A System Dynamics Model for Policy Evaluation of Energy Dependency

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Abstract

Iran's energy supply system is highly dependent on fossil fuels due to excessive cheap fuel consumption used in transportation and power generation, as well as the lack of fuel economy standards for the appropriate amount of consumption. In addition, import of fuel derivatives such as gasoline makes fossil fuel usage a path-dependent process. Such increasing energy demand which has led to high energy intensity, is a serious threat to Iran's energy security. Understanding the systematic structure of this dependency is the main interest of this study. System dynamics approach is applied to model energy dependency and test four different scenarios. Comparison of the results infers that there will be increasing energy dependence on fossil fuels. In an increasing fossil fuel supply scenario, the energy dependency index decreases and on the other hand, the energy security weakens due to the excessive consumption of fossil fuels resources. Nevertheless, if the energy supply increases via consumption of renewable energy resources, as in the second scenario, the energy dependency index decreases while there are no significant changes in the energy security index. In the last scenario, the demand-side management and energy demand reduction gained attraction in order to reduce the energy dependency index. However, this policy should be accompanied by increasing the renewable energy capacities to be able to reduce the energy efficiency and increase the energy security.

Keywords

Energy Dependency, Energy Security, Renewable Energy, System Dynamics

1. Introduction

The high and unreasonable demand for fuel in Iran, the excessive and sometimes irrational consumption of fuel in various sectors, including transportation along with cheap fuel supply for power generation plants, and the lack of proper standards for fuel consumption has brought a high dependence on fossil fuels energy supply to Iran. This issue, along with the import of some fuel derivatives, such as gasoline, to be used in transport and several other factors, has led to the formation of a path-dependent process in the use of fossil fuels, i.e. a process in which the passage of time makes it more difficult to make any change and the system locks in to one choice.

The high consumption of gasoline has had a negative effect on Iran's financial balance. The price of fuel in Iran was among the lowest in world energy prices, standing just after Venezuela. This encouraged extra consumption (both in per capita and also per GDP) and consequently turned Iran from one of the world's lowest energy consumers in 1980 to one of the world's biggest consumers in 2009. Before the implementation of the Iranian subsidy reform plan, the energy intensity in Iran was four times higher than that of the world [1]. The low price of fuel not only led to the consumption of insufficient returns in the country but also provided the opportunity for smuggling fuel to the neighboring countries, such as Afghanistan, Iraq, Pakistan, and Turkey. Gasoline prices in Turkey were 20 times higher than in Iran, and diesel prices were 50 times higher. The targeted subsidy plan with the aim of optimizing fuel consumption through the liberalizing of energy carriers was implemented in 2010 in Iran. Based on this plan, subsidies for gasoline, gas oil, gas, oil, electricity, water, and some other products were abandoned within five years, and they were offered at prices of Persian Gulf markets. Eventually, the plan failed to control and optimize gasoline consumption in the country, because of mismanagements in the entire economy system [2].

According to the International Monetary Fund (IMF) estimates, the cost of indirect subsidies allocated to Iran's oil for the government was more than 10% of Iran's annual Gross Domestic Product [3]. If the subsidy for natural gas and electricity was also counted, the subsidy costs for the government comprised more than 20% of GDP in the period from 2006 to 2009. In the case of electricity, the government pays a heavy subsidy to final electricity consumers by supplying fuel for power plants at a much lower price than the fuel economy costs. Another major challenge facing Iran in the energy sector has been the increased demand for electricity, which always has surpassed the GDP growth rate of the country. The low cost of electricity for the final consumer is surely one of the factors affecting the high demand for electricity consumption, which shows that energy consumption is largely done without considering the issue of productivity.

On the other hand, the International Energy Agency has introduced Iran as the largest subsidizing country in the world for fossil fuel consumption and announced that Iranian government had subsidized over 82 billion dollars in 2012, equivalent to one-tenth of the world's total subsidy paid. Regarding the paid subsidy rate in the world for the consumption of fossil fuels, the International Energy Agency has reported that despite the implementation of the targeted subsidy plan in Iran, the country is still known as one of the largest subsidizing countries for fuel consumption. In 2012, 544 billion dollars was earmarked for fossil fuels from countries around the world. One-tenth of this figure, that is, 82 billion dollars is related to subsidies paid by the Iranian government, which has made this country the largest subsidizing country for fossil fuels. According to this report, subsidies for fossil fuels are five times higher

than the subsidy allocated to renewable energy sources. By continuing to pay subsidies for fossil fuels and yet, not paying adequate subsidies for the development of renewable energy, in the future, the coverage of energy costs, which itself is rising at ascending rates, would not be possible. Indeed, dealing with a way to go beyond this dependency on fossil fuels will be more urgent than any other issue. Increasing energy costs by considering the increasing trend of energy demand, and especially the high energy intensity of the country, are serious threats to the country's energy security.

