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Mitigating Iran's Electricity Deficit through Household Photovoltaic Expansion: A System Dynamics Approach with Impact Analysis on CO_2 Emissions and Water Resources

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ABSTRACT

This study employs System Dynamics modeling to assess the expansion of household photovoltaic (PV) systems as a strategy to mitigate Iran's electricity deficit, which is exacerbated by urban air pollution, reliance on fossil fuels, and natural gas shortages. By evaluating five investment allocation scenarios between household PV and thermal power plants, the findings indicate that an optimal configuration consists of a 75% PV and 25% thermal power split. Under this scenario, the capacity deficit is reduced to 5.6 GW by 1412, significantly outperforming conventional thermal expansion, which results in a 25.2 GW shortfall. By 1430, this policy enables PV generation to reach 457.6 TWh, supplying 58.9% of total electricity demand while reducing CO_2 emissions by 69.8 million tons and water consumption by 340.1 billion m^3. These improvements contribute to enhanced air quality, reduced water scarcity, and decreased dependence on natural gas. Nevertheless, the results reveal that even extensive PV deployment cannot fully satisfy long-term electricity demand, with a projected shortfall of 15.4 GW by 1430 under the optimal scenario. While household PV systems offer substantial short- and mid-term advantages, a holistic energy strategy incorporating diverse solutions remains essential to ensuring Iran's long-term energy security

Keywords

Energy Imbalance, Household Photovoltaic, Energy Policy, CO2 emission reduction, Water resource management, System dynamics.

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1. Introduction

Electricity is a fundamental pillar of modern civilization, essential for socio-economic development, technological progress, and quality of life. Reliable electricity supply underpins industrial productivity, economic growth, and social stability, aligning with the United Nations Sustainable Development Goals (UN-SDGs), particularly Goal 7, which advocates for universal access to affordable, reliable, and sustainable energy by 2030 (Audinet et al., 2010; Danso-Wiredu et al., 2016; Doroodi et al., 2024; Khan et al., 2020; Mahbub, 2023; Mukhtar et al., 2021; Zhang et al., 2024). In developed nations, electricity consumption closely correlates with economic expansion, acting as a catalyst for prosperity (Bank, 2010; Danso-Wiredu et al., 2016; Vasconcelos et al., 2021).

Despite its abundant fossil fuel reserves and significant renewable energy potential, Iran faces critical challenges in its electricity sector. The country's heavy reliance on fossil fuels—primarily natural gas and oil, which constitute 88.1% of the energy mix—has become increasingly unsustainable as surging demand outpaces supply (Asadi et al., 2023). In the current Iranian year alone, electricity demand has risen by 6,000 megawatts (MW), pushing peak consumption to approximately 80,000 MW, while supply struggles to keep pace, resulting in a peak deficit of up to 18,000 MW (Energypress, 2024; Tehran Times, 2024).

This electricity crisis is exacerbated by several factors, including aging power generation infrastructure—many plants exceed 30 years in operation—leading to inefficiencies, high maintenance costs, and operational losses. Additionally, energy subsidies encourage excessive consumption while discouraging investment in efficient technologies and renewable energy (Aryanpur et al., 2019; Tofigh and Abedian, 2016). Despite a nominal generation capacity of around 90,000 MW, actual output remains significantly lower at approximately 75,000 MW due to inefficiencies and transmission losses of about 13% (Asadi et al., 2023; Tehran Times, 2024; Shokri, 2024).

The industrial sector bears the brunt of these shortages, with potential annual losses estimated between $6 billion and $8 billion due to production disruptions (News.Az, 2024; Shokri, 2024). Furthermore, power shortages disrupt essential services such as healthcare and education, contributing to economic instability. According to World Bank studies, power disruptions can reduce economic growth by 2% and GDP by approximately 7% (Fisher-Vanden et al., 2012; Usman, 2022; Zhang, 2018). Although Iran possesses favorable conditions for renewable energy, its share in electricity generation remains below 1%, highlighting a missed opportunity for diversification (Shokri, 2024).

Addressing these challenges requires a comprehensive transformation of Iran's energy policy. Key priorities include diversifying the energy mix by integrating renewable sources, improving efficiency through technological advancements and demand management, reforming energy pricing structures, and enhancing financial stability to attract private investment (Aryanpur et al., 2019; Tofigh and Abedian, 2016). A sustainable energy strategy that integrates household-level renewable solutions is crucial for mitigating Iran's electricity deficit while promoting economic growth and environmental sustainability.

This study examines the expansion of household photovoltaic (PV) systems as a viable solution, employing a system dynamics approach to model Iran's electricity sector. The system dynamics framework effectively captures the intricate interactions and feedback loops within energy systems, enabling a dynamic understanding of household PV adoption, infrastructure limitations, and policy interventions (Balázs et al., 2024; Roybal and Jeffers, 2013).

The study's goals are to (1) identify the key factors contributing to electricity deficits, with a focus on household consumption, (2) develop a system dynamics model that incorporates the impact of PV systems, (3) assess the effectiveness of policy measures such as incentives for PV installation and energy efficiency programs, and (4) propose long-term scenarios that highlight the role of household PV systems in mitigating electricity imbalance. This analysis aims to provide actionable recommendations for promoting household PV adoption as a cornerstone of sustainable electricity management in Iran.

The paper is organized as follows: Section 2 reviews electricity imbalances in Iran, the role of system dynamics, global renewable energy integration, research gaps in household photovoltaics, and the study's contribution. Section 3 outlines the methodology, including causal loop diagrams, stock and flow diagrams, investment redistribution, and environmental analysis. Section 4 presents the results, validation through behavior tests, and policy assessment. Section 5 concludes with findings and recommendations for addressing Iran's electricity challenges.

2. Literature review

The challenge of electricity deficits has been extensively studied, with various solutions proposed to enhance energy security. As shown in Table 1, which summarizes key literature in this field, researchers have approached this problem from multiple angles, including power shortage resilience, demand-side management, sustainable power system transitions, and renewable energy integration.

Research highlights that distributed photovoltaic (PV) generation can enhance energy resilience, reduce reliance on fossil fuels, and contribute to reductions in greenhouse gas (GHG) emissions. Karbasioun's study (Karbasioun et al., 2023), which applied System Dynamics modeling and Multi-Criteria Decision Analysis, examined Iran's sustainable power system transition over the 2016–2040 period. It prioritized combined cycle systems and water-efficient renewable technologies to address concerns about efficiency and water scarcity.

Studies on energy transitions in fossil-fuel-rich countries emphasize the integration of decentralized renewable energy sources into existing grids. However, they often focus on large-scale renewable projects rather than addressing immediate electricity deficits at the household level (Alasseri et al., 2017). Alasseri's research on Kuwait specifically recommended Incentive-Based Demand Response Programs (IBDRP) as more suitable than price-based programs due to the country's low, flat electricity rates.

Economic and environmental dispatch models have been explored to optimize the integration of renewable energy sources while maintaining grid stability. Pazheri's study in Malaysia investigated optimal energy dispatch strategies in renewable-rich areas using an optimization model that considered the integration of renewable energy and storage. However, financial barriers and the lack of regulatory frameworks continue to hinder the adoption of large-scale household PV (Pazheri et al., 2012) .Hsu (2012) examined the effectiveness of feed-in tariffs in promoting the adoption of renewable energy in Taiwan using System Dynamics modeling. While these studies acknowledge the benefits of renewable energy, they do not specifically focus on household PV systems as a direct solution to electricity deficits, leaving a critical gap in understanding their role in mitigating shortages in countries like Iran.

System Dynamics (SD) modeling has been widely applied to energy planning, particularly in assessing policy impacts and supply-demand dynamics. As evident from Table 1, multiple studies on Iran's electricity sector have employed SD approaches (Doroodi et al., 2024). Doroodi et al. (2024) evaluated long-term policy interventions on renewable energy deployment and fossil fuel consumption through 2040 using SD modeling combined with the Taguchi Design of Experiments for parameter optimization. Their study examined the impact of various factors, including export price, import cost, carbon damage, and budget allocation, on the economic and environmental sustainability of Iran's electricity industry.

Electricity subsidy policies have been studied to understand their effects on overconsumption and inefficiencies in power plant operations, highlighting the need for pricing reforms (Dehghan et al., 2021). Dehghan's research analyzed the impact of capacity payment mechanisms on

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generation capacity expansion decisions using SD modeling to simulate market behavior. In a subsequent study, Dehghan et al. (2022) proposed a Stackelberg game model for coordinating generation capacity expansion decisions, taking into account both electricity market competition and natural gas consumption optimization.

Scenario-based SD modeling has also been used to propose an 80% allocation of capacity development to renewable sources, demonstrating a significant reduction in CO_2 emissions (Doroodi et al., 2024). Kachoee et al. (2018) specifically addressed electricity demand and supply in Iran through 2040, using econometric methods for demand modeling and the LEAP model for supply simulation. They recommended policies to promote renewable energy development and decrease reliance on fossil fuels. However, these studies largely focus on energy transition strategies rather than addressing the immediate and growing electricity deficit, particularly through decentralized solutions such as household PV expansion.

The environmental and economic benefits of household PV adoption have been well documented. Large-scale PV deployment can help alleviate urban air pollution and mitigate the effects of climate change by replacing fossil fuel-based electricity generation (Masoomi et al., 2022). Masoomi's research, which utilized the LEAP software for demand simulation and supply optimization through 2035, highlighted that implementing demand-side management reduces social costs and emissions from thermal power plants, thereby contributing to economic, social, and environmental sustainability. In Iran, where water-intensive thermal power plants dominate the energy mix, shifting towards solar PV can substantially reduce water consumption. Studies emphasize the need for government incentives and consumer engagement to promote the adoption of renewable energy (Alasseri et al., 2017). However, there is a lack of research directly evaluating household PV as a targeted solution to Iran's electricity deficit.

Other relevant studies in Table 1 include power shortage resilience planning (Olausson, 2019), which recommended improvements to Sweden's STYREL planning system, and research on micro-combined heat and power in Great Britain's residential sector (Ben Maalla and Kunsch, 2008), which assessed the market penetration potential of this technology. Fasihizadeh et al. (2014) developed simulation algorithms to improve the operation of gas transmission networks in Iran, though their work focused specifically on natural gas rather than electricity.

