Original Research

System Dynamics Modeling and Simulation to Analyze the Role of Solar Energy in Secure Access to Sustainability

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Abstract
A truly renewable energy source, solar energy is considered within the context of climate change by various countries among which China, USA, and Germany rely more on solar power. Since there are rare studies regarding how energy drives secure access to sustainability, this study explores the role of solar energy generation in economic, social, and environmental sustainability and energy security in Iran as the main purpose. Using a system dynamics computer simulation model, this paper defines factors affecting the system including four sub-models such as energy and three aspects of sustainability. Besides, energy security is defined as the availability of adequate energy supply to satisfy existing demand. After determining a causal loop diagram, dynamic models, specific trends, and validation and simulation of the system, separate policies are presented along with a combined policy for system improvement. The policies include enhancing foreign investment, increasing tariffs of non-renewable energies, and decreasing energy intensity. This study further reviews relevant policies set forth in the USA, Germany, and China. According to the results, improvement policies are coming to an end. The main contributions are the insights into the sector to support policy-makers and finally, proposing policies for the system improvement.

Keywords - Solar energy industry; sustainability; energy security; system dynamics; policy making.

INTRODUCTION

Many countries attempt to develop their renewable energy generation capacity by considering energy policies, so as to achieve goals such as economic growth, employment, and environmental protection. With the help of energy, nations can expand and run industries, provide goods, jobs, homes, and facilities with heat, light, and power. Energy is the main driving factor for economic growth. Thus, countries tend to look at this sector as a potential engine for economic growth. They are threatened as more countries in the world compete for a fixed (some would say diminishing) quantity of oil to satisfy growing energy appetites. On the other hand, the dependency on oil sales in countries with large supplies of energy (e.g. Iran) has directly affected the country's economy, society, and environment. One of the most important avenues for reducing the oil dependency is to develop substitute(s) for and/or alternative(s) to oil. Promoting non-traditional energy sectors such as wind and solar production can be considered as another way to foster economic development, even the countries enjoying large oil and gas reserves. Using existing technology and energy storage, it is expected to achieve 100% renewable energy worldwide and reach zero carbon emissions by 2025. The structure of global power generation in 2050 will include solar photovoltaics (69%), wind energy (18%), hydropower plants (8%) and biomass (2%) [1].

In countries like Iran, abundant sources of energy have served as the main driving force for socio-economic developments in terms of population growth, industrialization, urbanization, transportation, and standards of living. However, failure to account for limitedness of natural reserves has brought about energy insecurity and climate instability problems for these countries, to the extent where, in many cases, the countries must import energy to satisfy their own demand for energy.

Although development is usually said to affect broader energy use, there are rare studies regarding how energy drives higher economic productivity and development. A major challenge is to find a balance among the use of energy, environmental protection, and production. Fossil fuels are the largest source of greenhouse gas emissions. Carbon emissions increased at the highest rate in 7 years [2]. However, in order to minimize the environmental damages incurred by the use of energy, a smart national policy should focus on alternatives such as renewable energy. The goal should be to increase reliance on secure, reliable, clean, sustainable, and cost-effective source of energy.

This paper aims to address potential role of renewable energies to enhance economic diversification and sustainability implications by exploring potential advantages of renewable energy deployment in three aspects of sustainability including environmental, social, and economic sustainability. Accelerating the transition to a renewable-based energy system represents a unique opportunity to meet climate goals while fueling economic growth, creating new employment opportunities and enhancing human welfare. In this study, among different types of renewable energies, solar energy is considered given that Iran has a unique geographical location where 90% of its area receives enough sunlight to generate solar power (i.e. 300 days per year). More precisely, Iran receives 520 watts per hour per square meter of solar radiation every day [3].

In addition to sustainability, energy security, which refers to availability of adequate and reliable energy supplies to satisfy existing demand, is analyzed and predicted. It is regarded in the present study because a change in oil prices tend to dramatically alter global economy, household budget, industrial costs, political stability, and vulnerability all over the world. Increased imports (measured as a fraction of total consumption) without considering either the country‘s limitations to supply further energy or the risen level of energy prices is likely to damage energy security. In order to establish energy security and independence, policymakers are trying to expand domestic energy supplies and address risks by either diversifying energy sources or modifying the pool of fuel types, e.g. increasing the share of renewable energies.

In this study, solar energy generation and its impacts on sustainability and energy security in Iran are modeled and simulated with system dynamics (SD) methodology. Presenting a causal loop diagram and dynamic model and testing the validation of the model, policies were proposed and compared with the policies set forth in three countries including USA, Germany, and China as they rely more on solar power.

The most contributions of this study are: 1) providing insights into Iran’s solar energy sector using the system dynamics methodology (SDM) which is a computer-aided method for the analysis and design of policy; 2) presenting causal loop diagrams; 3) defining a dynamic model as a mathematical modeling technique; 4) providing an effective tool to support policymakers; 5) proposing policies for the system improvement.

SYSTEM DYNAMICS METHODOLOGY (SDM)

System dynamics (SD) is an efficient methodology for policy development. SD is selected as the methodology of this study because of its flexibility. It causes unquantifiable variables to be integrated in models, replacing data with feedback relationships. This allows it to be suitable in systems design for unprecedented situations [4]. The analysis of the system structure (model) by policies provides an understanding of the system behavior over time [5].

SD is a modeling approach to comprehension, visualization and analysis of complicated dynamic feedback systems. With SD, one can utilize extracted essential structures of a system’s working mechanism and the development of efficient management strategies on the basis of an analysis of feedback structures inherent to the system, to facilitate understanding of the system [6]. Once finished with identifying problem areas or policy issues of concern to the management, in order to successfully employ SD as a learning tool, SD models incorporate positive and negative feedback loops, called casual loops, to identify the dynamics arisen from these interactions, so as to reveal the structure of the system which allows one to address the system’s behavior over a period of time [7]-[8].

SD modeling is unlike other quantitative energy models due to its endogenous approach as it helps system analyst to understand, and model the system's structure and therefore view and embed social aspects into the endogenous model structure [9]. SD method has been widely used in environmental studies because of some considerations like [10]:

- Following changes throughout time (dynamics),
- Complexity problems both detail complexity and dynamic complexity,
- Nonlinearity,
- Existence of a feedback.

SD can be utilized to map policy-makers' knowledge or mental model and other information about the business or social systems, which can then be converted into models and simulations [11]. SD provides the basis for decision-making. So, one can achieve better approaches to system management via eliciting, debating and facilitating changes in the corresponding mental models of decision-makers [12]. Moreover, SD can be incorporated into the process of policy making via three phases: analysis, planning, and control. Predicting the expected performance, SD serves as an essential element in the control phase with deviations indicating the need for further analyses [13]. SD helps researchers perceive how policies may perform over time and connect various policies to performance differences among firm over time. It can be applied for visualizing the firm policy structure and explain the reasons why some managers execute those policies that are relevant to competitive success [14].

Thereby, SD provides a holistic understanding of the whole system and the relevant policy responses for this study as well. Indeed, SD has found applications in many disciplines including social-economic systems, ecological systems, transportation systems, and environmental management and policy assessment (e.g. solid waste management, water resource management, greenhouse gas (GHG) mitigation, sustainable evaluation, and environmental planning). Energy management has also hosted SD models specially developed for this area (e.g. national energy policy evaluation, energy efficiency analysis and the development of energy industry) [15].

