renewable deployment leads to emission reductions, especially after 2035, confirming the effectiveness of timely energy transition strategies—an insight consistent with studies by Zhang et al (2024) and Soylu et al (2024), who showed that integrated policy and renewable investments can significantly reduce carbon emissions.

While many studies, such as those by Lu et al. (2013) and Mohamed et al.(2024) focus on sectoral strategies for emissions reduction, it contributes a holistic systems-based view that incorporates population dynamics into long-term energy planning. Unlike static or linear models, the feedback structure employed here enables dynamic responses to shifting demographic and technological conditions, a modelling approach similar to that employed by Trappey et al. (2012) in Taiwan.

Moreover, this research extends prior literature by addressing the Iranian context, where feedback-based modelling approaches remain underdeveloped. It confirms the relevance of population-related variables in shaping electricity demand, supporting findings by Sahari et al.(2024), who emphasised the role of demographic and behavioral factors in influencing carbon footprints.

From a policy perspective, the results underscore the need for long-term investment in solar, wind, and grid infrastructure, as well as the modernisation of energy systems. These findings echo those of Chinese and Malaysian case studies (Li, Raza and Cucculelli, 2024; Mohamed et al., 2024; Li and Ren, 2017), which advocate for cleaner energy infrastructure and innovation-led growth. The integration of substitution scenarios also provides practical benchmarks for planners, indicating the amount of renewable capacity required under various demographic conditions.

However, the study has some limitations. Substitution coefficients are based on hypothetical assumptions, and the model does not account for political, financial, or technological uncertainties. Additionally, while the focus on the electricity sector is deliberate, broader interactions with other systems, such as water, land, and the economy, were excluded—potentially affecting policy outcomes.

6. Conclusion

Future research avenues should prioritise the integration of uncertainty analysis to strengthen the model's predictive reliability. Expanding the scope of sectoral linkages and incorporating advanced machine learning techniques—consistent with recent literature—are essential steps to capture the complexity of the energy landscape. Furthermore, broadening the analytical focus to encompass alternative renewable energy sources, such as geothermal and biomass, alongside the inclusion of decentralised energy systems, will significantly enhance the model's capacity to provide actionable insights for Iran's low-carbon transition.

This study used system dynamics modelling to examine how population growth affects electricity demand and carbon dioxide emissions in Iran. The model showed that as the population increases, electricity consumption rises sharply. This growth in demand leads to a significant increase in CO_2 emissions, especially when no policy changes are made and the system continues as usual.

To find solutions, different scenarios were tested. These scenarios focused on increasing renewable energy. The results showed that small or gradual policy changes are ineffective. Emissions will not drop much with weak actions. Only sustained investment in renewables such as solar, wind, and hydropower can reduce emissions over time. Nuclear energy can provide a short- to medium-term benefit, but it cannot replace renewables in the long run.

Along with infrastructure, supportive laws and financial incentives are essential. These can encourage private and public investment in clean technologies and help reduce fossil fuel consumption. Policies should also aim to more strictly control emissions.

Although this model was developed for Iran, the insights apply to many other countries. Nations with rapid population growth and rising energy needs face similar challenges. This dynamic modelling approach can help design better policies and guide countries toward a cleaner and more sustainable energy future.

For researchers interested in related fields, the following suggestions are provided:

- This research treats carbon dioxide "production" as "emission" without distinguishing between the two. The model does not account for changes in the "carbon absorption rate." By incorporating absorbent filters and accounting for industrial carbon consumption, it is possible to prevent significant carbon emissions into the environment. Evaluating the carbon absorption rate using these filters can yield dynamic insights into carbon emission reduction.
- The population model should reflect more accurate changes in birth and death rates to better represent real-world population dynamics. The immigration rate was not considered in this research.
- Financial aspects were not explored in this research. Introducing financial terms related to the development and scaling of renewable energy infrastructure (e.g., solar, wind, hydropower) could optimise the research by combining a dynamic model with an optimisation study.
- Future research should enhance the renewable energy subsystem by incorporating more realistic dynamics such as intermittency, investment cycles, and grid capacity limits, which were simplified in the current model. In addition, scenario design should be more closely aligned with Iran's actual policy frameworks and technical constraints to improve the applicability and validity of the results.

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