This study addresses this critical gap by developing a System Dynamics model to assess household PV expansion as a direct solution to Iran's electricity deficit. Unlike previous research that primarily examines large-scale energy policies, this study focuses on how household PV adoption can effectively mitigate supply shortages. By integrating electricity

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supply-demand dynamics, technical constraints, and socio-economic factors, this research offers a novel perspective on utilizing decentralized renewable energy to address electricity deficits, rather than solely transitioning to renewables for long-term sustainability.

As indicated in Table 1, this study examines the 1404–1430 (2025–2052) time horizon in Iran, specifically focusing on household PV systems and thermal power plants using System Dynamics modeling. This study will present the optimal policy recommendation for financial investment, aiming to mitigate the capacity deficit. Additionally, the inclusion of an environmental analysis enhances the understanding of how household PV adoption contributes to sustainable electricity management. By filling this gap, this research aims to provide actionable insights into how household PV systems can serve as a key component in reducing Iran's electricity deficit while complementing broader energy policies.

In Table 1, the explanation of the "Purpose of the Model"column is as follows:

1. **Power shortage:** Does the model address issues related to electricity shortages or deficits?
2. **Supply-side management:** Does the model focus on managing and optimizing electricity generation and supply?
3. **Demand-side management:** Does the model consider strategies to influence and manage electricity consumption?
4. **Technical:** Does the model primarily address technical aspects of the electricity system, such as infrastructure and technology?
5. **Economic:** Does the model analyze economic factors related to electricity, such as costs, pricing, and investment?
6. **Environmental:** Does the model assess the environmental impacts of electricity generation and consumption?
7. **Social:** Does the model consider social implications related to electricity access, affordability, and equity?
8. **Renewable Energy and Pricing Integration:** Does the model examine the integration of renewable energy sources and their impact on electricity pricing?

Table 1. Overview of key studies on electricity deficits, renewable integration, and system dynamics modeling

Study Reference	Focus Area	Recommended Policy/Result	Methodology & Tools	Carriers/ Technologies Sector	Case Study	Time Horizon	Purpose of the Model* (Yes/No)							
							1	2	3	4	5	6	7	8
(Olausson, 2019)	Power shortage resilience planning	STYREL planning system improvements: - Increased resource allocation for local coordinators. - Enhanced feedback mechanisms for improved system trust and effectiveness.	Document analysis, interviews, and surveys of local and regional coordinators.	Electricity	Sweden	Not specified	✓	×	×	✓	×	×	✓	×
(Alasseri et al., 2017)	Demand-Side Management (DSM) in electricity markets	Implementation of Incentive-Based Demand Response Programs (IBDRP): - Due to Kuwait's low, flat electricity rates, Price-Based Demand Response Programs (PBDRP) are unsuitable. - IBDRP offers a more viable solution for reducing peak load and energy consumption.	Literature review and SWOT analysis of various DSM subcategories, including DR and IBDRP.	Electricity	Kuwait	Not specified	×	✓	✓	×	×	✓	×	×
(Karbasioun et al., 2023)	Sustainable power system transition in fossil fuel-rich countries	Prioritize combined cycle systems: Enhancing current energy system efficiency through the implementation of combined cycle systems is crucial. Implement water-efficient renewable technologies to address concerns about water scarcity.	SD modeling, Multi-Criteria Decision-Analysis (MCDA) using AHP-TOPSIS.	Electricity, Renewable Energy	Iran	2016-2040	×	×	×	✓	✓	✓	✓	✓
(Masoomi et al., 2022)	Demand-Side Management (DSM) for sustainability in Iran's electricity sector	Optimize electricity supply and demand: Implementing DSM reduces social costs and emissions from thermal power plants. - This contributes to economic, social, and environmental sustainability.	LEAP software for demand simulation and supply optimization, incorporating emission limit scenarios.	Electricity	Iran	Until 2035	×	×	✓	×	✓	✓	×	×
(Kachoee et al., 2018)	Electricity demand and supply in Iran	Develop renewable technologies: To reduce fossil fuel reliance and carbon emissions, implement policies that promote the development of renewable energy.	Econometric methods for demand modeling, the LEAP model for supply simulation under various scenarios.	Electricity, Renewable Energy	Iran	Until 2040	×	×	×	×	✓	✓	×	✓
(Ben Maalla and Kunsch, 2008)	Micro-combined heat and power (m-CHP) in the residential sector	The study focuses on assessing the potential of m-CHP technology.	System dynamics model to analyze the market penetration of m-CHP and forecast future installations.	Natural gas, electricity (m-CHP with Stirling engines)	Great Britain	Not specified	×	×	×	✓	✓	×	×	×

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Study Reference	Focus Area	Recommended Policy/Result	Methodology & Tools	Carriers/ Technologies Sector	Case Study	Time Horizon	Purpose of the Model* (Yes/No)							
							1	2	3	4	5	6	7	8
(Pazheri et al., 2012)	Economic and Environmental Dispatch in Renewable-Rich Areas	Investigate optimal energy dispatch strategies, including economic and environmental considerations, in areas with significant renewable energy potential.	Optimization model for economic and ecological dispatch, considering the integration of renewable energy and storage.	Electricity, Renewable Energy (solar, wind)	Malaysia (renewable-rich area)	Not specified	×	×	×	×	✓	✓	×	✓
(Fasihizadeh et al., 2014)	Natural Gas (NG) transmission network optimization in Iran	Develops simulation algorithms to improve the operation of gas transmission networks.	Simulation modeling using algorithms for optimizing gas transmission network operations.	Natural gas	Iran	Not specified	×	×	×	✓	×	×	×	×
(Dehghan et al., 2021)	Generation Capacity Expansion in Iran's Electricity Market	Analyzes the impact of capacity payment mechanisms on generation capacity expansion decisions, considering both short-term and long-term market dynamics.	SD modeling to simulate market behavior and capacity expansion decisions.	Electricity (includes thermal, hydro, and renewable sources)	Iran	Not specified	×	✓	✓	✓	✓	✓	×	✓
(Dehghan et al., 2022)	Sustainable Electricity Supply and Natural Gas Consumption Optimization in Iran	Proposes a Stackelberg game model for coordinating generation capacity expansion decisions, considering both electricity market competition and natural gas consumption optimization.	Bilevel optimization using the Stackelberg game model, considering electricity market dynamics and natural gas constraints.	Electricity (thermal, hydro, renewable) and Natural Gas	Iran	Not specified	×	✓	×	✓	✓	✓	×	×
(Doroodi et al., 2024)	Sustainable Electricity Industry Growth in Iran	Investigates the influence of various factors (export price, import cost, carbon damage, budget allocation) on the economic and environmental sustainability of Iran's electricity industry.	SD modeling combined with Taguchi Design of Experiments (TDOE) for parameter optimization.	Electricity (thermal, hydro, renewable)	Iran	Until 2040	×	×	×	×	✓	✓	×	✓
(C. W. Hsu, 2012)	Renewable energy development in Taiwan	Evaluates the effectiveness of feed-in tariffs (FITs) in promoting renewable energy adoption in Taiwan.	SD modeling to simulate the impact of FITs on renewable energy investments.	Renewable Energy (solar PV)	Taiwan	Not specified	×	×	×	×	✓	×	×	✓
This study	**Mitigating Iran's electricity deficit through household photovoltaic expansion**	**Optimal policy for financial investment reduces capacity deficit**	**SD modeling**	**Household PV systems, thermal power plants**	**Iran**	**1404–1430 (2025–2052)**	✓	✓	✓	✓	✓	✓	×	✓

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3. Research methodology and framework

The research methodology employed in this study consists of five key steps:

1. **Data Collection**: Relevant data were gathered based on the research questions to provide a structured foundation for the study.
2. **Case Study Selection and Policy Identification**: A case study was selected, and multiple policy scenarios were identified for analysis.
3. **Policy Design**: The identified policies were developed and structured to align with the study's objectives.
4. **Model Development**: A comprehensive modeling framework was designed and constructed, incorporating environmental factors for policy evaluation.
5. **Model Validation**: The gathered data were utilized to test, validate, and refine the developed model, ensuring its reliability and accuracy.

To simplify real-world complexities, this study incorporated several assumptions. These assumptions include:

- The system's primary variables were validated using a Structurally Oriented Behavior Test-Behavior Reproduction over 20 years, from 2005 to 2024 (corresponding to the years 1384 to 1403).
- It is assumed that over time, advancements in science and technology will reduce energy-related investment costs. However, for this study, investment costs were kept constant over the 27 years, maintaining the value from the first year.
- The model was designed to evaluate conditions in the medium term, focusing on a 27-year horizon from 1404 to 1430 (2025–2052), as it is anticipated that global policies will change after 2052. All costs are expressed in US dollars (USD), based on fixed values from 1394 (2015).
- Technological improvements in transformation and refinement were assumed to be integrated with the average characteristics of Iran's energy system.
- Due to Iran’s limited nuclear power capacity (10,000 MW) and slow development, nuclear power plants were excluded from the model. Additionally, this study focuses only on household photovoltaic systems, leaving the development of other renewable energy sources outside the scope.
- All domestic energy consumption, both renewable and non-renewable, was included in the calculations.
- Thermal recycling and cogeneration systems were excluded due to their limited implementation and minimal impact on energy production in Iran.

To gather the necessary data for model design and implementation, this study relied on various sources, including journals, the World Bank, the International Energy Agency (IEA), the Intergovernmental Panel on Climate Change (IPCC), the U.S. Energy Information Administration (EIA), as well as local references such as the Ministry of Energy, the Ministry of Petroleum, and the Central Bank of Iran. The datasets used for restructuring and evaluating the study’s results can be made available upon request.

3.1. Dynamics hypothesis, causal loop diagrams, and stock and flow diagrams

The causal loop diagram (CLD) in Figure 1 outlines the structure of Iran's electricity system, consisting of two main components: Total electricity demand and Total power generation. The difference between these two variables, the Power deficit, is the central focus of this study. Also, the stock and flow diagrams (SFD) of Iran's power industry are presented, with Figure 2 illustrating the technical modeling and policy implementation related to the power deficit issue, and Figure 3 highlighting the environmental analysis used to compare policy alternatives. The feedback loops incorporated into the System Dynamics (SD) model are detailed in Table 2.