LITERATURE OF SYSTEM DYNAMICS

The energy sector is essentially a dynamic and complex system because it is composed of many components with complex cause-and-effect relationships created through multiple feedback loops. This system consists of different sources of supply, complex use, and participation of multiple stakeholders with different management goals and interests. In addition, it is affected by diverse internal factors (demand fluctuations, energy policy developments, and sustainability) and external factors (political instability, natural disasters, and energy dependence). The presence of these factors together means that energy planners have to make decisions in uncertain situations, and therefore the development of the sector with a sustainability approach faces many challenges [16]. In general, energy systems include policy-related attributes, such as international interactions, coordinated and interactive agreements, institutionalized rules and, a complex and various range of stakeholder groups [2]. Energy systems are complex dynamic systems which are often associated with uncertain system behavior [17]. Numerous studies have been conducted to address climate change, renewable energy, and the sustainable use of resources, using system dynamics modeling as a tool. At the macro level, the system dynamics approach has been used to formulate practical policies and at the micro level, it has been applied to evaluate and measure the factors [18].

The SD model of U.S., FOSSIL2, about energy supply and demand has had a high influence on United States government policy than other SD works. The model has been refining and using for government energy planning and policy analysis [19]. SD has been used to discuss the Indonesian government that as a result of the large energy demand and the sustainable development concerns has tried to create a target in the final energy mix regarding new and renewable energy contribution and to represent some policies to achieve this target [20].

The effects of energy intensity on environmental pollutants and social costs have been analyzed following a SD approach. According to the research, intensity index was a measure of energy consumption per added-value. Compared to developed countries, Iran is very poor in the value of this index. This index affects energy consumption and added-value, thereby altering future energy use. Some social costs are incurred by the damaging effect of environmental pollutants on ecosystem and public costs [21].

A set of variables affecting the choice of renewable energy policies has been identified in Oman. These included national energy security, local air quality, economic growth, job creation, greenhouse gas (GHG) emissions, saving gas for export, and country's reputation. Accordingly, they modeled the system using three sub-models, namely economic, environmental, and social sub-models [22].

According to [23] variations in energy matrix and Gross Domestic Product (GDP) had contributions into CO2 emissions in Ecuador. GDP, share of different productive sectors in GDP, energy intensity of each sector, energy consumption, energy matrix, and carbon dioxide intensity together determine the level of CO2 emissions. They observed several connections between the CO2 emitted into the atmosphere and the model variables. Indeed, economic growth and associated activities demanded more energy, so that more energy was consumed, inducing higher CO2 emissions. However, this could be regulated by modifying the energy matrix and structure of productive sector of the country. It is worth noting that, the presence of a feedback mechanism contributes into the effect of renewable energy production on GDP.

A status change from a net oil exporter to a net oil importer has recently concerned Indonesian government about energy security. This is why oil import has become the center of attention of the Indonesia's energy security policy. In order to analyze energy security in Indonesia, [24] applied SD. their model consisted of one main sub-model (energy system) and two smaller sub-models (economic system and technology system).

[25] represented a source for elaborating a System Dynamics framework applied on renewable energy supply chain considering sustainability. The work showed the importance of system modelling regarding improving the understanding of supply chain in renewable energy and developing modelling and simulation approaches in renewable energy systems.

POLICIES TO GROW SOLAR ENERGY

Solar energy is considered within the context of climate change by various countries among which China, USA, and Germany rely more on solar power. Thus, this study reviews solar energy policies of these countries to have a better insight for policy making of the system under study.

I. Policies of U.S.

Federal, state, and local authorities in the U.S. have set forth effective policies to grow solar energy. Some of these policies are referred to in the following [26]:

a) For rooftop systems

- **Net metering:** This policy provides system owners with compensations in return of excess electricity generation on their utility bills.
- Feed-in tariffs: Under this policy, the solar power generated by home owners and businesses is purchased under standardized long-term contracts offering fixed prices.
- **Value-of-solar tariffs:** This policy has system owners paid based on the calculated value of the broad suite of benefits provided by the solar system. Such value-of-solar tariffs not only account for the benefits of providing electricity but also acknowledge the values of feeding power to the grid instantaneously, delaying or eliminating the need for system upgrades, and other environmental benefits gained by no use of fossil fuels.
- **Solar carve-outs:** In some states, small-scale solar systems are targeted as parts of broader efforts to extend investments on renewable energy.
- **Tax incentives and subsidies:** Tax incentives for home owners and businesses (e.g. property tax exemptions) in return of purchasing renewable energies.

b) Large-scale PV

- **Avoiding/mitigating disruptions in environment:** in large-scale projects, one may avoid disrupting the environment or at least minimize or mitigate such disruptions by careful site selection and project design, robust analysis of environmental and cultural consequences, and other efforts before, during, and after the project construction.
- **Renewable electricity standards:** A key driver of large-scale renewable energy development across U. S. has been the need for utilities to get specified amounts or percentages of electricity sales from renewable energy within certain time schedules.
- **Tax policies:** Solar investment tax credits are available not only to home owners, but also to large systems. The federal tax code further drives the economics of large-scale solar systems by allowing for accelerated depreciation of solar equipment; the 2010 federal stimulus bill made a foundation for even faster Depreciation.
- **Permitting reforms:** Local, state, and federal agencies are attempting to improve the permitting process to help reduce the significant time and cost for all parties involved. In most cases, large solar systems require permits at both the state and local levels.

c) Future plans

- **Renewable electricity standards:** States are required to not only preserve, but also enhance their key policies for further driving renewable energy (e.g. solar) investments.
- **Solar tax credit:** As a so important support for the rise of solar systems, the federal investment tax credit is set to decline from 30 percent to 10 percent at the end of 2016; this is when the congress will need to come into play and sustain that support.
- **Federal power plant carbon standards:** States should take measures to make sure that solar plays a key role in their plans to lower emissions in their attempts to comply with the new carbon standards released by Environmental Protection Agency.
- **Full value of solar:** Comprehensive evaluation of the benefits to be gained and the costs associated with solar systems, particularly rooftop solar, will help

policy makers go for the most appropriate solution to assist more people in adopting solar.

- **Storage:** Lower costs and the greater availability of energy storage systems are likely to lay a basis for providing solar electricity more consistently and at times of peak demand.
- **New utility business models:** Utilities need to modify their business models in such a way to widely adopt rooftop solar and encourage continued solar development, from rooftops to large-scale projects.
- **Research and development:** Solar prospects should be even further developed by continued progress in reducing associated costs—through greater economies of scale, increasing efficiencies of cell and module, improved inverters and mounting systems, better heat transfer, and streamlined transactions.