The present research analyzes the systemic structure of drivers of the issue of dependency on energy in Iran and role of renewable energies in reducing this dependency.

As shown in Fig. 1, the amount of primary energy consumption is increasing. In the industrial sector, despite the occurrence of an unstable economic growth in the last few years, the energy intensity is increasing. In fact, Figures 1 and 2 imply reinforcing loops in primary energy consumption.



Figure 1- The dynamic behavior of primary energy consumption in Iran

Figure 2- The dynamic behavior of primary energy intensity

On the other hand, Figure 3 shows the share of fossil fuels to this energy consumption which tends to zero. The changes in Iranian oil reservoirs, as shown in Figure 4, despite the growth, indicates a slower rate of fossil fuel resources.



Figure 3- The share of fossil fuels to total energy consumption

Figure 4- Iran's crude oil

The major problem addressed by the present research is that with the continuation of the ascending trend in demand, and by considering the lack of a proportional increasing trend in the country's oil resources, along with the import of energies such as gasoline, the issue of the dependence on fossil energy will intensify the energy security problem for the country in the future. One of the major solutions to reduce energy dependency is the development of renewable energies. Therefore, in the present study, it is attempted to analyze the effectiveness and convenience of these energies on reducing energy dependency with a system approach.

2. The literature and background

Energy security is the link between national security and the availability of reliable domestic primary energy resources to supply energy needs of the nation. From the perspective of the European Union, energy security is also the ability to assure future energy needs both in the use of domestic resources within the framework of economic criteria or strategic reservoirs as well as in the external sector as access to the supply of stable supplies [4]. Barton [5] believes that energy security is a condition in which a single nation, or most of them, can have adequate access to energy resources at current and future reasonable prices without the possibility of disconnection and high risk.

The term, energy security refers to continuous and reliable supply at reasonable prices in energy carriers. The concept of energy security should be looked at in a loop. On the contrary, demand security is addressed which is important for economy sectors, while on the other hand, reliability of supply is important for consumers [6].

Energy security depends on a variety of issues: the simplicity or complexity of discovering a source; instability and rebellion, or peace and development in an oil-rich country; transfer by pipelines or ships which are subject to piracy or attacking infrastructures and pipelines; supply shortages along with increasing demand; and finally crude oil prices are all addressed in modeling energy security. Energy security ensures the ability to access the energy resources needed for the sustainable development of national security. More clearly, energy security means providing available, accessible, affordable, and reliable, energy [7].

For the past few years, quantitative methods have been considered to determine the status of energy security. Several indexes and guides have been provided for energy security [8], energy dependency, resource estimates, Reserve-to-Production Ratios, resource variety, and import dependence are among the simple energy security indices [9]. Shannon-Wiener Index (SWI) and Herfindahl-Hirschman Index (HHI) are also among composite (aggregated) energy security indexes [10]. A simple index of energy security is the energy intensity index. Energy intensity is one of the indicators investigating energy consumption efficiency. This index is achieved by dividing a unit of energy on a unit of GDP [11]. High energy intensities indicate a high price or cost of converting energy into GDP.

Renewable energy refers to some types of energy where the generator source of that energy, unlike non-renewable energies, is capable of being recreated by nature in a short period of time, or, in other words, be renewed [12]. Renewable energy sources are not yet effectively exploited for various reasons, the most important of which is an economic factor. If most of them do not cause any pollution, they can provide the world's total needed and consumed energy. However, renewable energies do not play a significant role in global energy supplies yet, but will have a much more visible role in the coming decades; as long as they are predicted to become public until 2030, and until the beginning of the second half of the current century, they would be the major alternative to fossil fuels and other non-renewable energies. From among all renewable energies, hydroelectricity energy, solar energy, geothermal, wind energy, and biomass energy are among the most important applicable renewable energies in Iran.

In a large categorization, previous research studies in the area of the research subject can be categorized into two categories of dynamism associated with renewable energies, as well as dynamism associated with energy security.

Hsu [13] has examined the effects of subsidies and capital on tariffs of solar cell facilities and achieved the national goal such as reducing Carbon dioxide (CO₂) emissions. The Taiwan government plans to attract people and encourage investment in solar photovoltaic systems through policies such as subsidies and capital, and a huge budget is required to execute these policies for the government. Propagating solar cell applications may have the most economic benefits. In this research, System Dynamics (SD) approach is used to develop and evaluate these policies. Using this simulation approach, policymakers are able to analyze the cost-benefit and various combinations of it. The goals of the policy plan are to reduce CO₂ emissions and budget constraints. The simulation period was selected as 2011 to 2030, and the results indicate that if the Rate of Return (ROR) on capital is fixed, with the increase in the rate of subsidies, a great help would be done to reduce CO₂ emissions.