Table 2. Loops in the system dynamics modeling of the power generation industry of the study

Loop Type	Loop number	Loop name
Reinforcing	R1[1]	Population
	R2	Household Demand Propensity for Electricity
	R3	GDP
	R4	Natural Gas Consumption and Thermal Power Plant Generation
Balancing	B1[2]	Total Electricity Demand and Power Deficit
	B2	Price-Driven Household Electricity Demand
	B3	Production and Services Electricity Demand
	B4	Thermal Power Plant Capacity
	B5	Natural Gas Production Capacity
	B6	Household PV Capacity
	B7	Investment Absorbed for Household PV Expansion for Compensate Power Deficit
	B8	Investment Absorbed for Thermal Power Plant Expansion for Compensate Power Deficit (or Total Electricity Supply and Power Deficit)

[1] R: Reinforcing Loop

[2] B: Balancing Loop

 DOI: 10.22067/JSTINP.2025.91753.1140

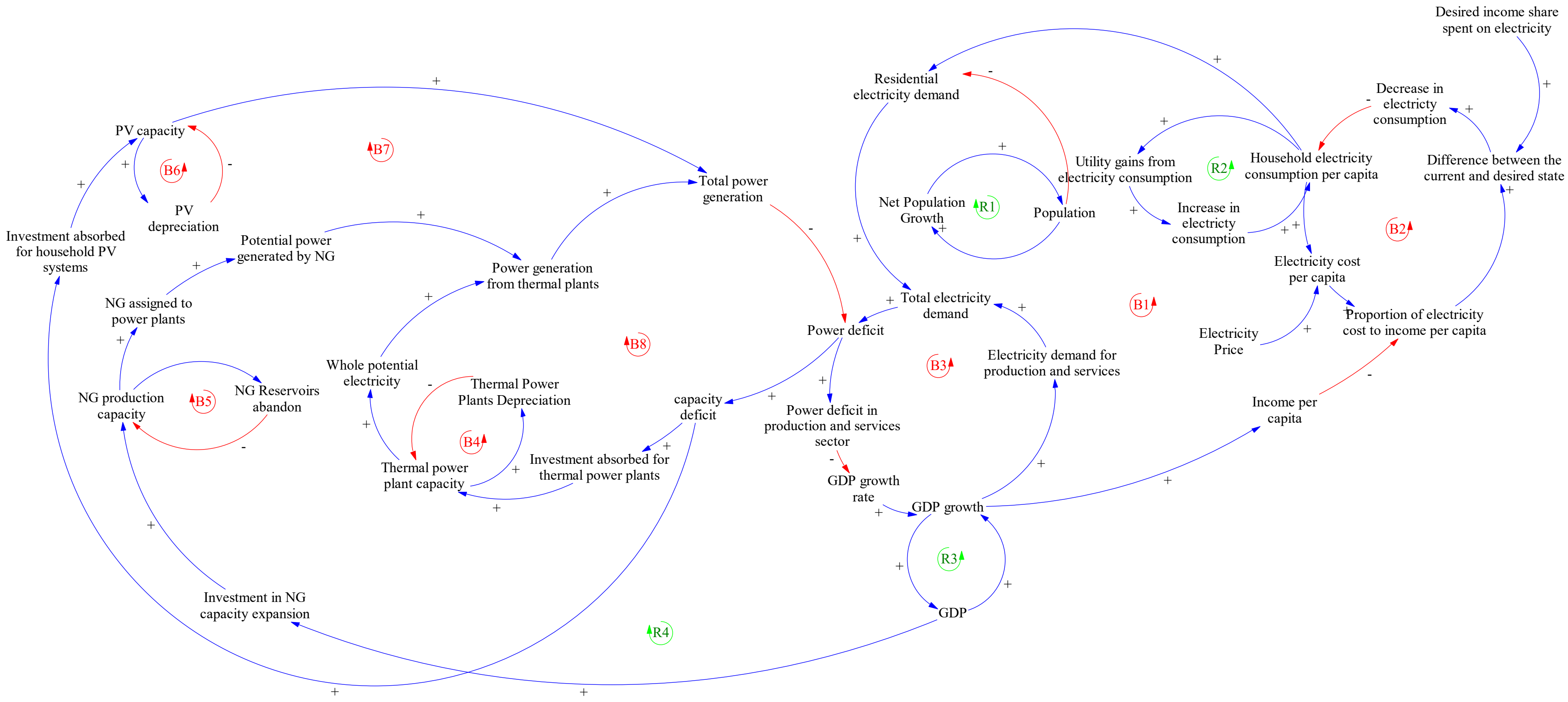

Figure 1.Casual loop diagram (CLD) of Iran's power industry highlighting the power deficit challenge

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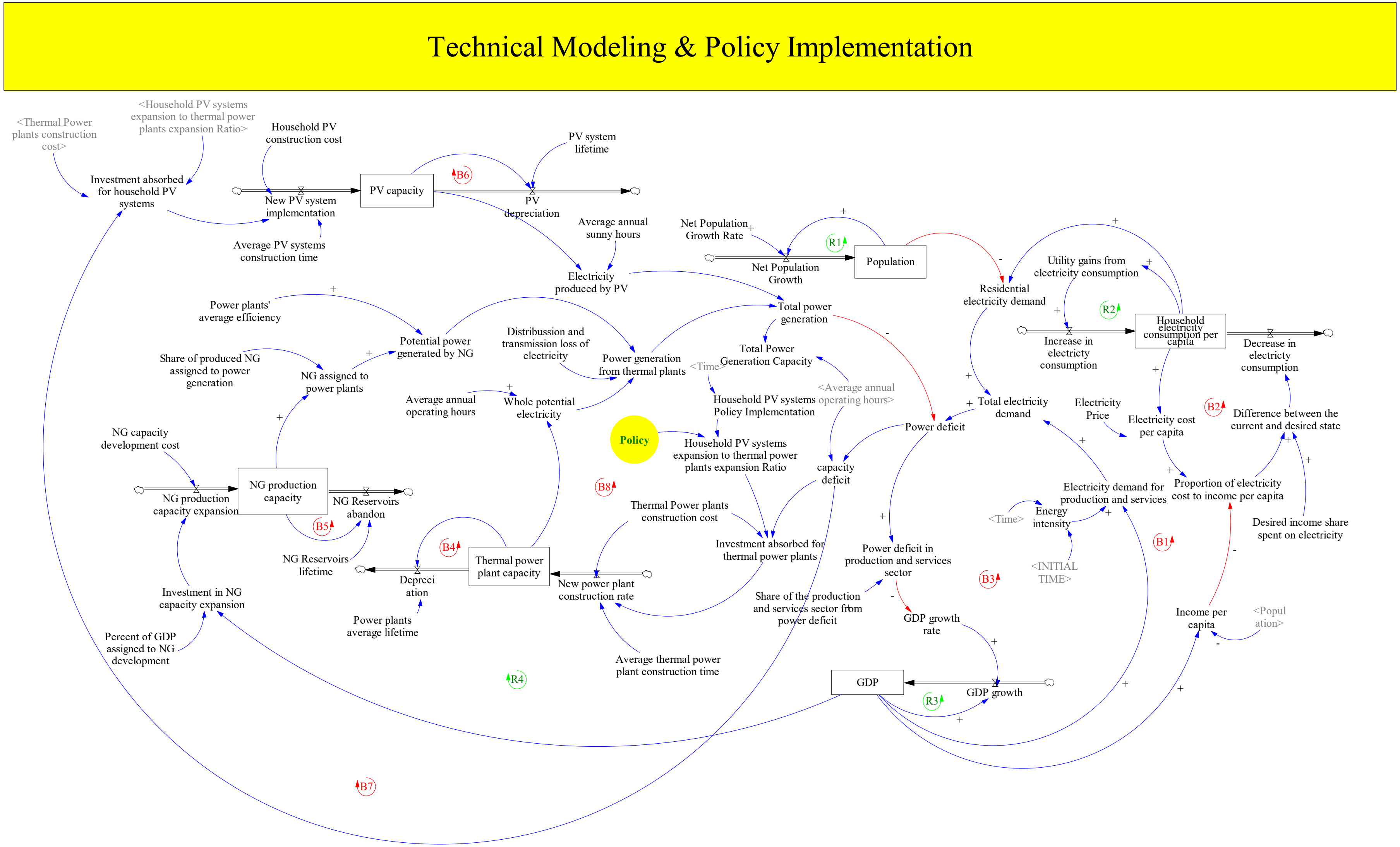

Figure 2. Stock and flow diagram (SFD) of Iran's power industry highlighting the power deficit issue - technical modeling, and policy implementation