II. Policies of China

China's policies include [27]:

- **Laws and regulation:** Chinese laws tend to stimulate the development and utilization of clean energy, particularly renewables.
- **Subsidies:** Both the central government of China and local Chinese governments provide fiscal incentives for renewable energies. The central government provides subsidies for the followings:
    - R&D to innovate and industrialize core renewable energy equipment. This includes advanced silicon technologies for solar PV.
    - Construction of renewable energy generation systems.
    - Township Electrification Program. Carried out during 2000-2003, this well-known program had its focus on rural utilization of off-grid solar PV systems, wherein more than 1,000 towns in western China were provided with the electricity generated by solar and small-scale wind energy systems.
    - Subsidies for rural end-users. In early 2009, China launched a subsidy program upon which rural households were supported to use electrical appliances.
- **Tax Policies:** In China, only limited tax incentives are offered for renewable energy development.
- **Pricing Schemes:** A variety of preferential pricing schemes are offered for the power generated from renewable sources in China.
- **Investment Policy:** In addition to the Chinese government, China‘s Treasury Bond also supports renewable energy and associated R&D, demonstration projects, and key equipment manufacturing.
- **Planning and Support:** China is one of the pioneers in implementing a national strategy on renewable energy; the strategy is grounded on both existing and more-recent laws and regulations.
    - Phase One (1996–2000): It refers to implementation of R&D and demonstration projects to upgrade most domestic renewable energy technologies to a level near or equal to advanced international standards. It includes commercializing a number of mature technologies, extending their application, and developing markets for those gradually.
    - Phase Two (2000–2010): Extending renewable energy technology to a wider scale, creating advanced industrial and technology research systems according to international standards to realize large-scale production and increase total development and use of all new and renewable sources of energy.
- **Industry Support:** Offering such financial supports as tax breaks, investment subsides, and bonuses, Chinese government tries its best to facilitate commercialization of renewable energy. The governmental stimulus activities include the establishment of special funds for manufacturing key equipment and deploying technologies to encourage solar thermal as well as wind and solar PV power generations.

III. Policies of China

During the past two decades, Germany has shifted from a publicly-financed R&D-focused approach to renewable energy toward policies to encourage the application and implementation of new technologies in the market place. Germany has developed five principle policies for promoting renewable energy [28]:

- Direct investment in R&D;
- Direct subsidies;
- Government-sponsored loans;
- Tax allowances;
- Subsidies for operational; and
- Costs/ feed-in tariffs.

By reviewing policies set forth in three countries (USA, Germany, and China), some changes to the overall structure of the Iranian solar energy sector can be recommended such as 1) undertaking R&D activities following the specification and prioritization of the required research projects, and 2) support the industry to facilitate the commercialization of renewable energies.

RESEARCH METHODOLOGY

The models were developed using SDM. Overall conceptual framework of the study was formed based on the literature review and the information gathered from five experts who have been working as managers in solar energy companies. Table 1 shows important measures and their references.

TABLE I
MEASURES AND REFERENCES

No.	Measure	Reference
1	Energy demand	[21]
2	greenhouse gas (GHG) emissions, job creation, trained workforce, energy production revenue, energy production, energy export, energy import	[22]
3	Gross Domestic Product (GDP), emissions, energy import	[23]
4	Energy supply, energy demand, energy import, GDP	[24]

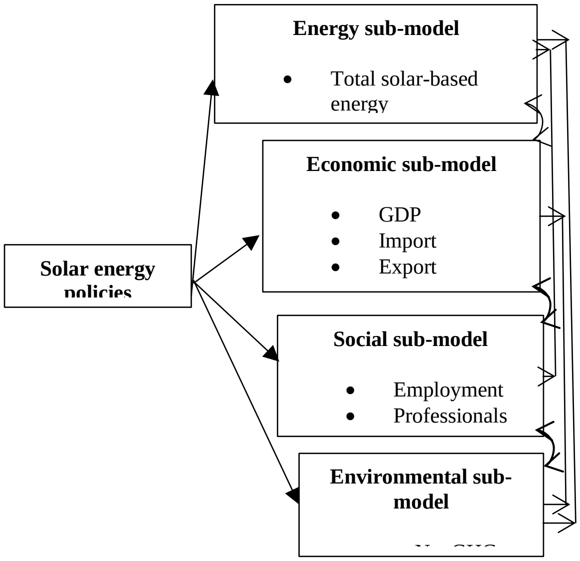

FIGURE 1. A CONCEPTUAL FRAMEWORK OF THE STUDY

As it is shown in Figure 1, sub-models of the primary model are important in choosing appropriate policies that have a potential role in promoting the solar energy generation, GDP, and energy security. These sub-models are classified in the following categories:

- Energy sub-model showing trend of solar energy generation and solar-based energy revenue,
- Economic sub-model focusing on GDP, import, export, and energy demand,
- Social sub-model focusing on employment, and professionals,
- Environment sub-model focusing on GHG emission.

CAUSAL LOOP DIAGRAM

Since the model purpose is to examine the theory that secure access to sustainability increases as solar energy increases, the reference mode is used to capture mental models and historical data for giving clues to appropriate model structure, and checking the quality of the built model. Some modelers can know which structures can produce which behavior modes, thus making the reference mode can be an invaluable resource during the modeling process. Additionally, verbal descriptions of experts about system behavior can perform the same as the graphic reference mode [29].

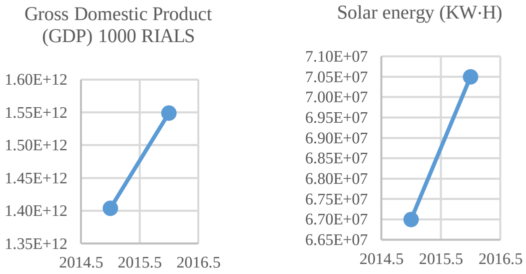

FIGURE 2. REFERENCE MODES OF GDP AND SOLAR ENERGY

Historical reference modes using historical data of GDP and solar energy generation can be seen in Figure 2.

As shown in Figure 3, there is a plan to harvest energy from solar systems. Accordingly, there is a balancing loop in which energy gap is defined as the difference between planned solar-based energy and total solar-based energy production. Total solar-based energy production decreases with decreasing the rate of solar-based energy production, and it increases with increasing the rate of solar-based energy production. Total solar-based energy production causes increases in solar-based energy revenue and GDP while declining the energy gap and non-renewable energy production.

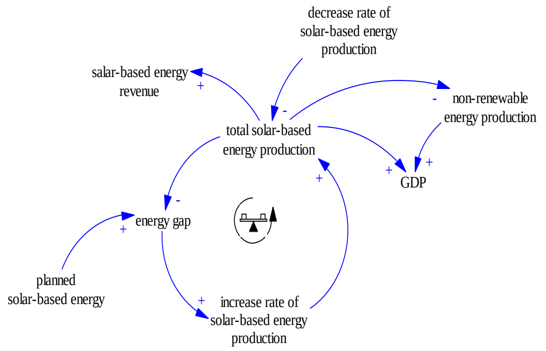

FIGURE 3. CAUSAL LOOP DIAGRAM OF ENERGY SUB-MODEL

Figure 4 represents the social sub-system which focuses on employment and training to have more professionals in solar industry. As it is clear, there is a recruitment plan derived from the solar-based energy plan. This plan creates a balancing loop in which workforce gap is defined as the difference between desired number of workforce and employment. More employment makes greater level of profession and further decreases the rate of employment.

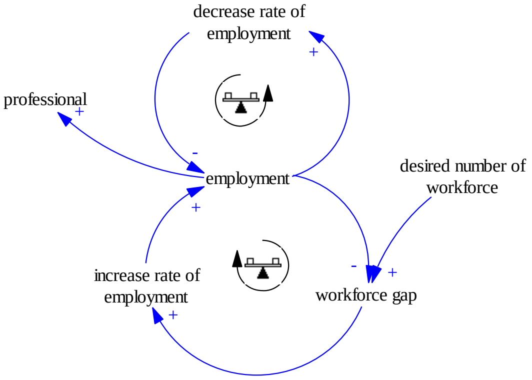

FIGURE 4. CAUSAL LOOP DIAGRAM OF SOCIAL SUB-SYSTEM

There are plans for exporting and importing electricity according to Figure 5. Due to these plans, there is a balancing loop for the export and another balancing loop for the import. Export gap is determined by the difference between planned export and actual export. Conversely, import gap is defined as the difference between planned import and actual import. The import increases total energy production, but it is decreased by export. Export generates revenue, leading to increased GDP. But import increases costs, causing a decline in GDP. The relationships between demand and GDP define a reinforcing loop. In other words, an increase in GDP boosts the demand, and vice versa. A share of GDP is earmarked for reducing pollution, which reduces GDP in a balancing loop.

