International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2025, 15(3), 194-203.

A System Dynamics Approach for Sustainability in the Natural Gas Energy Market

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Received: 04 December 2024 **Accepted:** 15 March 2025 **DOI:** https://doi.org/10.32479/ijeep.18840

ABSTRACT

The natural gas energy market is a dynamically-complex system, comprising various interconnected components and involving a diverse array of stakeholders. Achieving sustainable development within this sector necessitates a comprehensive understanding of its components and their dynamic es that focus solely on specifiinteractions. Traditional approaches to improving energy systems have often adopted narrow perspectivc components, disregarding their interconnected nature. Such approaches limit our comprehension of the system and hinder our ability to mitigate undesirable outcomes. This paper employs a System Dynamics approach to construct a comprehensive systems model of the natural gas energy market, employing a case study centered around Türkiye. The model provides a holistic visualization of the energy market, identifying crucial feedback mechanisms that shape the sector's behavior. Furthermore, this model serves as a shared language, facilitating a better understanding of the market among stakeholders and providing a platform to identify key leverage points for implementing systematic intervention strategies, thereby advancing the development of a sustainable natural gas energy market. Research findings reveal significant risks associated with policy decisions concerning energy security and environmental interventions, particularly in relation to the oil and gas components and CO_2 emissions.

Keywords: Systems Dynamics, Sustainable Development, Natural Gas Energy Market, Energy Policy
JEL Classifications: C63, Q41, Q48, Q54

1. INTRODUCTION

The natural gas energy market holds significant importance and continues to attract attention from policymakers and researchers worldwide. Access to reliable energy sources is crucial for ensuring economic growth and enhancing quality of life (Petrichenko et al., 2019). However, the increasing disparity between energy supply and demand, driven by population growth, rapid economic development, and the adverse effects (such as CO_2 emissions) of the energy sector on climate change, has compelled numerous countries to pursue sustainable energy systems (Koçaslan, 2007). Sustainable energy systems not only fulfill energy requirements and bolster national economies but also strive for environmental sustainability and address social needs, including job creation (Singh et al., 2019). Türkiye, like other nations, aspires to achieve a sustainable energy future but continues to face challenges jeopardizing energy sustainability, necessitating urgent reforms to realize this objective (Hale, 2022). Presently, energy, emissions, and climate change are subjects of intense political debate in Türkiye, particularly concerning renewable energy (RE) and the need for emission mitigation actions (Keleş and Bilgen, 2012).

Numerous studies have emphasized the interconnected nature of the energy sector, encompassing energy production, supply, demand, and emissions, which entail intricate interactions across economic, social, and environmental dimensions (Shabalov et al., 2021). The sector is also influenced by rapid changes, such as demand fluctuations (Zhang et al., 2021) and the utilization of diverse and complex supply sources (Bauer et al., 2017). Moreover, the energy sector involves a diverse range of stakeholders, including suppliers, intermediaries, and customers, each with distinct management objectives and interests, making the pursuit of sustainable outcomes a complex endeavor (Hamdan et al., 2021). The interaction among these factors that govern the energy sector constitutes an inherently dynamic and complex system.

Overall, a System Dynamics approach is required to address the sustainability challenges within the natural gas energy market comprehensively. By adopting this approach, we can gain a holistic understanding of the system, consider the interdependencies of its components, and identify effective strategies to promote sustainability.

Despite the complex dynamics inherent in the natural gas energy market, previous endeavors aimed at comprehending its practices and government policies have predominantly fixated on specific components, disregarding the interconnected nature of the system. In many instances, energy management, planning, and forecasting rely heavily on techniques grounded in historical data, such as time series analysis (Way et al., 2022), or on subsystem energy models like top-down models (Dudek et al., 2023), bottom-up models (Laimon et al., 2019), hybrid models (Fan et al., 2020), and combinations of top-down and bottom-up models (Spiliotis et al., 2020). These conventional approaches rely on historical data to predict future trends or outcomes, assuming that the future will resemble the past. However, in a dynamically complex system such as the natural gas energy market, conditions often evolve rapidly, rendering these techniques unreliable and impeding a comprehensive understanding of its intricacies and underlying rationale.

In light of these limitations, a System Dynamics approach is essential to tackle sustainability challenges within the natural gas energy market comprehensively. By adopting this approach, we can transcend the narrow focus on individual components and acknowledge the interdependencies and feedback loops that shape the system's behavior. Instead of relying solely on historical data, a systems model based on this approach can capture the dynamic nature of the market, account for changing conditions, and facilitate a more nuanced understanding of its complexity and underlying drivers.

Undoubtedly, the sustainability challenges in the natural gas energy market encompass a multitude of complex issues. These challenges cannot be adequately addressed or resolved in isolation or through single-dimensional approaches. Instead, integrated approaches are crucial for gaining a comprehensive understanding of the system and mitigating undesirable outcomes to establish a sustainable energy sector. In contrast to the linear (deterministic) approaches mentioned earlier, systems thinking offers a holistic mindset that emphasizes the significance of the entire system and the interactions among its constituent parts (Javanmardi et al., 2023). It provides a framework for conceptualizing the management of multifaceted or "wicked" problems (Nguyen et al., 2012), enabling a deeper comprehension of the system's dynamics.