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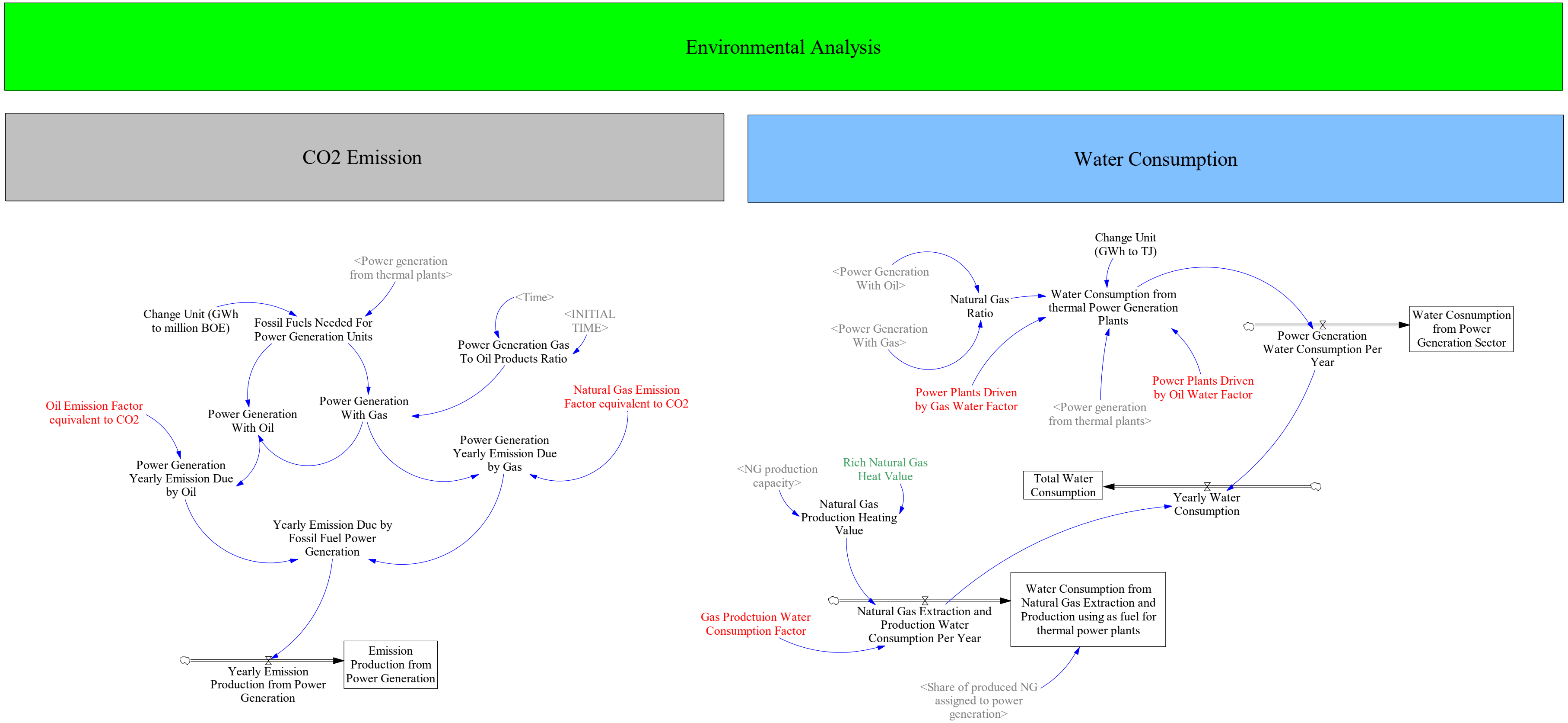

Figure 3. Stock and flow diagram (SFD) for environmental analysis for comparing policy alternatives

The relevant equations for this section are (1) to (3).

Power deficit = IF THEN ELSE (Total electricity demand<Total power generation, 0, Total electricity demand-Total power generation) [GWh] (1)

Total electricity demand = Electricity demand for production and services + Residential electricity demand [GWh] (2)

Total power generation = Electricity produced by PV + Power generation from thermal plants [GWh] (3)

Electricity demand is modeled across two main sectors: household demand and demand for production and services. Due to their distinct characteristics, separate models are constructed for each of them. Household electricity consumption is influenced by factors such as population growth (R1), electricity prices, and per capita income. Two feedback loops govern this sector: the reinforcing loop (R2), reflecting the tendency of households to increase electricity consumption to maximize utility, and the balancing loop (B2), as electricity prices and income constraints limit demand growth. Consumer theory helps explain these dynamics by modeling household behavior under the principles of utility maximization. In the reinforcing loop (R2), households allocate resources to electricity consumption as it enhances their utility, driven by the marginal utility derived from using appliances or maintaining comfort. However, as part of the balancing loop (B2), households face budget constraints that require trade-offs between electricity and other expenditures. Rising electricity prices reduce the relative affordability of electricity, while per capita income determines the extent to which these constraints can be managed. By evaluating the gap between the desired and actual income shares allocated to electricity, household adjust their consumption patterns, either by reducing usage or seeking efficiency improvements, thereby introducing mechanisms to regulate excessive usage and achieve a new consumer equilibrium. The relevant equations for this section are (4) to (12).

Population= ∫ (Net Population Growth) + 7.01826e+07 [Person] (4)

Net Population Growth = Population*Net Population Growth Rate [Person/Year] (5)

Household electricity consumption per capita = ∫ (Increase in electricity consumption - Decrease in electricity consumption) + 0.000628479 [GWh/Person] (6)

Utility gains from electricity consumption = 1-(0.8*(EXP (-0.5*Household electricity consumption per capita))) [1/Year] (7)

Increase in electricity consumption = Utility gains from electricity consumption*0.00013 [GWh/Person/Year] (8)

Electricity cost per capita = Household electricity consumption per capita*Electricity Price [Billion Dollar] (9)

Proportion of electricity cost to income per capita = Electricity cost per capita / Income per capita [-] (10)

Difference between the current and desired state = Proportion of electricity cost to income per capita/Desired income share spent on electricity [-] (11)

Decrease in electricity consumption = IF THEN ELSE (Difference between the current and desired state<1, 0, ((Difference between the current and desired state/10) *5e-05)) [GWh/Person/Year] (12)

The production and services demand sector includes industries, agriculture, commercial establishments, and public lighting. This demand is modeled using GDP as an energy intensity coefficient in loop (R3), as shown in equation (13).

Electricity demand for production and services = GDP*Energy intensity [GWh] (13)

Additionally, according to equations (14) to (17), electricity deficits negatively impact GDP growth, forming a feedback loop (B3) where reduced GDP leads to decreased electricity demand.

Power deficit in the production and services sector = Power deficit*Share of the production and services sector from power deficit [GWh/Year] (14)

GDP growth rate = 0.03-((Power deficit in production and services sector/10000)*0.01) [1/Year] (15)

GDP growth = GDP*GDP growth rate [Billion Dollars/Year] (16)

GDP = ∫ (GDP growth) + 333.229 [Billion Dollar] (17)

The interplay between Total Electricity Demand and Electricity Deficit is captured by the balancing loop B1, which reflects the effect of increasing demand on system capacity. Electricity generation in Iran relies heavily on fossil fuels, primarily natural gas. The supply side model incorporates investments in natural gas capacity expansion, driven by GDP growth (R4), to enhance the availability of natural gas for thermal power generation. However, the depletion of natural gas reserves over time is captured by the balancing loop B5, while the aging of thermal power plants impacts supply capacity, modeled through balancing loop B4. The relevant equations for this section are (18) to (28). In modeling power generation from thermal plants, the total output is determined by the lesser of two factors: the nominal capacity of the plants (the whole potential electricity) and the possible power generated based on the natural gas supplied as fuel. This approach accounts for the fact that either the plant’s capacity or the available fuel supply can limit total generation. Additionally, electricity distribution and transmission losses are incorporated into the model.

Investment in NG capacity expansion = GDP*Percent of GDP assigned to NG development [Billion Dollars] (18)

NG production capacity expansion = Investment in NG capacity expansion / NG capacity development cost [million m^3/Year] (19)

NG reservoirs depreciation = NG production capacity / NG Reservoirs lifetime [million m^3/Year] (20)

NG production capacity = ∫ (NG production capacity expansion - NG reservoirs depreciation) + 151018 [million m^3] (21)

NG assigned to power plants = NG production capacity*Share of produced NG assigned to power generation [million m^3] (22)

Potential power generated by NG = NG assigned to power plants*Power plants' average efficiency [GWh] (23)

New power plant construction rate = Investment absorbed for thermal power plants / (Thermal Power plants construction cost*Average thermal power plant construction time) [GW/Year] (24)

Thermal power plants depreciation = Thermal power plant capacity / Power plants' average lifetime [GW/Year] (25)

Thermal power plant capacity = ∫ (New power plant construction rate - Thermal power plants depreciation) + 26.2441 [GW] (26)

Whole potential electricity = Thermal power plant capacity*Average annual operating hours [GWh] (27)

Power generation from thermal plants = MIN (Whole potential electricity, Potential power generated by NG) *Distribution and transmission loss of electricity [GWh] (28)

To address the electricity deficit, the study hypothesizes that government investments should align with forecasted deficits. The approach involves expanding both thermal power plants and household photovoltaic (PV) systems. The financial investment allocation is first calculated for the thermal power plants required to compensate for the electricity deficit. The policies then define how this total investment is redistributed between household PV systems and thermal power plants. The relevant equations for this section are (29) to (36).

Household PV systems Policy Implementation = IF THEN ELSE(Time>1403, 1, 0) [-] (29)

Household PV systems expansion to thermal power plants expansion Ratio = Policy*Household PV systems Policy Implementation [-] (30)

Investment absorbed for thermal power plants = (capacity deficit*Thermal Power plants construction cost) *(1-Household PV systems expansion to thermal power plants expansion Ratio) [Dollar] (31)

Investment absorbed for household PV systems = (capacity deficit*Thermal Power plants construction cost) *(Household PV systems expansion to thermal power plants expansion Ratio) [Dollar] (32)

New PV system implementation = Investment absorbed for household PV systems / (Household PV construction cost*Average PV systems construction time) [GW/Year] (33)

PV depreciation = PV capacity / PV system lifetime [GW/Year] (34)

PV capacity = ∫ (New PV system implementation-PV depreciation) + 0 [GW] (35)

Electricity produced by PV = Average annual sunny hours*PV capacity [GWh] (36)

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For instance, Policy 2: a 25% investment in household PV systems and 75% in thermal power plants implies that 25% of the total financial investment initially earmarked for thermal power plants is instead allocated to household PV systems, leaving 75% for thermal power plant expansion. The study examines five policy scenarios:

- **Policy 1**: 0% investment in household PV systems; 100% in thermal power plants.
- **Policy 2**: 25% investment in household PV systems; 75% in thermal power plants.
- **Policy 3**: 50% investment in both household PV systems and thermal power plants.
- **Policy 4**: 75% investment in household PV systems; 25% in thermal power plants.
- **Policy 5**: 100% investment in household PV systems; 0% in thermal power plants.

These policies account for the lifespans of thermal power plants (B4) and household PV systems (B6), as well as the delays inherent in constructing these systems. The balancing loop B7 captures the dynamics of investment absorbed for household PV expansion, while balancing loop B8 reflects the investment absorbed for thermal power plant expansion. Both loops model the effect of these investments on reducing the electricity deficit.

3.2. Benefits of redistributing financial investment

Redistributing financial investment between household photovoltaic (PV) systems and thermal power plants offers several significant benefits, particularly in addressing the electricity deficit and ensuring a more sustainable and efficient energy system:

3.2.1. Diversification of energy sources

Allocating a portion of the investment to household PV systems reduces the dependence on fossil fuel-based thermal power plants. This diversification enhances the resilience of the electricity supply by incorporating renewable energy sources, making the system less vulnerable to fluctuations in fuel availability or prices.