DYNAMIC MODEL

Energy sub-model is composed of two stock variables, namely ‘total solar-based energy production’ and ‘solar-based energy revenue’, as is indicated in the model shown on Figure 6.

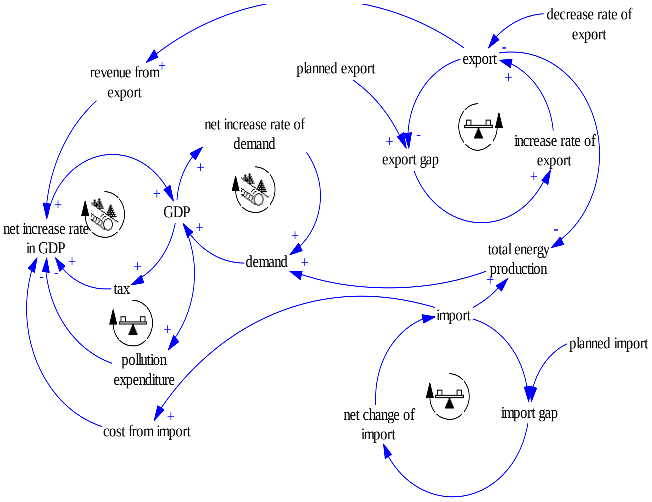

FIGURE 5. CAUSAL LOOP DIAGRAM OF ECONOMIC SUB-MODEL

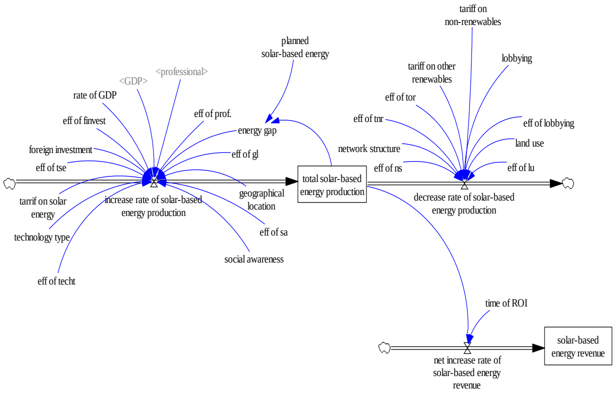

FIGURE6. DYNAMIC MODEL OF ENERGY SUB-MODEL

Some variables affecting this sub-model are presented in Table 2.

total solar-based energy production = "increase rate of solar-based energy production"-"decrease rate of solar-based energy production" (1) solar-based energy revenue = "net increase rate of solar-based energy revenue" (2)

energy gap= "planned solar-based energy"-"total solar-based energy production" (3)

net increase rate of solar-based energy revenue = "total solar-based energy production"/time of ROI (4)

TABLE2. SOME VARIABLES USED IN ENERGY SUB-MODEL

No.	Variable	Description	Type
1	Total solar-based energy production	Energy produced by solar systems	Stock
2	Solar-based energy revenue	Revenue earned by solar systems	Stock
3	Increase rate of solar-based energy production	Increasing rate of energy produced by energy systems	Rate
4	Decrease rate of solar-based energy production	Decreasing rate of energy produced by energy systems	Rate
5	Energy gap	The difference between planned solar-based energy and total solar-based energy production	Auxiliary
6	Net increase rate of solar-based energy revenue	Net change of revenue earned by solar energy	Rate
7	Time of return on investment (ROI) (The delay time specified)	5 years	constant

Social sub-model is composed of two stock variables, namely “employment” and “profession”, as clarified in the dynamic model shown in Figure 7.

Some variables affecting this sub-model are presented in Table 3.

employment = increase rate of employment-decrease rate of employment (5)

professional = training rate (6)

increase rate of employment= workforce gap×absorption rate (7)

decrease rate of employment = employment×rate of leave (8)

workforce gap = desired number of workforce-employment (9)

desired number of workforce = "total solar-based energy production"×"workforce per solar-based energy production" (10)

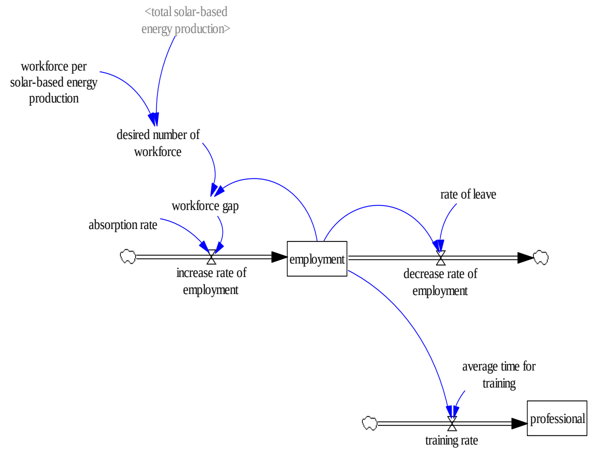

FIGURE 7. DYNAMIC MODEL OF SOCIAL SUB-MODEL

TABLE 3. SOME VARIABLES USED IN SOCIAL SUB-MODEL

No.	Variable	Description	Type
1	Employment	The number of new entrant employees	Stock
2	Professional	Trained and experienced employees	Stock
3	Training rate	Rate of training employees	Rate
4	Increase rate of employment	Rate of increasing employment	Rate
5	Workforce gap	Distance between current workforce and desired one	auxiliary
6	Desired number of workforce	Desired number of workforce	Auxiliary

Economic sub-model can be described by six stock variables, namely “GDP”, “energy demand”, “import”, “cost of import”, “export”, and “revenue from export”, as shown in Figure 8.

Some variables affecting this sub-model are presented in Table 4.

Export = increase rate of export-decrease rate of export (11)

revenue from export = increase rate of revenue from export (12)

import = net change of import (13)

$$\text{GDP} = \text{net increase rate in GDP} \tag{14}$$

$$\text{Demand} = \text{net increase rate of demand} \tag{15}$$

$$\text{increase rate of export} = \text{export gap}/12 \tag{16}$$

$$\text{export gap} = \text{planned export-export} \tag{17}$$

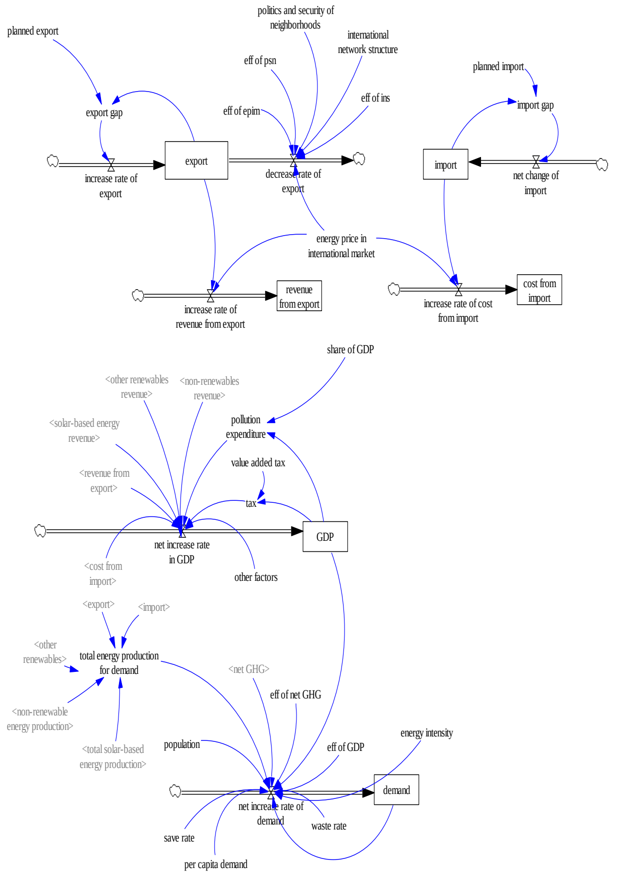

FIGURE 8. DYNAMIC MODEL OF ECONOMIC SUB-MODEL

$$\text{increase rate of revenue from export} = \text{energy price in international market} \times \text{export} \tag{18}$$