Aslani and Wong [14] in their research dealt with the evaluation of different costs of using renewable energies to generate electricity for the United States. Concerns about these energies, such as energy supply security, limitations, and fluctuations in the price of fossil fuels and threats to climate change, have forced US policymakers to think and argue about the diversity of energy supply strategies and the promotion of renewable energies, and the research seeks to provide an innovation to use these energies between 2010 and 2030. The results of the research revealed that while the cost of renewable energies in 2010 in a market is close to 10 billion dollars (at cost level), in 2030, the total value of renewable energy upgrades and exploitation in the United States would be over 170 billion dollars (at cost level).

Aslani, Helo [15] in another study examined the role of renewable energies' policies in Finland's energy dependency with a SD approach, and examined three different scenarios of renewable energies in Finland by 2020. The three scenarios of different dynamics were the reduction of energy dependency and different savings amounts. The results reveal that while energy and electricity consumption for heating will rise by 7% by 2020, the level of dependency on imported resources will decrease from 1 to 7% in the scenarios under consideration.

Ahmad and bin Mat Tahar [16] used the SD approach to examine the assessment of renewable energy capacity in Malaysia for electricity generation. Electricity generation in Malaysia is heavily based on fossil fuel consumption and the policy of diversification into fossil fuels has been on the government agenda since 2010. They considered the development of energy capacity in the three intervals of short, medium, and long term, and their results indicated that Photovoltaics (PV) and biomass electricity, need the highest technological capability, respectively.

3. Method

The research method is based on the steps of the System Dynamics (SD) methodology. System dynamics approach provides the possibility of learning from the operation and behavior of a complex system by utilizing a system approach in analyzing a system as well as the ability to consider stock, flow and delay variables.

In this method, one fundamental assumption is that the behavior of a complex system is as a result of the causal structure dominating it, and if this structure can be represented, then prediction of the future behavior of the system variables would be possible. Also, having the

causal structure of the behavior generator, one can obtain learning from the system and a deep insight from the way it works by doing a what-if analysis. With the help of such an insight, the behavior of the system can be directed toward the desired behavior and goal through effective policies.

The application of the SD approach in solving complex problems is increasing [17-22]. There have also been several reports of the use of this methodology in solving energy-related problems [23-29].

In applying SD methodology, the problem is solved in five steps as given below.

- 1. Identifying and defining the problem
- 2. Mapping causal loop diagrams
- 3. Developing the mathematical model (Stock and flow diagram)
- 4. Model simulation and validation
- 5. Scenarios generation, evaluation, and selecting the most appropriate solution [30].

4. Modeling

4.1. Dynamic Hypothesis

Electricity consumption and fuel consumption are the two main sectors of total energy consumption in Iran. Electricity consumption is calculated both in the domestic and public sector with its per capita level, as well as in the sector of industry and services with different per capita amounts. Fuel consumption is also done by the population for public use and transportation, as well as for the production of the required energy. With increasing total consumption including fuel and electricity, the country's energy intensity has increased and this intensifies energy dependency and reduces energy security. Increasing energy intensity will lead to a policy of liberalizing energy prices after a while, which could lead to a reduction in the number of manufacturing firms due to increased production costs, which, as a result, will reduce the GDP of the country and increase the intensity of energy again. This will create a reinforcing loop for energy intensity. Increased consumption will increase demand and in order to cover the demand, the need for energy supply will be created, and supply can be provided via two mechanisms; one to emphasize the consumption of fossil fuels for the generation of energy, which, along with exploitation of fossil resources and energy exports, will lead to a reduction in energy reservoirs in the country, and this will weaken energy security. The second mechanism focuses on renewable energies that currently play a very less important role in Iran's energy supply. Renewable energies and their increase will have a positive effect in energy security. Reducing fossil resources and energy dependency has negative effects on it.

4.2. Mapping Causal Model

By considering the formulated dynamic hypothesis, the causal model of the problem is as follows.



Figure 5-Causal Loop Diagram

4.3. Explaining Feedback Loops

The R1 and B1 loops are the famous loops of population growth and regulation, and the major dynamics of the population is due to the interaction of these two loops. B2 loops indicate the fact that increased consumption will increase energy intensity and, as a result of this increase, the government will execute a plan to liberalize the real price of energy carriers. With the liberalization of prices, production costs for industrial units have increased by over 10 people, and most of these units are shut down over time, which will lead to a reduction in GDP, and this, with the R4 loop, reinforces the problem of increased energy intensity.

B3 loop also shows the effect of electricity consumption on total consumption. The R2 loop also represents the positive loop of the presence of industrial units in increasing the country's GDP.