Moreover, systems thinking facilitates the identification of leverage points within the system—points where small interventions can generate significant changes leading to lasting improvements throughout the entire system (Kellner, 2023). Importantly, this approach enables the forecasting of policy outcomes and the anticipation of unintended consequences resulting from intervention programs and strategies (Petropoulos et al., 2022). Despite its rich history, applications of this innovative approach have been largely absent in the realm of energy management.

By embracing a System Dynamics approach, we can bring about a paradigm shift in addressing sustainability within the natural gas energy market. This approach will empower us to transcend the limitations of traditional linear methods, comprehend the interconnections and complexities of the system, and forecast the consequences of policy decisions and intervention strategies. By leveraging this holistic approach, we can unlock transformative changes and drive enduring improvements in the pursuit of a sustainable natural gas energy sector.

In the context of achieving sustainability in the natural gas energy market, this paper employs a System Dynamics approach to construct a dynamic hypothesis or conceptual model of the energy sector. By applying this approach, we aim to evaluate the potential ramifications of existing energy policies and propose enhancements that promote sustainable development. The case study conducted focuses specifically on the Turkish natural gas energy sector, offering insights into its dynamics and challenges. Within this study, the analysis encompasses both renewable energy (RE) and non-renewable energy resources, as we strive to comprehensively address the sustainability of the natural gas energy market.

2. RESEARCH METHODS

2.1. Overview of the Natural Gas Energy Market in Türkiye

The Turkish energy sector faces three critical challenges concerning energy supply and utilization. Firstly, ensuring sufficient accessible energy resources is imperative. Secondly, assessing the impact of future energy dependence and high oil prices is crucial. Lastly, reducing greenhouse gas emissions is a pressing concern (Kısacık, 2023). It is noteworthy that Türkiye's oil resources are finite, and the country is increasingly reliant on imports to meet the demand for transport fuels. Furthermore, Türkiye ranks poorly in several categories according to the climate change performance ındex (CCPI), including greenhouse gas emissions, energy use, and climate policy. Türkiye stands among the highest per-capita emissions countries globally (International Energy Agency [IEA], 2021). These issues are interconnected with the continuous growth of the economy and population and contribute to the broader challenges facing the Turkish energy sector, including the uncertainty surrounding energy policy. The lack of clarity in setting energy policies has implications for Türkiye's future energy generation options and creates an environment of uncertainty that may discourage investment.

With a consistent rise in energy demand over the past four decades, driven by population and economic growth, the Turkish energy sector confronts numerous challenges. Notably, there is an increasing dependence to meet the country's energy requirements, as depicted in Figure 1. High levels of CO_2 emissions contribute to environmental deterioration, including climate change, placing Türkiye among countries with significant per capita emissions, as shown in Figure 2. The lack of a coherent energy policy creates uncertainty, hindering investments in both renewable (RE) and non-renewable energy sectors, impacting the economy and job creation. The manufacturing industry and workforce are affected by high energy prices. Furthermore, a considerable proportion of Türkiye's power stations are set to close or be replaced in the near future, exerting substantial impacts on the economy, environment, workforce, and electricity prices. Considering the aforementioned challenges, the Turkish energy sector is characterized as unstable and significantly distant from achieving sustainability.

In light of these concerns, a System Dynamics approach is imperative to address the sustainability of the natural gas energy market comprehensively. By adopting this approach, we can holistically assess the interdependencies within the energy sector, consider the potential consequences of current policies, and develop strategies for achieving sustainable outcomes. The dynamic and interconnected nature of the energy sector necessitates a systematic approach that accounts for various stakeholders, environmental factors, economic considerations, and technological advancements. Through the application of systems thinking, we can work towards transforming the Turkish energy sector into a sustainable and resilient system.

Figure 1: Turkish energy consumption per person (Ritchie et al., 2020).

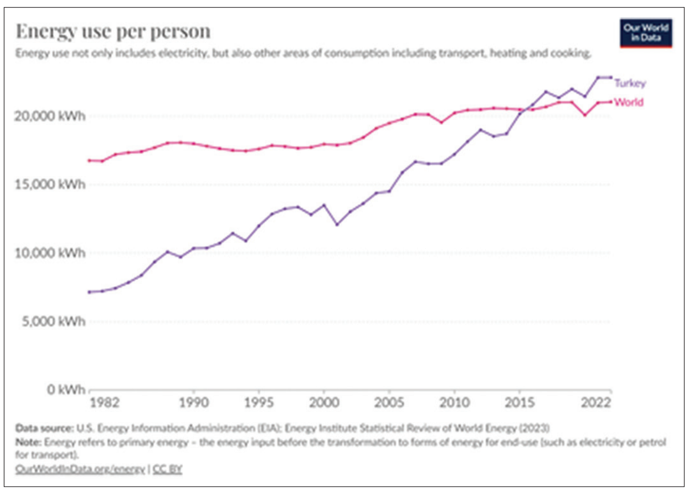
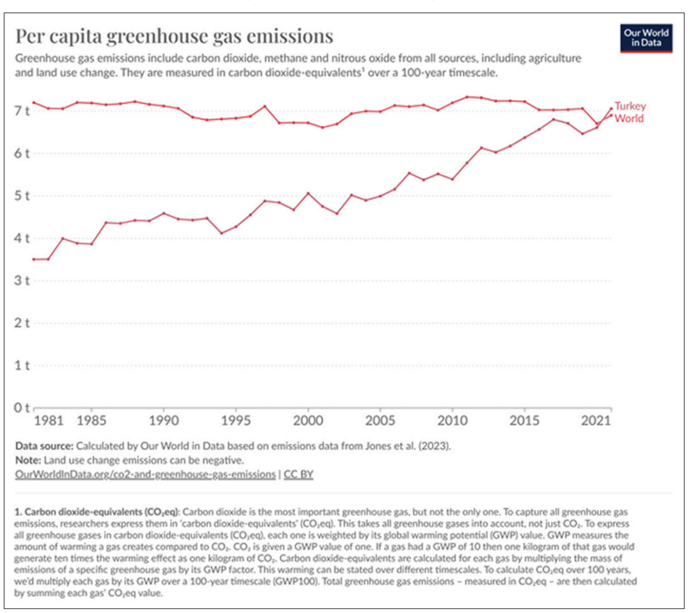