$$\text{net change of import} = \text{import gap}/12 \tag{19}$$

$$\text{import gap} = \text{import-planned import} \tag{20}$$

$$\text{increase rate of cost from import} = \text{energy price in international market} \times \text{import} \tag{21}$$

$$\text{net increase in GDP} = \text{"non-renewables revenue"} + \text{other renewables revenue} + \text{"solar-based energy revenue"} + \text{tax} - \text{pollution expenditure} \tag{22}$$

$$\text{pollution expenditure} = \text{GDP} \times \text{share of GDP} \tag{23}$$

$$\text{tax} = \text{GDP} \times \text{direct tax} + \text{GDP} \times \text{value added tax} \tag{24}$$

$$\text{total energy production} = \text{"non-renewable energy production"} + \text{other renewables} + \text{"total solar-based energy production"} + \text{export} \tag{25}$$

$$\text{net GHG} = \text{increase rate of pollution-decrease rate of pollution} \tag{26}$$

$$\text{increase rate of pollution} = \text{influencing rate} \times \text{"non-renewable energy production"} \tag{27}$$

$$\text{decrease rate of pollution} = \text{eff of pe} \times \text{pollution expenditure} \tag{28}$$

TABLE 4. SOME VARIABLES USED IN ECONOMIC SUB-MODEL

No.	Variable	Description	Type
1	Export	Real export of electricity	Stock
2	Import	Real import of electricity	Stock
3	Increase rate of export	Increasing rate of export	Rate
4	Decrease rate of export	Decreasing rate of export	Rate
5	Net change of import	Net changes in import	Rate
6	Revenue from export	Revenue gained from export	Stock
7	Cost from import	Costs paid to import	Stock
8	Export gap	Difference between planned export and actual export	Auxiliary
9	Import gap	Difference between planned import and actual import	Auxiliary
10	Increase rate of revenue from export	Increasing rate of revenue gained from export	Rate
11	Increase rate of cost from import	Increasing rate of costs paid to import	Rate
12	GDP	Monetary measure of the market value of all produced energies, products, and services	Stock
13	Net increase in GDP	Net change of GDP	Rate
14	Demand	Energy demand in the country	Stock
15	Net increase rate of demand	Net increase rate in energy demand	Rate
16	Total energy production for demand	Difference between energy produced from total solar-based energy production, import, other renewables, non-renewable energy production, and export	Auxiliary

In the case of environmental sub-model, there is a stock variable named ‘net GHG’ which is shown in Figure 9.

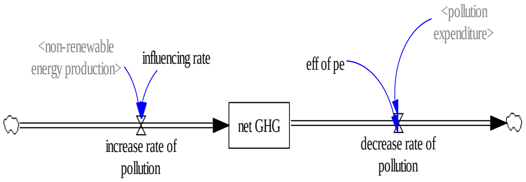

FIGURE 9. DYNAMIC MODEL OF ENVIRONMENTAL MODEL

Some variables affecting this sub-model are presented in Table 5.

TABLE 5. SOME VARIABLES USED IN ENVIRONMENTAL SUB-MODEL

No.	Variable	Description	Type
1	Net GHG	Net greenhouse gas	Stock
2	Increase rate of pollution	Increase rate in net GHG	Rate
3	Decrease rate of pollution	Decrease rate in net GHG	Rate
4	Pollution expenditure	Required costs to overcome pollution	Shadow

ANALYSIS OF THE STATUS QUO

Based on Figure 10, it is clear that:

- Total energy generation increases gradually during 2015-2019 period at about 3% per year.
- Non-renewable energies decline by 30% during 2015-2016 period. Then, from 2016 to 2019, it increases gradually at some 3% per year.
- Other renewable energies exhibit considerable growth by about 7 folds during 2015-2016 period, after when those follow an increasing trend at about 3% per year.
- Total solar energy rises by 5% during 2015-2016 period, 35% during 2016-2017 period, 40% during 2017-2018 period, and 600% during 2018-2019 period.
- Imports grow slightly by about 0.1% from 2015 to 2016, 3% from 2016 to 2017, 4% from 2017 to 2018, and 5% from 2018 to 2019.
- Exports increase by about 3% from 2015 to 2016, 5% from 2016 to 2017, 8% from 2017 to 2018, and 15% from 2018 to 2019.

According to the results, the focus of the government is on increasing the share of renewable energies in total energy production. As such, solar energy experiences faster growth than other renewables. It is shown that, there is a significant decline in non-renewable energy production due to the fast increase in renewables. In addition, the growth rate of export is more that the growth rate of import.

With the expansion of solar industry, the rate of employment in this industry is increasing. Experiencing a two-year training program to gain the required deal of experience, the number of professional staffs is gradually increasing in the industry (Figure 11):

- The rate of employment increases by 3 folds from 2015 to 2016, 70% from 2016 to 2017, 50% from 2017 to 2018, and again 50% from 2018 to 2019.

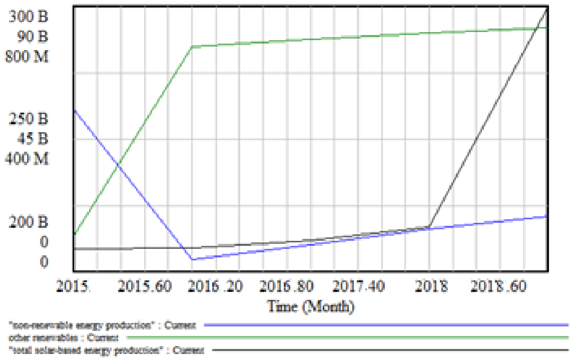

FIGURE 10. THE AMOUNT OF ALL TYPES OF ENERGIES (KW·H) FROM THE YEAR 2015 TO 2019

TABLE 6. THE AMOUNT OF ALL TYPES OF ENERGIES (KW·H) FROM THE YEAR 2015 TO 2019

	Total energy	Non-renewable energies	Other renewable energies	Total solar-based energy	import	Export
2015	2.81e+011	2.60919e+011	1.2404e+010	6.7e+007	4.148e+009	7.61e+009
2016	2.89e+011	2.04743e+011	7.63574e+010	7.05756e+007	4.15392e+009	7.82908e+009
2017	2.97e+011	2.09994e+011	7.86248e+010	9.51749e+007	4.26225e+009	8.28588e+009
2018	3.06e+011	2.15881e+011	8.0947e+010	1.3502e+008	4.45096e+009	9.03739e+009
2019	3.15e+011	2.20765e+011	8.27147e+010	7.99263e+008	4.70534e+009	1.07212e+010

- The count of professional staffs increases by 10% from 2015 to 2016, 20% from 2016 to 2017, 30% from 2017 to 2018, and 40% from 2018 to 2019.