3.2.2. Reduction in greenhouse gas emissions

Household PV systems utilize solar energy, a clean and renewable source. Shifting investment toward PV systems reduces reliance on fossil fuels, significantly lowering carbon emissions and contributing to climate change mitigation efforts.

3.2.3. Improved energy access and decentralization

Investing in household PV systems enables decentralized energy production, bringing electricity closer to end-users. This decentralization enhances energy access, especially in remote or underserved areas, and reduces transmission and distribution losses commonly associated with centralized thermal power generation.

3.2.4. *Long-term cost savings*

The cost of PV systems per kilowatt of generated electricity has significantly decreased due to advancements in solar technology, making them increasingly economically viable. While the initial investment may still be higher compared to thermal power plants, PV systems offer substantial long-term savings due to their minimal operational and maintenance costs. Moreover, the absence of fuel costs in PV systems provides a significant advantage, as it eliminates exposure to fluctuations in fuel prices and ensures greater financial stability over time.

3.2.5. *Enhanced energy security*

Incorporating PV systems reduces the country's reliance on imported fuels and slows the depletion of domestic natural gas reserves. This shift enhances energy security by enabling the nation to meet its electricity demands more independently. Moreover, the natural gas saved from being used for electricity generation can be redirected toward more valuable applications, such as export for economic gain, use as a feedstock in petrochemical industries, or storage for future strategic purposes. This approach not only bolsters energy security but also maximizes the economic and strategic value of natural gas resources.

3.2.6. *Support for energy transition goals*

Allocating financial resources to PV systems aligns with global energy transition goals, supporting commitments to renewable energy adoption and achieving sustainability targets.

3.2.7. *Economic and social benefits*

The development and installation of PV systems can stimulate local economies by creating jobs in manufacturing, installation, and maintenance. It also promotes energy equity by enabling households to generate their own electricity, potentially reducing their utility bills and enhancing their financial well-being.

3.2.8. *Mitigation of capacity expansion delays*

Expanding thermal power plants often involves lengthy construction timelines and regulatory approvals. In contrast, PV systems can be deployed relatively quickly, providing a more immediate solution to mitigating electricity deficits.

By redistributing investments between thermal power plants and household PV systems, the proposed approach strikes a balance between addressing immediate electricity deficits and advancing long-term sustainability goals. This strategic allocation ensures a more robust, environmentally friendly, and cost-effective energy system for the country.

3.3. *Environmental analysis*

This study includes an environmental analysis to evaluate and compare different policies for developing household PV systems, primarily aimed at addressing the country's power deficit. Two key ecological factors are considered (Karbasioun et al., 2023):

3.3.1. *Greenhouse gas emissions*

The analysis accounts for emissions resulting from fuel consumption in thermal power plants. Emission calculations are based on the Intergovernmental Panel on Climate Change (IPCC) guidelines and are tailored to Iran's average emission factors. The relevant equations for this section are (37) to (41).

Fossil Fuels Needed for Power Generation Units = Power generation from thermal plants*"Change Unit (GWh to million BOE)" [million BOE/Year]	(37)
Power Generation with Gas = Fossil Fuels Needed for Power Generation Units*Power Generation Gas to Oil Products Ratio [million BOE/Year]	(38)
Power Generation with Oil = Fossil Fuels Needed for Power Generation Units - Power Generation with Gas [million BOE/Year]	(39)
Yearly Emission Production from Power Generation = Yearly Emission Due by Fossil Fuel Power Generation = Power Generation Yearly Emission Due by Oil + Power Generation Yearly Emission Due by Gas [million Tons CO_2 equivalent/Year]	(40)
Emission Production from Power Generation = ∫ (Yearly Emission Production from Power Generation) + 0 [million Tons CO_2 equivalent]	(41)

3.3.2. *Water consumption*

Total water usage is assessed by calculating the water footprint associated with the natural gas supply chain used as fuel for thermal power plants, as well as the water requirements during the construction and operational phases of these power plants. The relevant equations for this section are (42) to (49).

Natural Gas Ratio = Power Generation with Gas / (Power Generation with Oil + Power Generation with Gas) [-]	(42)
Water Consumption from thermal Power Generation Plants = Water Consumption from thermal Power Generation Plants = ((Power generation from thermal plants) *"Change Unit (GWh to TJ)"*(Natural Gas Ratio*Power Plants Driven by Gas Water Factor + (1-Natural Gas Ratio) *Power Plants Driven by Oil Water Factor)) *1000 [million m^3/Year]	(43)

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Water Consumption from Power Generation Sector = ∫ (Power Generation Water Consumption Per Year) + 0 [million m^3] (44)

Natural Gas Production Heating Value = Rich Natural Gas Heat Value * NG production capacity [TJ] (45)

Natural Gas Extraction and Production Water Consumption Per Year = Gas Production Water Consumption Factor * Natural Gas Production Heating Value [million m^3/Year] (46)

Water Consumption from Natural Gas Extraction and Production using as fuel for thermal power plants = ∫ (Natural Gas Extraction and Production Water Consumption Per Year) *Share of produced NG assigned to power generation + 0 [million m^3] (47)

Yearly Water Consumption = Power Generation Water Consumption Per Year + Natural Gas Extraction and Production Water Consumption Per Year [million m^3/Year] (48)

Total Water Consumption = ∫ (Yearly Water Consumption) + 0 [million m^3] (49)

By examining these factors, the study provides a comprehensive environmental comparison of thermal power plant expansion versus the development of household PV systems. This approach highlights the potential environmental benefits of shifting investments towards PV systems, particularly in terms of reducing emissions and conserving water resources. These insights are crucial for formulating environmentally sustainable solutions to the country's power deficit challenge. Additionally, it is important to note that the exogenous variables used in this model are listed in Table 3.

Table 3. exogenous variables of the study

Exogenous variable	Value	Reference
Oil Emission Factor equivalent to CO2	0.449936 million Tons CO2 equivalent/ (million BOE*Year)	(Karbasioun et al., 2023)
Natural Gas Emission Factor equivalent to CO2	0.343553 million Tons CO2 equivalent/ (million BOE*Year)	(Karbasioun et al., 2023)
Power Plants Driven by Gas Water Factor	(1 + 267) * 1e-06 million m3/TJ	(Karbasioun et al., 2023)
Power Plants Driven by Oil Water Factor	(1+485) *1e-06 million m3/TJ	(Karbasioun et al., 2023)
Rich Natural Gas Heat Value	0.0985 * 1000 TJ/million m3	(Karbasioun et al., 2023)
Gas Production Water Consumption Factor	2.2 * 1e-06 million m3/TJ	(Karbasioun et al., 2023)
Average PV systems construction time	1 Year	(Hoorayesh, 2021)
Household PV construction cost	4.5e+08 Dollar/GW	(Hoorayesh, 2021)
PV system lifetime	25Year	(Hoorayesh, 2021)
Average annual sunny hours	2000 GWh/GW	(techsunsanat, n.d.)
Net Population Growth Rate	0.0145 1/Year	Experts' comments
Desired income share spent on electricity	0.02 Dmnl	Experts' comments
Electricity Price	6000 dollars/GWh	Experts' comments
Share of the production and services sector from the power deficit	0.1 1/Year	Experts' comments
Distribution and transmission loss of electricity	0.15	(“Barghnews,” 2019.)
Average annual operating hours	6800 GWh/GW	(Karbasioun et al., 2023)
Thermal Power plants construction cost	8.4e+08 Dollar/GW	(Foroutan, 2024)
Average thermal power plant construction time	3 Year	(Karbasioun et al., 2023)
Power plants' average lifetime	30 Year	(Karbasioun et al., 2023)
Percent of GDP assigned to NG development	0.0004 Dmnl	Experts' comments
NG Reservoirs lifetime	150 Year	(khabaronline,2011 n.d.)
NG capacity development cost	1/ (141*365) Billion Dollars/million cubic meter	(Shana, 2025)
Share of produced NG assigned to power generation	0.275 Dmnl	(Safari Dehkordi, 2024)
Power plants' average efficiency	0.35	(Karbasioun et al., 2023)

4. Results and discussion

4.1. Extreme condition test

In this test, the model's outputs should exhibit logical behavior when subjected to extremely large and small input values within its boundary conditions (Sterman, 2000). This approach was applied to assess the impact of *Electricity Price* on *Residential Electricity Demand*. Specifically, when the *Electricity Price* parameter increased from 6,000 (as shown in Table 3) to 10,000,000 $/GWh (approaching an infinitely high value), the *Residential Electricity Demand* declined to nearly zero, demonstrating expected system behavior as depicted in Figure 4.

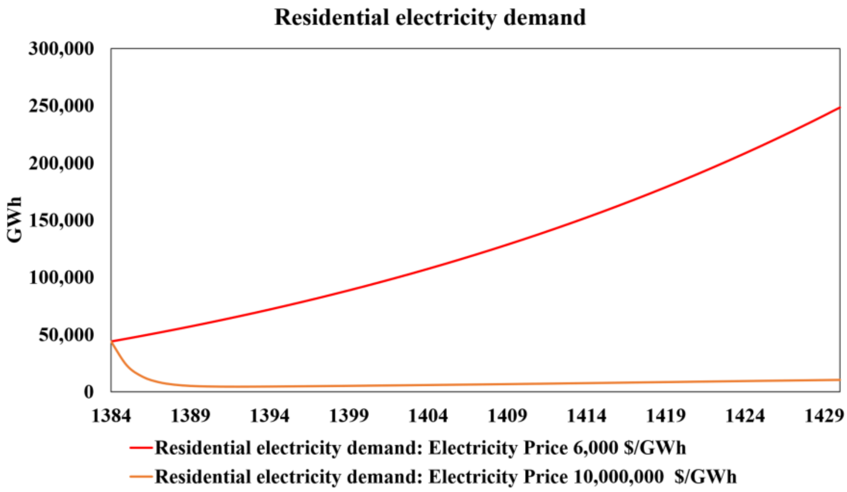

Figure 4. Extreme condition test- the impact of “Electricity Price” on “Residential Electricity Demand”

4.2. Dimensional consistency test

The dimensional consistency test ensures that all parameters in the model have appropriate units and that the units used across all equations are consistent. To evaluate the developed model, the unit check function in Vensim software was utilized. The findings confirm that the assigned units are fully consistent within the model (Sterman, 2000).