Figure 2: Per capita greenhouse gas emissions for Türkiye (Ritchie et al., 2023).



2.2. Development of a Conceptual Model for the Natural Gas Energy Market

Applying a System Dynamics approach and modeling, the formulation of a conceptual model for the natural gas energy market involves five interrelated steps (Sığrı, 2019). The initial two steps focus on qualitative modeling, aiming to develop a conceptual model that captures the dynamic interactions among the components of the system. The subsequent three steps emphasize quantitative modeling, aiming to create a computer-based simulation model that simulates the dynamic relationships among these components. In this paper, we have adopted the first two steps—problem articulation and formulation of dynamic hypotheses—to comprehend the dynamic complexity of the natural gas energy market and identify systemic intervention strategies for sustainable energy development.

A dynamic hypothesis, also known as a conceptual model, was constructed for the natural gas energy market in Türkiye using a causal loop diagram (CLD). A CLD comprises variables represented by words or phrases and arrows that depict the causal relationships between pairs of variables. These arrows within the CLD establish connections, either reinforcing (positive) or balancing (negative) feedback loops. Reinforcing feedback loops result in exponential growth or decline over time, while balancing feedback loops work to stabilize system behavior.

The development of the CLD involved four main stages. Firstly, we identified key issues specific to the natural gas energy market through a thorough review of relevant literature, media reports, and policy documents, thus defining the variables within the model. Secondly, based on these variables, a preliminary CLD was constructed, establishing connections, polarities, and time delays between the variables. In the third stage, the preliminary CLD was refined and validated through consultations with multiple experts in the natural gas energy sector. During these consultations, the preliminary CLD was broken down into feedback loops, and experts were invited to suggest modifications to the variables and their associated connections. The working CLD resulting from these consultations was then reviewed, and any errors or inconsistencies were addressed to produce the final CLD for the natural gas energy market.

Through this System Dynamics approach and the development of the conceptual model, we aim to gain a comprehensive understanding of the dynamics and interrelationships within the natural gas energy market. This will facilitate the identification of leverage points and inform sustainable intervention strategies that contribute to the long-term sustainability and resilience of the natural gas energy market.

2.3. Identification of Leverage Points and Intervention Strategies

Identifying leverage points within a system is a challenging task, as they are not easily accessible, potential high leverage points exist in various aspects of the system, including the rules and regulations governing the system, the structure of information flows, the amplification or gain associated with reinforcing feedback loops, and the strength of balancing feedback loops. The rules of the system are established by the government, which holds the authority to shape and modify them. The structure of information flows involves delivering information strategically to influence behavioral change. The gain associated with reinforcing feedback loops and the strength of balancing feedback loops play crucial roles in determining the system's behavior.

To further analyze these feedback loops and their impact, the study incorporates system archetypes (SAs). SAs are diagrams that resemble Causal Loop Diagrams (CLDs) but serve a distinct purpose. They represent mechanisms and generic patterns of behavior in isolation, simplifying the complexity of the CLD and highlighting the core structural elements of the system. This approach helps to identify problems and leverage points more clearly (Schaffernicht, 2010).

By applying this System Dynamics approach and utilizing SAs, we can better understand the underlying dynamics of the natural gas energy market and identify potential leverage points for intervention strategies. These leverage points can be found within the government's rules and regulations, the effective flow of information, the reinforcement or amplification of desired behaviors, and the balancing of system dynamics. Targeted interventions in these areas have the potential to drive significant changes and foster sustainable development within the natural gas energy market.