The results show that the growth rate of employment follows a decreasing trend while that of professional staffs is increasing.

Based on Figure 12, both the demand for energy and total energy production increase from 2015 to 2019 at almost 20% and less than 10% per year, respectively. According to the results, since 2017, demand for energy will exceed total energy production, so that the demand for energy can no more be met since 2017.

Based on the results demonstrated in Figure 13, revenues are proportional to production.

- Non-renewables revenue has fallen by about 10% from 2015 to 2016. But following 2016, it increases gradually by about 10% per year. The revenues made from non-renewables in 2016 and 2017 are lower than that in 2015, but in the following years, non-renewables are likely to generate more revenues than the revenue in 2015.

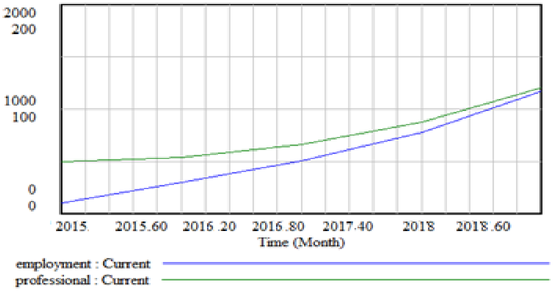

FIGURE 11. THE AMOUNT OF EMPLOYMENT AND PROFESSIONAL STAFFS FROM THE YEAR 2015 TO 2019

TABLE7. THE AMOUNT OF EMPLOYMENT AND PROFESSIONAL STAFFS FROM THE YEAR 2015 TO 2019

	2015	2016	2017	2018	2019
Employment	100	299	504.746	780.176	1169.63
Professional	50	54.1667	66.625	87.6561	120.163

- The revenue from other renewables has risen by five folds from 2015 to 2016, while following a steadily increasing trend in the subsequent years.
- Solar-based energy revenue, revenue from export, and cost of import have followed very slightly increasing trends during the years.
- GDP will increase by about 10% per year during 2015-2019 period.
- Pollution expenditure and value added tax follow the same trend as GDP.

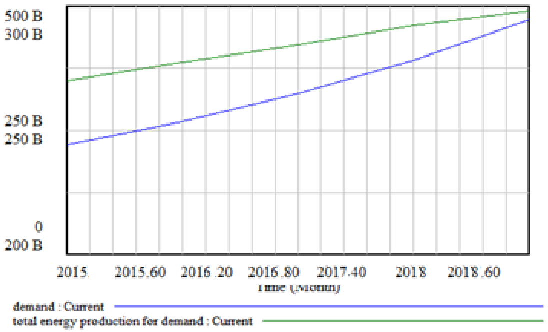

FIGURE 12. THE AMOUNT OF ENERGY DEMAND, AND TOTAL ENERGY PRODUCTION, FROM THE YEAR 2015 TO 2019

TABLE8. THE AMOUNT OF ENERGY DEMAND, TOTAL ENERGY PRODUCTION, AND ENERGY SECURITY FROM THE YEAR 2015 TO 2019

	2015	2016	2017	2018	2019
Demand	2.212e+011	2.68191e+011	3.24408e+011	3.92053e+011	4.73853e+011
Total energy production for demand	2.69928e+011	2.77496e+011	2.84691e+011	2.92376e+011	2.98263e+011
Energy security	4.8728e+010	9.30493e+010	-3.97171e+010	-9.96762e+010	-1.7559e+011

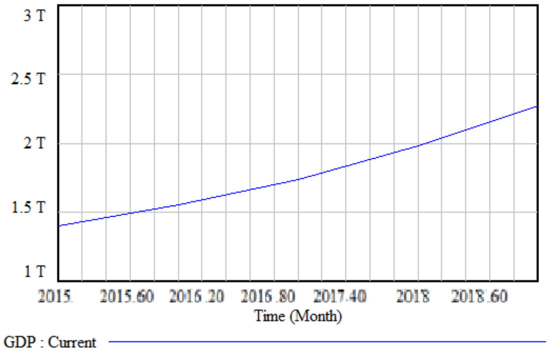

FIGURE 13. THE AMOUNT OF GDP (ONE THOUSAND RIALS) FROM THE YEAR 2015 TO 2019

According to Figure 14, although share of GDP is devoted to be spent on reducing pollution, net GHG still increases.

TABLE 9. THE AMOUNT OF GDP AND ITS INFLUENCING FACTORS (ONE THOUSAND RIALS) FROM THE YEAR 2015 TO 2019

	2015	2016	2017	2018	2019
GDP	1.40359e+012	1.54963e+012	1.73839e+012	1.97743e+012	2.27147e+012
Non-renewables revenue	3.06841e+010	2.64937e+010	2.98822e+010	3.38069e+010	3.80378e+010
Other renewables revenue	4.3414e+009	2.06165e+010	2.12287e+010	2.18557e+010	2.2333e+010
Revenue from export	2.34749e+013	2.34774e+013	2.348e+013	2.34827e+013	2.34857e+013
Solar-based energy revenue	7.01937e+009	7.02049e+009	7.02166e+009	7.02325e+009	7.0255e+009
value added tax	1.26323e+011	1.39467e+011	1.56455e+011	1.77968e+011	2.04432e+011
Pollution expenditure	3.50898e+010	3.87409e+010	4.34598e+010	4.94357e+010	5.67866e+010
Cost from import	9.85565e+012	9.85702e+012	9.85839e+012	9.85979e+012	9.86126e+012

MODEL VALIDATION

Besides having the model checked in the software, the following three methods were used to have the model calibrated and validated [30]:

- Testing model structure – i.e. structure verification test,
- Testing model behavior – i.e. behavior reproduction tests, and
- Behavior prediction tests.

Structure verification refers to the comparisons made directly between the model structure and that of the corresponding real system. In other words, a model should have its structure consistent with that of the corresponding real system, so as to be able to pass the structure verification test. Hence it involves checking model assumptions with five experts, managers and decision-makers of solar energy companies. In this regard, the managers' viewpoints concerning solar energy generation and its role on sustainability factors and energy security indicated that the model structure well fitted to the real structure of Iran's solar energy sector.

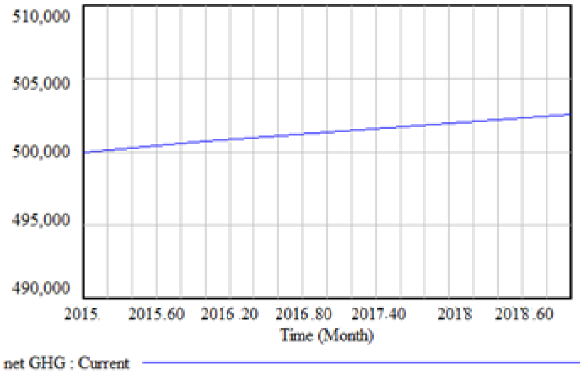

FIGURE 14. THE AMOUNT OF NET GHG (GHG NET EMISSIONS/REMOVALS WITH LUCF[1]) FROM THE YEAR 2015 TO 2019

TABLE 10. THE AMOUNT OF NET GHG (GHG NET EMISSIONS/REMOVALS WITH LUCF) FROM THE YEAR 2015 TO 2019

	2015	2016	2017	2018	2019
Net GHG	499955	500731	501337	501959	502596

Furthermore, behavior reproduction tests examine how well the model behavior conforms to actually observed behavior of the corresponding real system. If the model does not produce behavior similar to historical observations (reference modes), it is an indication that the model requires to be modified [29]. In this case, the model behavior was seen to match the data from the past two years with a very little deviation (It is clear, for example, by comparing reference modes of GDP and solar energy generation presented in Figure 2 and the results of the simulation.)