In addition, the R3 loop shows the intensive energy consumption loop and the need for supply and, consequently, more fossil fuels, to supply the demanded energy. With regard to the oilbased economy of the country, fossil resources are decreasing with the B4 balancing loop through sales and exports.

4.4. Stock and Flow Model

With regard to the represented causal structure, the stock and flow model were designed and the model equations were extracted.



Figure 6-The Stock and Flow Model

Some of the mathematical equations and formulations of the model are mentioned below.

 $Energy \ Intensity = \frac{Total \ Consumption}{GDP}$ $Energy \ Dependency = \frac{Energy \ Demand}{Energy \ Supply}$ $Energy \ Supply = Fossil \ Fuel \ Resource + Renewable \ Energy$ $Energy \ Demand = 1.1 \times Total \ Consumption$

4.5. Scenario Generation

Four scenarios are addressed to evaluate different security policies and energy dependencies. The first scenario indicates the non-variation in the current situation and the continuation of the existing trend. This scenario serves as a basis for policy comparison. The second scenario is the increase in energy supply from the site of increased consumption of fossil fuels. According to the definition of the index used to represent energy dependency, in order to increase it, either the

demand for energy should be reduced or its supply should be increased. In the second scenario, energy supply will increase, and given the 98% contribution of fossil fuels in energy supply, naturally, fossil fuel consumption should increase in this scenario.

In the third scenario, with investment and time consumption, the renewable energy infrastructure is increased and the energy supply would be increased from the unused extra fossil fuels. In the fourth scenario with Demand Side Management (DSM), only energy consumption changes and no change is done in supply.

| a . | Description | Affected Variables | | |
|----------|-------------------------------------------|---------------------------------------------------|-----------|-----------|
| Scenario | | Name | Old Value | New Value |
| 1 | Continuing with of existing situation | - | - | - |
| 2 | Energy supply by consumption fossil fuels | Consumption fraction | 1e-009 | 1e-008 |
| 3 | Energy supply by renewable energy | Geo-Thermal Growth Rate | 0.05 | 0.21 |
| | | Hydro Growth Rate | 0.07 | 0.14 |
| | | Wind Growth Rate | 0.03 | 0.06 |
| | | Solar System Growth Rate | 0.09 | 0.018 |
| 4 | Energy consumption management by DSM | Electricity Consumption Per Capita (Industry) | 0.14033 | 0.14 |
| | | Electricity Consumption Per Capita (Household) | 0.02825 | 0.02625 |
| | | Fuel Consumption Per Capita (Industry) | 1.34417 | 1.33417 |
| | | Fuel Consumption Per Capita (Household) | 8.47 | 6.47 |

Table 1. The implications and the affected variables of each scenario

4.6. Simulation

As shown below, the results of implementing different decision-making policies are presented in the form of different scenarios.



Figure 7- Simulation of Energy Intensity and Energy Dependency in Scenario 1

With continuity of current status, the energy dependency index will increase due to increasing trend in energy demand.







Figure 8- Simulation of consumption in Scenario 4-DSM

As shown in Figure 7, in the second scenario, energy supply increases by fossil fuel consumption. However, due to the downside of the country's fossil fuel resources, the energy supply from this sources will decrease on the long run. In the third scenario, renewable energy infrastructure will be double, and Figure 7 shows an increase in the energy supply from renewable energy sources. Figure 8 shows the simulated trend of the behavior of the consumption variable and a slight decrease in it due to implementation of DSM.



Figure 7-Result of simulation of scenarios on Energy Dependency

Given that the energy dependency index is considered as the ratio of energy demand to energy supply, the least amount of energy dependency is provided in the case of energy supply from fossil fuels. Increasing the use of fossil fuels can cover the gap between supply and demand over the research time period, but with long-term resource availability, this policy cannot be considered as a sustainable solution for high security energy supply. In other scenarios, the third scenario shows that increased energy supply from renewable energy sources can reduce the energy dependency in the long term in comparison with other policies.

5. Conclusion

From the comparison of the four scenarios tested on the model, it could be said that by continuing the current state, dependence on energy would increase. By implementing the second scenario and increasing the supply of energy through fossil fuels, the energy dependency index decreases due to increased supply, but considering the more intense fossil fuel reduction, the country's energy security will be weakened.

In the third scenario, by increasing supply via renewable energies, the rate of energy dependency index decreases and the energy security index does not change. Finally, in the last scenario, with demand-side management and energy demand reduction, the energy dependency index would decrease, and this rate is higher than renewable energy capacity development, and in terms of energy dependency index, it is a more efficient policy, but given that the majority of energy supply in this scenario is also achieved through fossil fuels and their resources are coming to an end, this policy does not have a long-term sustainability and it is recommended that the demand-side management policy and the development of renewable energy capacities be implemented simultaneously in order to decrease energy dependency and increase energy security.

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