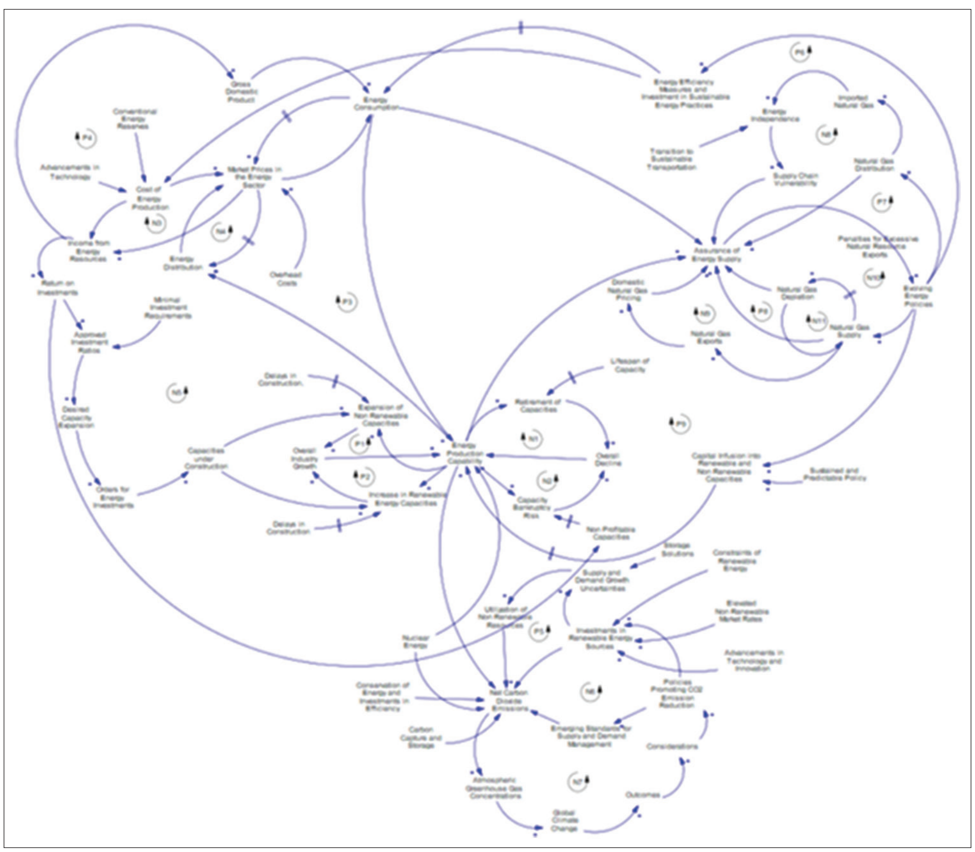
3. RESULTS

3.1. The Conceptual Model of the Natural Gas Energy Market

The final causal loop diagram (CLD) representing the natural gas energy market is depicted in Figure 3. This comprehensive model encompasses twenty-one feedback loops, consisting of ten positive feedback loops (P1 to P9) and eleven negative feedback loops (N1 to N11). The CLD highlights the key components of the energy sector in relation to Türkiye's energy policy. These components include energy resources (P1 and P2), energy production, supply, and demand (P3, N3, and N4), energy economics (N5 and P4), energy emissions and energy emissions policies (P5, N6, and N7), and energy policy developments (P6, N8, P7, N9, P8, N10, P9, and N11). The following section provides a brief description of these feedback loops.

The CLD serves as a powerful tool for understanding the interconnectedness and dynamics within the natural gas energy market. It reveals the complex relationships between various factors that influence the sector's behavior and sustainability. The identified feedback loops shed light on the causal connections and interdependencies, which are crucial for devising effective

Figure 3: Dynamic causal loop diagram of Turkish natural gas energy sector



intervention strategies to promote sustainable development within the natural gas energy market.

3.2. Description of the Conceptual Model of the Natural Gas Energy Market

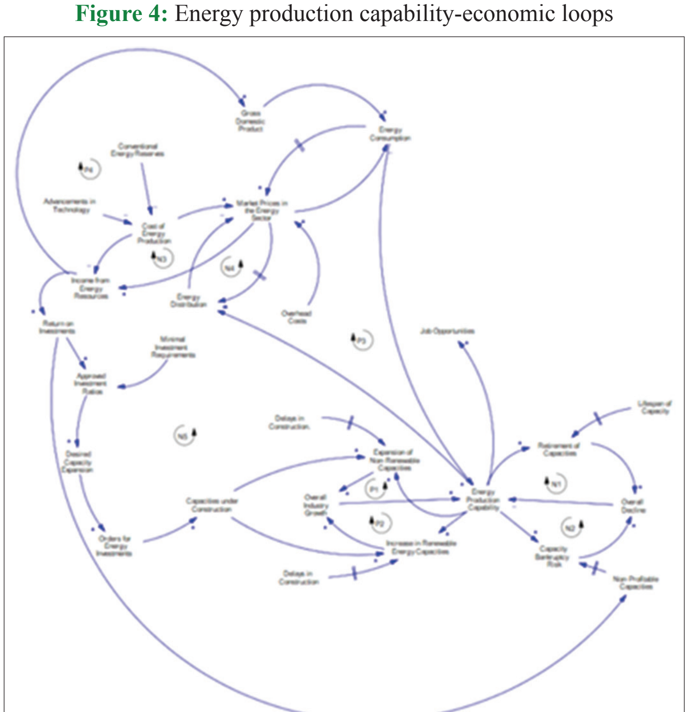
3.2.1. Energy production capacity-economic loops

Figure 4 illustrates the interactions between energy production capacity, investments in new capacities, and gross domestic product (GDP). This section focuses on the energy resources construction pipeline loops (P1, P2, N1, N2, and N5), supply-demand balance loops (P3, N3, and N4), and the GDP loop (P4).

The energy resources construction pipeline loops consist of two positive feedback loops (P1 and P2) and three negative feedback loops (N1, N2, and N5). These loops represent the developmental pipelines for both renewable energy (RE) and non-renewable energy (non-RE) resources in Türkiye. P1 and P2 reflect the overall growth of RE and non-RE energy resources, considering the construction delays associated with infrastructure development. N1 and N2 represent the decline in capacities due to bankruptcies and retirement, with unprofitable capacity and capacity lifespan acting as limiting factors, respectively. Negative feedback loop N5 reflects the desire to invest in additional capacities, which is motivated by strong energy revenues or a promising return on ınvestment (ROI). However, excessive investments can lead to overcapacity, price collapse, reduced energy revenues, and negative ROI. To maintain balance, demand growth or closures should align supply with demand. Disinvestment or closure is only considered when reduced negative energy revenue or profitability is sustained for a certain period. Operating capacity during this period depresses prices, profitability, and impedes further investment.