In addition, behavior prediction tests are used to determine whether a model reproduces correct, in terms of quality, patterns of future behavior. The model behavior was seen to have a slight deviation from the predicted patterns by the managers for the three years to come. Figure 14 shows the result of comparing the actual behavior of GDP in reality to predicted patterns by simulation. In the case of the other variables such as solar energy generation, employment, and net GHG, the model was found to be consistent.

According to the statistical tests of correlation and regression, for instance, for the variables of GDP and solar energy production, there is a high positive correlation equal to 0.90 between them and the regression equation is GDP=

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[1] Land Use Change and Forestry

8956.6 Solar Energy + 9E+11 based on historical data which can present the validity of the model.

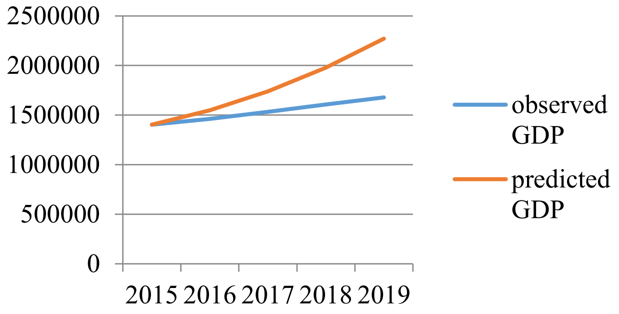

FIGURE 14. GDP (THOUSAND-MILLION TOMANS), ACTUALLY OBSERVED BEHAVIOR AND PREDICTED PATTERNS

POLICIES

In this study, some policies are proposed to improve the system. These policies include:

- Enhancing foreign investment,
- Increasing tariffs of non-renewable energies, and
- Decreasing energy intensity.

I. Doubling the investment

As it is clear from Table 11, if the amount of foreign investment is doubled compared to the planned amounts since 2017, the amount of solar-based energy produced in 2018 will increase by 30% compared to the planned level. As a result of this policy, solar-based energy will further increase by 80% in 2019. With this increase in solar-based energy, however, the revenue from this energy will increase only slightly in 2019. Investment absorption and increased solar-based energy generation will lead to increased employment in this industry (98% increase in employment in 2019).

TABLE 11. RESULTS OF DOUBLE INVESTMENT

	2015	2016	2017	2018	2019
Total solar-based energy	6.7e+007	7.05756e+007	9.51749e+007	1.74847e+008	1.43748e+009
Solar-based energy revenue	7.01937e+009	7.02049e+009	7.02166e+009	7.02325e+009	7.02616e+009
Employment	100	299	504.746	780.176	1289.11

II. Doubling non-renewables tariffs

Based on Table 12, by doubling the tariffs of non-renewable energies, the corresponding revenues will be doubled, and this increase will have very little effect on GDP.

TABLE 12. RESULTS OF DOUBLE NON-RENEWABLES TARIFFS

	2015	2016	2017	2018	2019
Non-renewables revenue	3.06841e+010	2.64937e+010	5.97643e+010	6.76138e+010	7.60755e+010
GDP	1.40359e+012	1.54963e+012	1.73839e+012	1.97986e+012	2.27673e+012

III. Decreasing energy intensity by 10%

As it is seen in Table 13, if instead of one tenth growth per year, we manage to reduce the energy intensity by 10% per year since 2017, the demands for energy in 2018 and 2019 will slightly decrease, thereby increasing energy security by about 5% per year since 2018.

TABLE 13. RESULTS OF ON TENTH DECREASE IN ENERGY INTENSITY

	2015	2016	2017	2018	2019
Demand	2.212e+011	2.68191e+011	3.24408e+011	3.86646e+011	4.54747e+011

IV.A combined policy

Applying all the policies shown in Table 14 causes:

- Increased solar-based energy generation and solar-based energy revenue,
- Increased employment in solar energy industry,
- Increased revenue from non-renewable energies,
- Increased GDP,
- Decreased demand for energy, and
- Enhanced energy security.

CONCLUSION

In this study, system dynamics methodology (SDM) was used to model the impact of solar energy generation on economic, social, and environmental sustainability and energy security. For this purpose, a conceptual framework was formed based on literature review and the information collected from five experts from solar energy companies. This framework showed the main factors of the system and classified them into four categories: energy, society, economy, and environment. According to the results, policies were presented to improve the system performance once finished with defining a causal loop diagram, dynamic models, specified trends, system validation and simulation. Energy security was analyzed by the observed behavior of two variables of the system: total energy generation and demand.

In many cases, Iran's law favors foreign investment. In this regard, the Freedom of Information and Protection of Privacy Act (FIPPA) and many bilateral treaties provide some protection against expropriation and discrimination and ensure return on capital and profits. Moreover, being among member states of the World Intellectual Property Organization (WIPO) and having signed various international treaties on intellectual properties, Iran has already provide a suitable basis for protecting foreign investors' intellectual properties.

TABLE 14. RESULTS OF APPLYING ALL POLICIES

	2015	2016	2017	2018	2019
Total solar-based energy	6.7e+007	7.05756e+007	9.51749e+007	1.74847e+008	1.43748e+009
Solar-based energy revenue	7.01937e+009	7.02049e+009	7.02166e+009	7.02325e+009	7.02616e+009
Employment	100	299	504.746	780.176	1289.11
Non-renewables revenue	3.06841e+010	2.64937e+010	5.97643e+010	6.76138e+010	7.60755e+010
GDP	1.40359e+012	1.54963e+012	1.73839e+012	1.98043e+012	2.28067e+012
Demand	2.212e+011	2.68191e+011	3.24408e+011	3.86646e+011	4.54747e+011
Energy security	4.8728e+010	9.30493e+010	-3.97172e+010	-9.42697e+010	-1.56485e+011

Accepting non-Iranian laws as governing law and opening to international arbitrations are other major measures taken to favor foreign investment. According to Iranian law, foreigners are eligible to hold 100% of shares in Iranian companies.

Regarding energy projects, Iranian renewable sector can be transformed into a charming market by enhancing the feed-in-tariffs and adopting adjustment mechanisms wherein inflation and change of the currency exchange rate are taken into account. As a measure of the energy efficiency and national economy, energy intensity (defined as units of energy consumed per unit gross domestic product (GDP)) has to be reduced for the improvement of the system. By applying these policies, solar-based energy, revenue from solar-based energy, revenue from non-renewable energies, employment in solar industry, and GDP will grow in contrary to the reduction of energy demand, all of which tend to improve energy security.

By reviewing policies set forth in three countries including USA, Germany, and China, some changes to the overall structure of the Iranian system were recommended as: undertaking R&D activities following the specification and prioritization of the required research projects, and support the industry to facilitate the commercialization of renewable energies.

The main contributions of this paper include: (1) providing a deeper understanding of Iranian solar energy sector, (2) developing a dynamic model on the basis of SDM for the aim of supporting policy-makers, and (3) proposing policies for having a higher level of performance.

REFERENCES

[1] Gu, C., Ye, X., Cao, Q., Guan, W., Peng, C., Wu, Y., Zhai, W. (2020) "System dynamics modelling of urbanization under energy constraints in China," *Nature*, 9956. Retrieved on 27th February 2021 from https://www.nature.com/articles/s41598-020-66125-3.