4.3. Validation: structurally oriented behavior test - behavior reproduction

The Behavior Reproduction Test is widely recognized as one of the most reliable methods for evaluating a model's performance. This test compares historical data with simulated results to validate the model’s ability to replicate real-world behavior. While models inherently represent simplified versions of reality, their evaluation must consider both the structural logic of the model and the accuracy of the values it produces (Sterman, 2000).

For this study, historical data spanning the period from 1384 to 1403 (2005–2024) were used to validate the model. Seven key variables were assessed, and their behavioral trends are illustrated in Figure 5. The diagrams demonstrate that the simulated results align closely with actual historical values, displaying consistent trends and indicating strong validity.

To complement the visual comparison, the Mean Absolute Percentage Error (MAPE) was calculated for all seven variables, yielding the following results:

1. Real Household Electricity Consumption per Capita: **3.36%**
2. Total Electricity Demand: **1.97%**
3. Thermal Power Plant Capacity: **8.76%**
4. Natural Gas Production Capacity: **5.81%**
5. GDP: **3.79%**
6. Population: **0.57%**

The low MAPE values for most variables confirm the favorable consistency between historical data and simulation outcomes. Although the capacity deficit exhibits a relatively higher error, this is due to its inherently dynamic and unpredictable nature. In conclusion, the high validity and accuracy of the model, as evidenced by the Behavior Reproduction Test and MAPE analysis, provide confidence in its ability to predict future trends based on the current system structure.

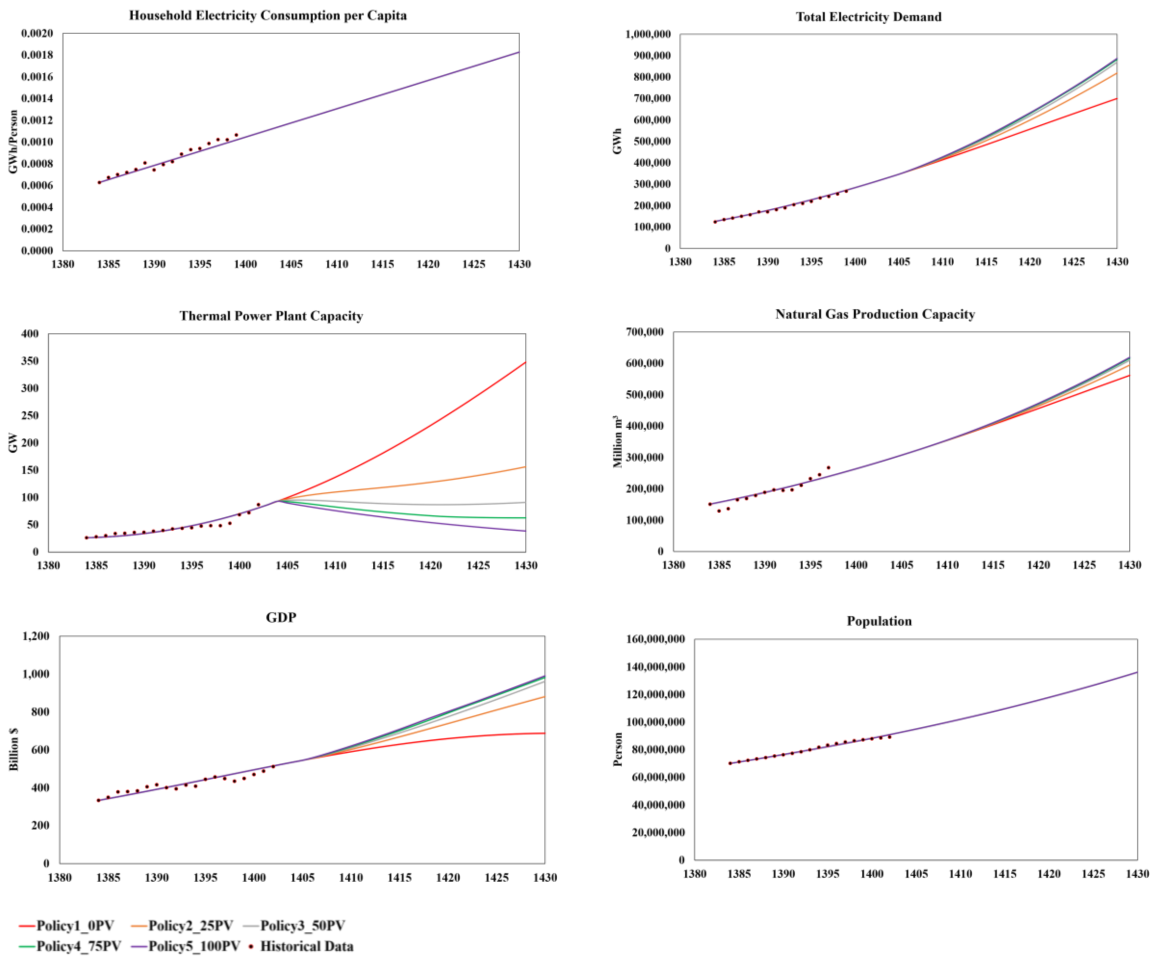

Figure 5. Structurally Oriented Behavior Test - Behavior Reproduction for the main variables of the model

4.4. *Policy assessment and analysis*

This section evaluates key variables for assessing various policy scenarios related to household PV development and their impacts on capacity deficit, electricity generation, water consumption, and emissions.

4.4.1. Electricity produced by PV

The implementation of policies promoting household PV development results in an increase in electricity generation from PV systems across all scenarios. As the power deficit grows due to rising total electricity demand, the financial investments required to address the deficit also increase. Consequently, a higher emphasis on household PV development leads to greater PV allocation. Accordingly, the projected electricity generation from PV systems in the year 1430 for policies 1 through 5 is as follows: 0, 246,875, 330,866, 457,612, and 589,250 GWh (Figure 6).

4.4.2. Power generation from thermal plants

Since the policies provide financial support for household PV systems, the budget allocated for the expansion of thermal power plants will be redirected towards household PV development. Consequently, the investment in thermal power plant expansion decreases in 1418 and 1421 under policies 5 and 4, respectively (Figure 6). However, under policies 2 and 3, both household PV systems and thermal power plants are developed simultaneously to address the power shortage, relying on government financial support.

4.4.3. Total power generation

Total power generation comprises the sum of electricity produced by thermal power plants and photovoltaic (PV) systems. This variable grows under all policies supporting household PV development. In 1404, total power generation was 215,469 GWh. By 1430, under policies 1 through 5, the increase is 405,661, 676,411, 771,188, 777,198, and 785,977 GWh, respectively (Figure 6). It indicates that without household PV expansion, total power generation grows by only 88.27%. However, with household PV development at 25%, 50%, 75%, and 100% levels, growth reaches 213.92%, 257.91%, 260.70%, and 264.77%, respectively, highlighting its effectiveness in addressing power deficits. The primary reasons for this substantial growth include the lower cost of household PV installations per unit of electricity produced, their higher efficiency, and shorter installation timelines compared to thermal power plants, enabling faster and greater electricity generation under PV expansion policies.

4.4.4. Capacity deficit

The primary objective of this study is to analyze household PV expansion policies as a solution for addressing electricity deficits. As illustrated in Figure 5, the capacity deficit is projected to reach 43.3263 GW by 1430 if the government relies solely on developing thermal power plants. However, implementing household PV expansion policies significantly mitigates this power shortage, with reductions evident from the start of policy implementation in 1404.

By 1412, household PV policies can reduce the deficit to 12.9769, 7.86729, 5.59681, and 4.40932 GW under 25%, 50%, 75%, and 100% PV expansion scenarios, respectively. In contrast, relying exclusively on thermal power plant development results in a capacity deficit of 25.2102 GW. However, after 1416, nearly all PV expansion policies experience a gradual increase in capacity deficit, culminating by 1430 at 43.3263, 21.0619, 14.4305, 15.4442, and 14.94 GW for 0%, 25%, 50%, 75%, and 100% PV expansion scenarios, respectively. This increase is driven by rising electricity demand across residential, industrial, and service sectors.

This trend is reasonable because reducing the power deficit leads to GDP growth, which drives higher electricity demand in the production, service, and agricultural sectors. Higher GDP also raises per capita income, enabling greater electricity consumption. Additionally, GDP growth fosters increased investment in natural gas capacity expansion, boosting power generation from thermal power plants. However, this alone is insufficient to address the electricity deficit, necessitating complementary strategies, such as expanding household PV systems.

Over the long term, after 1421, policies 3, 4, and 5 (50%, 75%, and 100% PV expansion) outperform policies 1 and 2 (0% and 25% PV expansion) in reducing the capacity deficit. This demonstrates the effectiveness of household PV expansion as a critical measure for addressing power shortages and supporting sustainable energy planning.

4.4.5. Total water consumption

As illustrated in Figure 6, total water consumption in the power industry under Policy 5 (7,267,200 m^3) begins to decline compared to Policy 1 (7,267,530 m^3) in 1419, and under Policy 4 (9,294,160 m^3) compared to Policy 1 (9,324,920 m^3) in 1424. In both cases, the downward trend relative to Policy 1 continues steadily through 1430. However, the impact of household PV expansion on water consumption is not immediately apparent and becomes significant only in the long term. This effect is most pronounced under the 75% and 100% PV expansion scenarios, resulting in reductions in water consumption of 3.03% and 11.51% relative to Policy 1, respectively. By 1430, water consumption is projected to be approximately 11,237,200, 11,383,500, 11,456,300, 10,897,100, and 9,943,260 million cubic meters for policies 1 through 5, respectively. These findings highlight the long-term benefits of household PV expansion in reducing water usage in the power sector, particularly under more ambitious deployment scenarios.