The supply-demand negative feedback loops (P3, N3, and N4) depict the relationship between energy price, energy supply, energy demand, and energy production capacity. The demand side encompasses both transportation and non-transportation sectors, including industries and households. The supply side consists of both RE (biomass, solar, wind) and non-RE (coal, oil, gas) resources.

Figure 4: Energy production capability-economic loops



These loops, particularly the essential-core negative feedback loops (N3 and N4), ensure a balance between the growth in energy production capacity and increasing energy demand. Energy price plays a pivotal role, linking energy supply, energy demand, and energy production capacity while maintaining a self-correcting feedback balance in supply and demand, commonly known as the law of supply and demand. Energy price serves as an incentive for capacity expansion but may lead to overcapacity, resulting in price decreases (N3). Loop N4 represents the demand side, where higher energy demand leads to higher energy prices, while lower demand corresponds to lower energy prices. The supply-demand balance depicted in these loops drives the growth of energy production capacity (P3).

The GDP loop (P4) demonstrates the positive influence of energy revenues on GDP growth. GDP, in turn, positively affects energy demand. Energy demand, driven by GDP growth, increases energy market prices, resulting in higher energy revenues and contributing to GDP growth (Li and Leung, 2021).

Understanding and managing these intricate interactions within the energy production capacity-economic loops is essential for devising effective intervention strategies that promote sustainable development in the natural gas energy market.

3.2.2. Energy production capacity-emissions loops

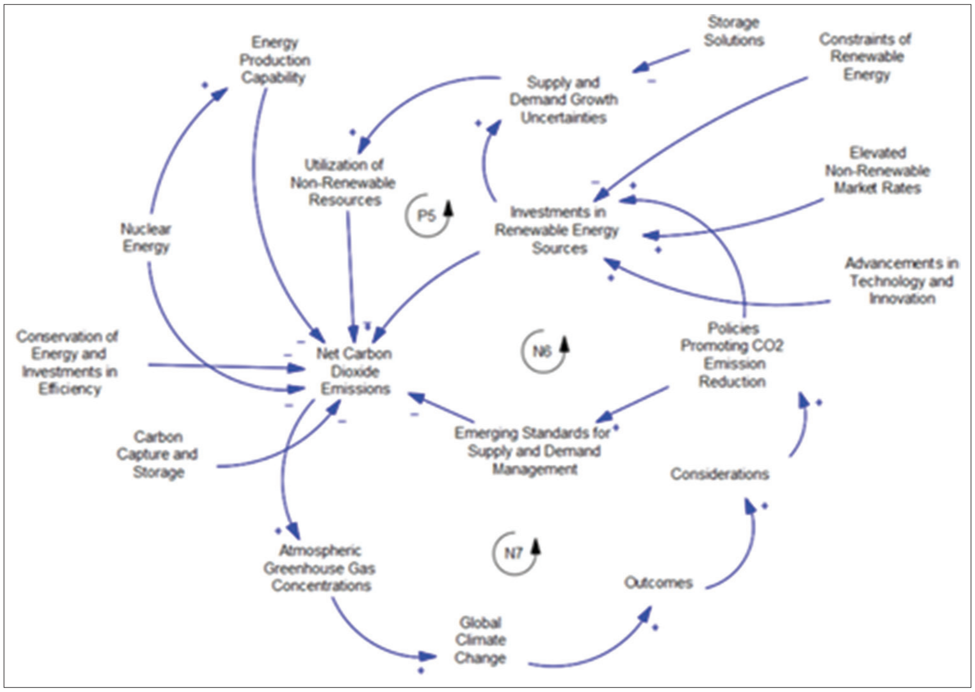
Figure 5 focuses on loops related to the contribution of energy production to emissions. Climate change and the issues associated with CO_2 emissions are primarily driven by energy usage, as it accounts for 80% of greenhouse gas emissions (Akpan and Akpan, 2012).

The loops P5, N6, and N7 illustrate the interaction between environmental concerns (CO2 emissions), energy production capacity, and energy policy. Türkiye has several options in its energy policy to mitigate CO_2 emissions, including nuclear power, carbon capture and storage (CCS), investments in renewable energy (RE), energy conservation, investments in energy efficiency, and the establishment of new norms on the supply and demand sides (N7).

Understanding the interplay between energy production capacity, social factors, and emissions is crucial for developing effective intervention strategies aimed at promoting sustainability within the natural gas energy market. By considering the complexities and feedback mechanisms associated with these interactions, policymakers and stakeholders can make informed decisions and implement measures that address both social and environmental concerns.

Currently, Türkiye's focus lies primarily on the third option within its energy policy, particularly in the electricity sector, which

Figure 5: Energy production capability-emissions loops



includes a renewable energy target (RET). The RET is divided into two parts: the large scale renewable energy target (LRET) and the small scale renewable energy scheme (SRES). The LRET sets a specific target for new large-scale RE power plants, such as wind farms, solar plants, and hydroelectric stations. On the other hand, the SRES promotes small-scale renewables, including rooftop solar, solar hot water, and heat pumps.