[2] Arroyo M., F. R., & Miguel, L.J. (2020) "The role of renewable energies for the sustainable energy governance and environmental policies for the mitigation of climate change in Ecuador," Energies,13(3883), 1-18.

[3] Atabi, F. (2004) "Renewable energy in Iran: Challenges and opportunities for sustainable development," International Journal of Environmental Science & Technology, 1(1): 69-80.

[4] Sy, C., Ching, P.M., Juan, J.L.S., Bernardo, E., Miguel, A., Mayol A. P., Culaba, A., Ubando, A., Mutuc, J.E. (2021) "Systems dynamics modeling of pandemic influenza for strategic policy development: a simulation-based analysis of the COVID-19 case," Process Integration and Optimization for Sustainability. Retrieved on 27th February 2021 from https://link.springer.com/article/10.1007/s41660-021-00156-9.

[5] Sokame, B.M., Tonnang, H.E.Z., Subramanian, S., Bruce, A.Y., Dubois, T., Ekesi, S., Calatayud, P.A. (2021) "A system dynamics model for pests and natural enemies interactions," Nature, 11 (1401). Retrieved on 27th February 2021 from https://www.nature.com/articles/s41598-020-79553-y

[6] Park S., B.-J. Kim and S.-Y. Jung. (2014) "Simulation methods of a system dynamics model for efficient operations and planning of capacity expansion of activated-sludge wastewater treatment plants," Procedia Engineering, 70, 1289 – 1295.

[7] Zaim S., N. Bayyurt, M. Tarim, H. Zaim, Y. Guc. (2013) " System dynamics modeling of a knowledge management process: A case study in Turkish Airlines," Procedia - Social and Behavioral Sciences, 99, 545 – 552.

[8] Zhang, H., Calvo-Amodio, J., Haapala, K. R. (2013) "A conceptual model for assisting sustainable manufacturing through system dynamics," Journal of Manufacturing Systems, 32, 543– 549.

[9] Gravelsins, A., Bazbauers, G., Blumberga, A., Blumberga, D., Bolwig, S., Klitkou, A., Lund, P.D. (2018) "Modelling energy production flexibility: system dynamics approach," Energy Procedia, 147, 503-509.

[10] Rusiawan, W., Tjiptoherijanto, P., Suganda, E., Darmajanti, L. (2015) "System dynamics modeling for urban economic growth and CO2

emission: a case study of Jakarta Indonesia," Procedia Environmental Sciences, 28, 330 – 340.

[11]Morecroft, J. D.W. (1988) "System dynamics and micro worlds for policymakers," European Journal of Operational Research,35, 301-320.

[12]Lane, D. C. (2000) "Should system dynamics be described as a hard or deterministic systems approach," Systems Research and Behavioral Science System, 17, 3-22.

[13]Lyneis, J. M. (2009) "Business policy and strategy, system dynamics applications to," in: Meyers, R. A. (Eds.), Encyclopedia of Complexity and Systems Science. Springer, pp. 665-688.

[14]Torres, J.P., Kunc, M., Frances, O. (2017) "Supporting strategy using system dynamics," European Journal of Operational Research, 260 (3), 1081-1094.

[15]Feng, Y.Y., Chen, S.Q., Zhang, L.X. (2013) "System dynamics modeling for urban energy consumption and CO2 emissions: A case study of Beijing, China," Ecological Modelling, 252, 44– 52.

[16]Laimon, M., Mai, T., Goh, S., and Yusaf, T. (2020) "Energy sector development: System dynamics analysis," Applied Sciences, 10(134), 1-19.

[17]Mutingi, M., Mbohwa, C., Kommula, V.P. (2017) "System dynamics approaches to energy policy modelling and simulation," Energy Procedia, 141,532-539.

[18]Brent, A.C., Mokheseng, M.B., Amigun, B., Tazvinga, H., and Musango, J.K. (2011) "Systems dynamics modelling to assess the sustainability of renewable energy technologies in developing countries," WIT Transactions on Ecology and the Environment, 143, 13-24.

[19]Naill, R.F. (1992) "A system dynamics model for national energy policy planning," System Dynamics Review, 8(1), 1 – 19.

[20]Hidayatno, A., Dhamayanti, R., Rahmawan, A. (2019) " Model conceptualization for policy analysis in renewable energy development in Indonesia by using system dynamics," International Journal of Smart Grid and Clean Energy, 8(1), 54-58.

[21]Rajabi, A., and Moosavihaghighi, M. (2014) "The effects of energy consumption on environmental pollutants and social costs in Iran using system dynamics approach," Retrieved on 12th March 2019 from http://www.systemdynamics.org/conferences/2014/proceed/papers/P1168.pdf.

[22]Al-Sarihi, A., Contestabile, M., Cherni, J.A. (2015) "Renewable energy policy evaluation using a system dynamics approach: the case of Oman," The Conference Proceedings of The 33rd International Conference of the System Dynamics Society, Cambridge, Massachusetts, USA. Retrieved on 12th March 2019 from http://www.systemdynamics.org/conferences/2015/papers/P1003.pdf

[23]Robalino-L´opez, A., Mena-Nieto, A., Garc´ıa-Ramos, J.E. (2014) "System dynamics modeling for renewable energy and CO2 emissions: A case study of Ecuador. Energy for Sustainable Development," Retrieved on 12th March 2019 from http://rabida.uhu.es/dspace/bitstream/handle/10272/7743/System_dynamics_modeling.pdf?sequence=2.

[24]Prambudia, Y., and Nakano, M. (2010) "Scenario analysis of Indonesia's energy security by using a system-dynamics approach," Retrieved on 12th March 2019 from http://waset.org/publications/10822/scenario-analysis-of-indonesia-s-energy-security-by-using-a-system-dynamics-approach

[25]RicardoSaavedra M. M., Horade O. Fontes, C., GaudêncioM. Freires, F. (2018) "Sustainable and renewable energy supply chain: A system dynamics overview," Renewable and Sustainable Energy Reviews, 82(1), 247-259.

[26]Rogers, J., and Wisland, L. (2014) "Solar power on the rise, the technologies and policies behind a booming energy sector," Retrieved on 14th March 2019 from http://www.ucsusa.org/sites/default/files/attach/2014/08/Solar-Power-on-the-Rise.pdf.

[27]REN21 (2009) "Recommendations for improving the effectiveness of renewable energy, policies in China," Retrieved on 14th March 2019 from http://www.geni.org/globalenergy/library/technical-articles/generation/general-renewable-energy/ren21/Recommendations_for_RE_Policies_in_China.pdf.

[28]Runci, P. J. (2005) "Renewable energy policy in Germany: an overview and assessment," Pacific Northwest National Laboratory Technical Report PNWD-3526, Joint Global Change Research Institute. Retrieved on 14th March 2019 from http://www.globalchange.umd.edu/data/publications/PNWD-3526.pdf.

[29]Albin, S. (1997). "Building a system dynamics model Part 1: Conceptualization". Massachusetts Institute of Technology. Retrieved on 9th April 2020 from https://ocw.mit.edu/courses/sloan-school-of-management/15-988-system-dynamics-self-study-fall-1998-spring-1999/readings/building.pdf.

[30]Forrester, J. W., Senge, P. M. (1979) "Tests for building confidence in system dynamic models" Retrieved on 10th May 2019 from http://clexchange.org/ftp/documents/Roadmaps/RM10/D-2926-7.pdf.