4.4.6. Emissions from power generation

As depicted in Figure 6, emissions from power generation under policy 5 (1463.67 Mt) begin to decline compared to Policy 1 (1463.75 Mt) in 1419. A similar trend is observed under Policy 4, where emissions (1877.29 Mt) fall below those of Policy 1 (1883.63 Mt) in 1424. This declining pattern relative to Policy 1 continues consistently up to 1430 for both Policy 4 and Policy 5.. However, the impact of household PV expansion on emission reductions remains minimal until 1430, indicating a long-term effect. This impact is particularly pronounced under the 75% and 100% PV expansion scenarios, resulting in emissions reductions of 3.07% and 11.64%, respectively, compared to policy 1. By 1,430, emissions are projected to be approximately 2,275.52, 2,305.46, 2,320.34, 2,205.74, and 2,010.59 million tons of CO2 equivalent for policies 1 through 5, respectively. These findings underscore the significant potential of extensive household PV expansion to mitigate emissions over the long term.

These findings highlight the significance of household PV expansion in addressing electricity deficits, optimizing resource consumption, and reducing environmental impacts.

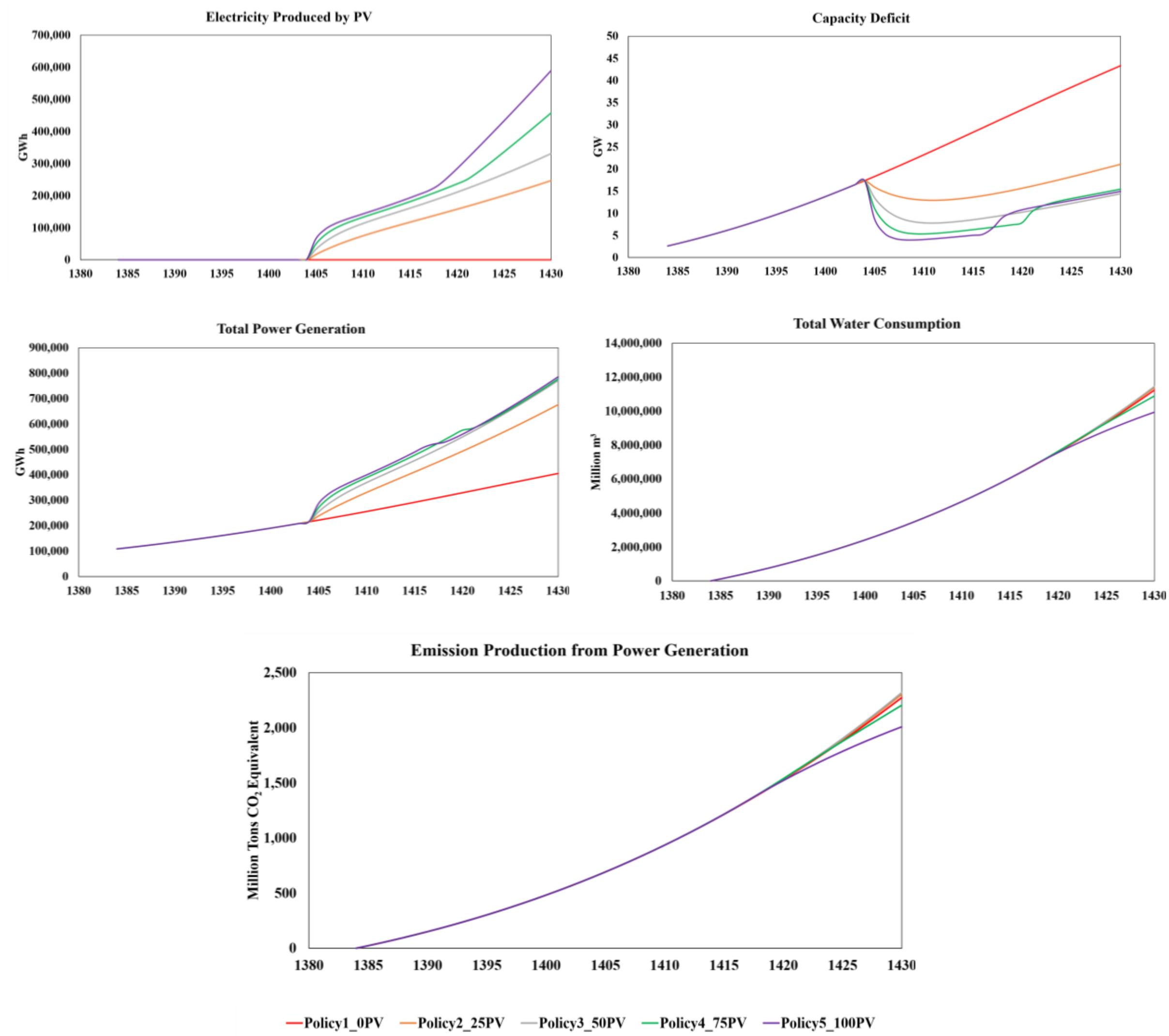

Figure 6. Trends of key variables for policy evaluation under various policy scenarios

5. Conclusion

This study assessed the effectiveness of household photovoltaic (PV) expansion policies in addressing Iran's electricity deficit, as well as their impact on CO_2 emissions and water consumption. The findings underscore the potential of household PV systems as a critical component of Iran's energy strategy, particularly in the short to mid-term. However, the results also reveal that household PV systems alone are insufficient to address the long-term power deficit, emphasizing the need for a comprehensive and diversified energy strategy. By employing a comprehensive system dynamic modeling approach with a low Mean Absolute Percentage Error (MAPE) of 1.97-8.76% across key variables, we provide a robust framework for informed policy recommendations that address critical gaps in the literature.

5.1. Key findings

- Our findings highlight the substantial potential of household PV systems in addressing electricity shortages through decentralized renewable solutions:
- **Significant PV generation capacity:** Household PV expansion policies can lead to electricity generation of up to 589,250 GWh by 1430 under the most ambitious scenario, underscoring the untapped potential of distributed solar energy in Iran.
- **Enhanced total power generation:** Expansion policies increase total power generation by 213.92% to 264.77% by 1430, compared to 88.27% growth under conventional thermal expansion alone, demonstrating the efficiency and feasibility of household PV systems.
- **Short-term deficit reduction:** PV expansion effectively mitigates the immediate electricity deficit, reducing it from 25.2102 GW in a thermal-only scenario to as low as 4.40932 GW under a 100% PV expansion policy by 1412.
- **Long-term deficit trends:** Despite short-term improvements, capacity deficits rise again after 1416 due to increasing demand, reaching 14.94-43.3263 GW by 1430, emphasizing the need for a holistic energy strategy.
- **Environmental benefits:** Ambitious PV deployment scenarios lead to CO_2 emission reductions of up to 11.64% and water savings of 11.51% by 1430, addressing Iran's water scarcity concerns while advancing sustainability objectives.

5.2. Contributions to energy policy and research

This study makes several critical contributions to energy policy planning and scientific literature:

- Decentralized renewable strategy: Unlike prior studies that focus on large-scale renewable projects, our research presents household PV as a direct and viable solution to electricity shortages, thereby bridging an important gap in the literature.
- Optimal investment strategy: We identify a 75% energy budget allocation for household PV as the most effective balance between deficit reduction, environmental benefits, and implementation feasibility, diverging from the broader renewable energy allocations in prior studies.
- Comprehensive system dynamics framework: Our model integrates supply-demand dynamics, technical constraints, and socio-economic factors, offering a holistic tool for evaluating household PV adoption and its impact on electricity deficits.
- Temporal deficit analysis: By assessing deficit trends across different timeframes, we demonstrate the necessity of complementary strategies beyond household PV for long-term sustainability.
- Environmental-economic balance: Our study quantifies the water and emissions savings associated with household PV adoption, providing a critical perspective on Iran's energy-water nexus.

5.3. Policy implications and future directions

The findings strongly support the adoption of Policy 4 (75% PV expansion) as the most balanced and effective strategy for Iran's electricity sector during the 1404-1430 (2025-2052) period. This approach provides multiple benefits:

1. **A 77.78% reduction in capacity deficit** by 1412 compared to thermal expansion alone.

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2. **Environmental benefits**, including a 3.07% reduction in emissions and a 3.03% decrease in water consumption by 1430.
3. **Energy system stability**, by maintaining partial investment in thermal infrastructure while prioritizing household PV development.

Despite these advantages, additional measures will be required to address the projected long-term deficit of 15.4442 GW by 1430. Household PV systems should serve as a cornerstone of Iran's sustainable electricity strategy, but must be integrated with broader efforts, including efficiency improvements, grid modernization, and other renewable technologies.

Future research should explore complementary renewable sources, demand-side management, and advanced storage technologies to further enhance the resilience of Iran's energy system. Our validated system dynamics model provides a valuable tool for ongoing policy assessment and adaptation, ensuring a robust response to evolving energy challenges.

5.4. Limitations and suggestions

Despite its advantages, household PV systems alone cannot meet the long-term growing electricity demand. By 1430, even the most aggressive PV expansion scenarios reveal increasing capacity deficits driven by rising demand across residential, industrial, and service sectors. It underscores the urgency of adopting complementary strategies, including:

- **Investment in energy efficiency:** Enhancing energy efficiency across all sectors to curb electricity demand growth.
- **Diversification of renewable energy sources:** Expanding investments in wind, geothermal, and other renewable technologies to supplement PV systems.
- **Grid modernization:** Upgrading infrastructure to support decentralized generation and improved energy storage capabilities.
- **Demand-side management (DSM):** Implementing demand response programs and time-of-use pricing to optimize consumption patterns.
- **Natural gas utilization:** Allocating natural gas for export or as a transitional fuel in high-efficiency combined-cycle power plants to reduce emissions.

5.5. Limitations in broader applications

The proposed system dynamics model is designed specifically for Iran's electricity sector, and its direct application to other regions may require modifications due to differences in regulatory frameworks, economic conditions, and energy infrastructure. Key limitations include:

- **Financial and policy constraints:** The model assumes fixed financial investment scenarios and does not account for potential fluctuations in subsidies, tax incentives, or evolving regulatory policies that could impact PV adoption.

- **Storage and grid integration challenges:** The study does not explicitly model advancements in battery storage technologies or grid integration constraints, which could influence the feasibility of large-scale PV adoption in other contexts.
- **Regional variability:** Factors such as solar irradiance, land availability, and grid stability vary significantly across different regions, requiring localized assessments for effective implementation.
- **Socioeconomic considerations:** The model does not account for potential social acceptance challenges, behavioral factors, or economic inequalities that may influence household PV adoption in other markets.