Several factors contribute to increased investments in RE, including non-RE market prices, technological advancements, and consistent and stable RE policies. Technological developments and innovations enhance power production efficiency, reduce costs, and improve scalability and energy storage capacity. However, limitations in RE supply capabilities can hinder investments in new RE capacities and create uncertainty in future energy supplies, leading to increased reliance on non-RE resources and subsequent CO_2 emissions. Limitations such as cost, small capacities, location constraints, and supply reliability can impact RE deployment.

Cost and scale limitations can be addressed through technology advancements, as mentioned earlier. Location issues can be resolved through grid extensions that connect various RE feed-in points (e.g., wind farms, ocean power systems, solar plants, biomass plants) to a common grid and the conversion of thermal energy into transportable forms (e.g., hydrogen). Ensuring supply reliability involves continuous power delivery on demand. Continuous RE resources (e.g., biomass and geothermal energy) offer reliable and continuous power generation, while intermittent RE resources (e.g., solar, wind) coupled with storage technologies can enhance supply flexibility (Zebra et al., 2021).

Taking a System Dynamics approach allows for a comprehensive understanding of the complexities and interdependencies involved in promoting sustainability within the natural gas energy market. It enables policymakers and stakeholders to consider the various factors impacting investments in RE and devise strategies that address limitations while maximizing the potential benefits of renewable energy sources.

3.2.3. Energy production capacity-energy policy developments loops

Growing energy demand typically leads to increased energy dependency and decreased energy security (Kartal, 2022). Energy dependency refers to the extent to which a country relies on energy imports to meet its energy needs (Esen, 2016). Türkiye's increasing dependence on other countries to fulfill its natural gas requirements, which constitutes a significant portion of its energy mix, exemplifies energy dependency. The Turkish energy policy defines energy security as ensuring sufficient energy with minimal disruptions at affordable prices across the electricity, and natural gas sectors. However, energy security can be more broadly defined as the availability, affordability, reliability, and accessibility of diverse long-term national energy resources to meet future energy needs while considering environmental concerns and maintaining the flexibility to respond promptly to disruptions. Energy security is considered a crucial indicator of sustainable development (Gunnarsdottir et al., 2020)

Through expert consultations, energy security emerged as one of the most significant variables discussed during the interviews. The experts identified several factors that could influence energy security in Türkiye. Factors contributing to decreased energy security include misleading information, particularly regarding energy demand; excessive exports of natural resources; political instability; the threat of natural disasters; and energy dependency. Conversely, numerous factors can enhance energy security, including the exploration of new resources, effective demand management, access to new technologies, diversification of energy resources, community awareness and engagement, reliable energy supply, the utilization of dispatchable generation from multiple resources, regionalization of energy markets, storage capacity, and the consideration of nuclear power. In an increasingly volatile world characterized by political, economic, and environmental uncertainties, reducing energy dependency and strengthening energy security should be a priority for any country.

Adopting a System Dynamics approach allows for a comprehensive understanding of the intricate interactions between energy production capacity, energy policy developments, and energy security within the natural gas energy market. By considering these interdependencies, policymakers and stakeholders can develop strategies that promote sustainable development while safeguarding energy security and reducing dependency on external energy sources.

In response to the challenges and complexities in the energy sector, the government reviews and amends energy policies to meet demand and support the industry (Figure 6). Government support takes various forms, including mandates such as renewable fuels standards, non-mandatory targets, subsidies, and incentives. One of the outcomes of government support is increased investment in energy efficiency (loop P6), leading to a reduction in energy demand and consumption. Lowering energy demand helps maintain the balance between energy demand and supply, resulting in resource conservation and emissions mitigation. By saving natural resources, lowering supply and demand, and improving energy security, investment in energy efficiency becomes a crucial factor for achieving a sustainable energy future.

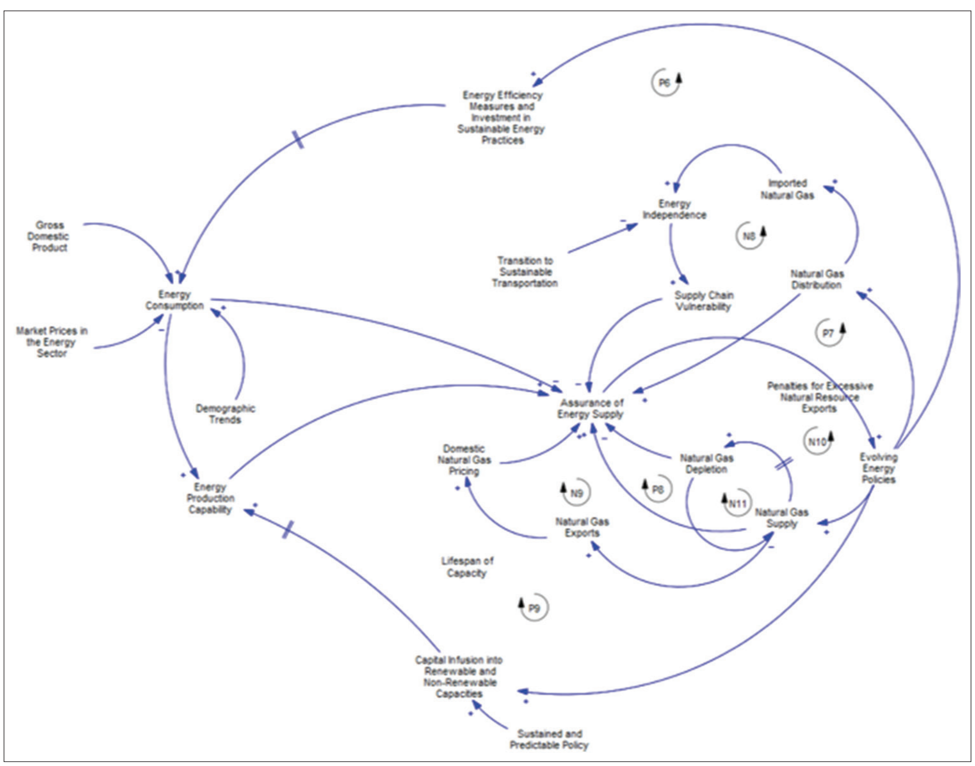
Investments in energy efficiency also drive the attraction of investments in new renewable energy (RE) and non-renewable energy (non-RE) capacities (loop P9) to meet the growing energy demand. This increase in energy production capacity and competition is expected to reduce energy prices, enhance reliability, and improve security. These investments in energy efficiency, as well as new RE and non-RE capacities, contribute to improving the national energy security of Türkiye. Energy efficiency measures reduce demand, while the expansion of energy production capacities ensures a reliable energy supply. However, consistent, effective, and stable energy policy development is essential to avoid policy hindrances that can impede investments.

It is crucial for Türkiye to address its natural gas needs (loop P7) and increase domestic natural gas supply (loop P8) to meet both domestic and export demands. With growing dependency on imported natural gas raises concerns about a potential supply catastrophe. In terms of natural gas supply, it is projected that gas exports will rise (loop N9), leading to increased domestic gas prices due to the reduction in the domestic share. Higher gas prices have a direct impact on electricity prices, as gas is one of the energy sources used for electricity generation. Excessive natural gas exports can also deplete gas reserves (loop N10).

Applying a System Dynamics approach enables a comprehensive assessment of the interdependencies and feedback loops within the natural gas energy market. It allows policymakers and stakeholders to identify leverage points and implement intervention strategies that promote sustainability, enhance energy security, and address the challenges associated with energy policy development, efficiency, and supply in Türkiye.

In this study, two system archetypes have been identified: "Limits to Growth" and "Fixes that Fail." The "Limits to Growth"

Figure 6: Energy production capability-evolving energy policies loops



archetype is characterized by growth followed by stagnation or potential collapse when reaching the system's limits (Banson et al., 2016). In the context of the Turkish energy sector, the growth of energy production is driven by the total expansion of renewable energy (RE) and non-renewable energy (non-RE) resources (loops P1 and P2). The motivation for investors to contribute to additional capacity is the energy revenues generated. However, there is a limit to this growth, as illustrated by loop N2. Reaching this limit can result in overcapacity and a potential collapse in energy prices. Consequently, reduced energy revenues may lead to bankruptcy and disinvestment in unprofitable capacity, resulting in a decline in overall capacity. Capacity bankruptcy occurs when the energy market price falls below the cost of energy production for an extended period.

To address the "Limits to Growth" archetype, controlling fluctuations in supply and demand and managing the limiting factor of unprofitable capacity (loop N2) is crucial. By achieving equilibrium between energy supply and demand, excessive losses can be controlled. It is important to address misleading information regarding the capacity of energy production to meet demand, as such misinformation contributes to fluctuations between energy supply and demand, further exacerbating the archetype's dynamics.

Understanding and addressing these system archetypes through a System Dynamics approach is essential for promoting sustainability and addressing challenges within the natural gas energy market. By identifying the underlying dynamics and feedback loops, policymakers and stakeholders can implement effective intervention strategies to ensure a balanced and sustainable energy sector.

The "Fixes that Fail" archetype refers to interventions that lead to unintended and undesirable consequences despite good intentions (Benninger et al., 2021). In the context of the Turkish energy sector, energy security is crucial for sustainable energy development. The government's intervention to meet the growing demand for natural gas focuses on increasing natural gas supply in the short term (loop P7). However, this fix fails to guarantee long-term energy security as it increases dependency on imported natural gas, thereby heightening the risk of supply disruptions and reducing overall energy security (loop N8).

Similarly, in the gas sector, the intervention involves increasing gas supply to meet domestic and export demands, which improves gas security in the short term (loop P8). However, commitments to gas exports result in higher domestic gas prices, reducing energy security (loop N9). Additionally, the increased extraction of gas resources for domestic and international purposes depletes gas reserves, leading to decreased energy security in the long term (loop N10).

Moreover, energy security is inversely related to energy emissions, where higher emissions indicate lower energy security. The government intervenes by investing in renewable energy (RE) to mitigate CO_2 emissions (loop N6), primarily focusing on renewable electricity. While investing in RE is important, uncertainties in supply and meeting demand growth may result in increased reliance on non-renewable energy sources, leading to a net increase in CO_2 emissions (loop P5). To strengthen loop N6 and effectively reduce CO_2 emissions, it is essential to broaden the focus beyond the electricity sector and address other sectors like transportation. Consistent and stable energy policy, along with technology development and innovation, play crucial roles in attracting investments in RE. Technology advancements can lower costs and create a stable investment environment. Alternative options like nuclear power and carbon capture and storage (CCS) have their limitations and should be considered alongside other approaches. Enhancing energy conservation, investing in energy efficiency, addressing intermittency in RE through storage technologies, and implementing new norms on the supply and demand side (loop N7) are important measures to significantly reduce CO_2 emissions if nuclear power and CCS are not viable options.