Future research should address these limitations by incorporating dynamic policy models, exploring energy storage innovations, and analyzing broader socioeconomic impacts to refine the proposed strategies. By adopting a multifaceted approach that integrates household PV expansion with complementary measures, policymakers can effectively address Iran's electricity deficit, mitigate environmental impacts, and lay the groundwork for a sustainable and resilient energy future

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

Alasseri, R., Tripathi, A., Rao, T.J. and Sreekanth, K.J., 2017. A review on implementation strategies for demand side management (DSM) in Kuwait through incentive-based demand response programs. *Renewable and Sustainable Energy Reviews*, *77*, pp.617-635. https://doi.org/10.1016/j.rser.2017.04.023.

Aryanpur, V., Atabaki, M.S., Marzband, M., Siano, P. and Ghayoumi, K., 2019. An overview of energy planning in Iran and transition pathways towards sustainable electricity supply sector. *Renewable and Sustainable Energy Reviews*, *112*, pp.58-74. https://doi.org/10.1016/j.rser.2019.05.047.

Asadi, M., Larki, I., Forootan, M.M., Ahmadi, R. and Farajollahi, M., 2023. Long-term scenario analysis of electricity supply and demand in Iran: Time series analysis, renewable electricity development, energy efficiency and conservation. *Sustainability*, *15*(5), p.4618. https://doi.org/10.3390/su15054618.

Audinet, Pierre; Rodriguez Pardina, Martin Augusto, 2010. *Managing an electricity shortfall : a guide for policymakers (English)*. Energy Sector Management Assistance Program (ESMAP) Washington, DC: World Bank. Available at: http://documents.worldbank.org/curated/en/337601468017341236.

Balázs, I., Fodor, A. and Magyar, A., 2024. Short-term system imbalance forecast using linear and non-linear methods. *Energy Systems*, pp.1-22. https://doi.org/10.1007/s12667-024-00667-7.

BarghNews, 2019. *Comparison of power grid loss percentage in Iran with other countries*. Available at: Available at: https://barghnews.com/000AVe. [in Persian].

Ben Maalla, El Mehdi and Kunsch, P.L., 2008. Simulation of micro-CHP diffusion by means of system dynamics. *Energy Policy*, *36*(7), pp.2308-2319. URL: https://ideas.repec.org/a/eee/enepol/v36y2008i7p2308-2319.html.

Danso-Wiredu, E.Y., Dadson, Y.I. and Amoako-Andoh, F.O., 2016. Social, economic and environmental impacts of the recent electricity crisis in Ghana: A study of Winneba. *Journal of Social Sciences*, *49*(3-1), pp.277-288. https://doi.org/10.1080/09718923.2016.11893621.

Dehghan, H., Amin-Naseri, M.R. and Nahavandi, N., 2021. A system dynamics model to analyze future electricity supply and demand in Iran under alternative pricing policies. *Utilities Policy*, *69*, p.101165. https://doi.org/10.1016/j.jup.2020.101165.

Dehghan, H., Nahavandi, N., Chaharsooghi, S.K., Zarei, J. and Amin-Naseri, M.R., 2022. A hybrid game theory and system dynamics model to determine optimal electricity generation mix. *Computers & Chemical Engineering*, *166*, p.107990. https://doi.org/10.1016/j.compchemeng.2022.107990.

Doroodi, M., Ostadi, B., Kashan, A.H. and Zegordi, S.H., 2024. A hybrid method of system dynamics and design of experiments for investigating the economic and environmental indicators of electricity industry. *Heliyon*, *10*(11). URL: https://www.cell.com/heliyon/fulltext/S2405-8440(24)07291-8.

Energypress, 2024. *We are facing an 18,000 megawatt electricity imbalance/We do not want to say under what circumstances we took over the government*. Energypress. Available at: https://energypress.ir/en/?p=2526.

Fasihizadeh, M., Sefti, M.V. and Torbati, H.M., 2014. Improving gas transmission networks operation using simulation algorithms: Case study of the National Iranian Gas Network. *Journal of natural gas science and engineering*, *20*, pp.319-327. https://doi.org/10.1016/j.jngse.2014.07.018.

Fisher-Vanden, K., Mansur, E.T. and Wang, Q.J., 2012. *Costly blackouts? Measuring productivity and environmental effects of electricity shortages* (No. w17741). National Bureau of Economic Research. URL: https://www.nber.org/papers/w17741.

Foroutan, F., 2024. *Electricity price of thermal power plant*. Clean Energy. Available at: https://clean-energy.ir/thermal-power-plant/. [in Persian].

Hoorayesh, 2021. *Steps to register and set up a home solar power plant*. Available at: https://hoorayesh.com/bargh.[in Persian].

Hsu, C.W., 2012. Using a system dynamics model to assess the effects of capital subsidies and feed-in tariffs on solar PV installations. *Applied energy*, *100*, pp.205-217. https://doi.org/10.1016/j.apenergy.2012.02.039.

Kachoee, M.S., Salimi, M. and Amidpour, M., 2018. The long-term scenario and greenhouse gas effects cost-benefit analysis of Iran's electricity sector. *Energy*, *143*, pp.585-596. https://doi.org/10.1016/j.energy.2017.11.049.

Karbasioun, M., Gholamalipour, A., Safaie, N., Shirazizadeh, R. and Amidpour, M., 2023. Developing sustainable power systems by evaluating techno-economic, environmental, and social indicators from a system dynamics approach. *Utilities Policy*, *82*, p.101566. https://doi.org/10.1016/j.jup.2023.101566.

Khabaronline, 2011. Deputy Minister of Oil: Iran's Gas Will Last 156 More Years. Available at: https://khabaronline.ir/x3dWq. [in Persian].

Khan, R.M., Farooq, S. and Gilal, M., 2020. A.(2020). Electricity Consumption and Economic Growth: A Time-Series Study on Pakistan. *Global Economics Review*, *1*, pp.24-37. http://dx.doi.org/10.31703/ger.2020 (V-I).03.

Mahbub, T., 2023. *Encouraging Foreign Direct Investment (FDI) in Bangladesh's Power Sector*. pringerBriefs in Energy. Springer Nature Switzerland, Cham. https://doi.org/10.1007/978-3-031-27990-4.

Masoomi, M., Panahi, M. and Samadi, R., 2022. Demand side management for electricity in Iran: cost and emission analysis using LEAP modeling framework. *Environment, Development and Sustainability*, *24*(4), pp.5667-5693. https://doi.org/10.1007/s10668-021-01676-7.

Mukhtar, M., Obiora, S., Yimen, N., Quixin, Z., Bamisile, O., Jidele, P. and Irivboje, Y.I., 2021. Effect of inadequate electrification on Nigeria's economic development and environmental sustainability. *Sustainability*, *13*(4), p.2229. https://doi.org/10.3390/su13042229.

News.Az, 2024. Iran's steel production drops sharply amid power shortages. News.Az. Available at: https://news.az/news/irans-steel-production-drops-sharply-amid-power-shortages

Olausson, P.M., 2019. Planning for resilience in the case of power shortage: The Swedish STYREL policy. *Central European Journal of Public Policy*, *13*(1), pp.12-22. https://doi.org/10.2478/cejpp-2019-0004.

Pazheri, F.R., Othman, M.F., Malik, N.H. and Safoora, O.K., 2012. Economic and environmental dispatch at highly potential renewable area with renewable storage. *International Journal of Environmental Science and Development*, *3*(2), pp.177-182.

Roybal, L.G. and Jeffers, R.F., 2013. *Using system dynamics to define, study, and implement smart control strategies on the electric power grid* (No. INL/CON-13-28641). Idaho National Lab.(INL), Idaho Falls, ID (United States). URL: https://www.osti.gov/biblio/1097180.

Safari Dehkordi, F., 2024. One-third of the country's gas allocated to power plants. Mehr News Agency. Available at**:** https://mehrnews.com/x36n3g. [in Persian].

Shana, 2025. Power plants set new gas consumption record: 312 million cubic meters in one day. Shana. Available at: https://www.shana.ir/news/662545. [in Persian].

Shokri, U., 2024. *Powering change: Iran's electricity crisis and the path forward under Pezeshkian***.** bne IntelliNews. Available at: https://www.intellinews.com/powering-change-iran-s-electricity-crisis-and-the-path-forward-under-pezeshkian-333922/

Sterman, J.D., 2000. Business Dynamics: Systems thinking and modeling for a complex world. *MacGraw-Hill Company*.

TechsunSanat, n.d. How much does it cost to set up and install a home solar panel? Available at: https://techsunsanat.ir/blog/howmuch-does-it-cost-to-setup-and-install-a-home-solar-panel/ [in Persian].

Tehran Times, 2024. Electricity consumption in Iran rises 6,000 MW. Tehran Times. Available at: https://www.tehrantimes.com/news/502153/Electricity-consumption-in-Iran-rises-6-000-MW**.** [in Persian].

Tofigh, A.A. and Abedian, M., 2016. Analysis of energy status in Iran for designing sustainable energy roadmap. *Renewable and Sustainable Energy Reviews*, *57*, pp.1296-1306. https://doi.org/10.1016/j.rser.2015.12.209.

Usman, M. and Jie, Z., 2022. Power shortages in Pakistan Causes and Solutions: Power shortages in Pakistan Causes and Solutions. *Journal of Social Sciences and Economics*, *1*(1), pp.24-29. http://dx.doi.org/10.61363/jsse.v1i1.38.

Vasconcelos, P.N., de Souza, A.Z., Ribeiro, P.F. and Balestrassi, P.P., 2021, April. Modeling the Power Sector of Wonderland: an integrated system dynamics model to assess a sustainable regional development. In *2021 IEEE Mexican Humanitarian Technology Conference (MHTC)* (pp. 38-45). IEEE. . https://doi.org/10.1109/MHTC52069.2021.9419950.

Zhang, F., 2018. *In the dark: how much do power sector distortions cost south Asia?*. World Bank Publications.

Zhang, W., Ji, C., Liu, Y., Hao, Y., Song, Y., Cao, Y. and Qi, H., 2024. Dynamic interactions of carbon trading, green certificate trading, and electricity markets: Insights from system dynamics modeling. *PLoS One*, *19*(6), p.e0304478. https://doi.org/10.1371/journal.pone.0304478.