By understanding the dynamics of the "Fixes that Fail" archetype, policymakers and stakeholders can identify potential unintended consequences and develop more comprehensive and sustainable strategies within the natural gas energy market.

4. DISCUSSION

The findings of this research reveal significant risks associated with energy security and environmental interventions in the Turkish energy sector. Energy security is recognized as a fundamental requirement for a sustainable energy future, as it is directly linked to national economic security, sustainable development, environmental security, and social stability. Achieving a sustainable energy future is contingent upon establishing a balance between supply and demand and reducing emissions. This requires investments in new capacities, consistent and stable energy policies, and technology development and innovation.

One key factor contributing to policy failure in the Turkish energy sector is policy volatility, which creates uncertainty and hinders growth and investment. To address this, several strategies are suggested. Strengthening the feedback mechanism of energy market signals and engaging the market can foster technological innovation and adoption. Incorporating missing feedback loops, particularly those related to information flow, can influence behavior change. Implementing optional or compelling feedback information, such as energy consumption and emissions data, can improve the energy system. For instance, using devices with high efficiency factors and smart digital control technologies can positively impact energy demand/consumption. Reporting emissions publicly can also incentivize high-emission industries to reduce their emissions. Additionally, imposing tax penalties on excessive natural resource exports can prevent unsustainable resource depletion and ensure domestic consumption remains balanced with export prices. The incorporation of these missing feedback loops as new norms within the Turkish energy sector (N7) can enhance stakeholder behavior, inform energy policy decisions, and improve the overall energy system.

Mitigating CO_2 emissions requires a diverse energy mix that includes continuous and discontinuous renewable energy resources, as well as low-emission fossil fuel options. Models have suggested various combinations of biofuels, wind, solar, hydro, gas, coal, and oil to meet Türkiye's electricity needs while reducing emissions. However, it is crucial to address heat and transport energy systems as well, as the electricity supply sector accounts for only a portion of energy consumption in Türkiye. Taking cues from other countries, focusing on transitioning to electric vehicles and expanding renewable energy policies beyond the electricity sector can effectively reduce CO2 emissions. By adopting storage technologies and converting intermittent renewable energy into dispatchable power, the uncertainty in supply can be mitigated. It is important to recognize that relying solely on renewable energy may inadvertently lead to an increase in the use of non-renewable resources to meet growing demand, resulting in higher CO_2 emissions. Therefore, energy conservation, investments in energy efficiency, and expanding renewable energy across multiple sectors are crucial for achieving significant reductions in CO_2 emissions.

Furthermore, the discussion highlights the importance of improving energy efficiency to lower energy bills, reduce emissions, improve health and welfare, increase productivity, and foster job and economic growth. Although the rebound effects of energy efficiency measures remain a topic of debate, reducing dependency on fossil fuels and accelerating the transition to full renewable systems can mitigate any potential rebound effect and contribute to overall welfare improvement. Strengthening the feedback power of energy market signals, incorporating information flows into feedback loops, focusing on energy conservation, increasing investments in energy efficiency and renewable energy, promoting technology development and innovation, and maintaining consistent and stable energy policies are critical factors for enhancing energy security and advancing the Turkish energy sector towards sustainability.

In conclusion, adopting a System Dynamics approach in the natural gas energy market requires comprehensive strategies that address energy security, environmental concerns, and the complex dynamics of the energy sector. By considering the interactions and feedback loops within the system, policymakers and stakeholders can develop effective and sustainable solutions that promote a secure, reliable, and environmentally friendly energy future.

5. CONCLUSION

The journey towards a sustainable energy sector requires a holistic understanding of its components and their intricate relationships. This study has delved into these components, identified leverage points within the system, and proposed intervention strategies to foster a sustainable energy future. Focusing on Türkiye as a case study, a System Dynamics approach has been employed to comprehend the energy system's structure and complex dynamics. As the demand for effective strategies to address energy sector challenges grows, applying such an approach can lead to more informed decisions and policy changes, yielding improved outcomes while avoiding undesired consequences.

The research findings underscore the instability and unsustainability of Türkiye's current energy sector, primarily driven by a volatile and inconsistent energy policy context. Government interventions aimed at meeting escalating energy demands are poised to exacerbate energy dependency, raise energy prices, increase CO_2 emissions, and perpetuate unsustainable fossil fuel extraction.

The conceptual model of the Turkish energy sector proposed in this study offers a valuable framework for charting a path towards a sustainable energy sector. However, it is essential to acknowledge that the conceptual model remains qualitative in nature, and the feedback loops presented are hypotheses that require empirical analysis and testing. Therefore, to provide a comprehensive analysis and verify the feedback loops that govern system equilibrium, the next step would involve constructing an empirical analysis and simulation model in a subsequent paper. This quantitative modelling approach will allow for an in-depth investigation into the system dynamics of the Turkish energy sector, based on the conceptual model developed in this study.

By combining qualitative and quantitative methodologies, policymakers and stakeholders can gain deeper insights into the complexities of the energy sector and develop targeted interventions that lead to a sustainable energy future. The ongoing pursuit of sustainability in the natural gas energy market necessitates a continuous and iterative process of analysis, evaluation, and adaptation to address evolving challenges and opportunities in the energy landscape.

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