Caspian Journal of Environmental Sciences
Online ISSN: 1735-3866
Print ISSN: 1735-3033

Causal effects of population growth on energy utilization and environmental pollution: A system dynamics approach

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ABSTRACT
Population growth will change the demand for food and energy resources and environmental pollution. Although early energy resources modeling has made vital efforts to model the energy system in the world, because of increasing complexity and integration of environmental, social, and economic functions, these models still need to be developed to show a system close to the real world to enhance sustainable management of natural resources. Hence, the main objective of this study is to design a system dynamics model for the food production system and energy demand in Iran in order to evaluate the effects of different population scenarios on key variables. In this regard, an integrated system dynamics simulation model was developed in Iran where managing energy resources is seriously challenging due to population growth and increasing food demand. The results of the behavioral test showed that the designed model can be used to investigate and simulate the effects of different population growth rate scenarios. Findings illustrated that by increasing population, if no further energy demand management policies were implemented, the total food demand and energy use increase by more than 1.35% and 3.31% respectively. Also, the annual air pollution change during 2014-2030 is expected to be around 4.41%. By changing the population growth rate in the form of population scenarios, the average annual energy demand in the first population scenario will be 20,277 barrels of crude oil and in the second population scenario will be 20049 barrels of crude oil. It seems that the change in the population growth rate will lead to an increase of 3.23% and 2.16% in average annual energy demand, respectively. The results showed that in the first population scenario, with a further increase in population variables, food demand and energy demand, the average change in pollution emission is 4.79%, which is at a higher level than the baseline conditions. In the second population scenario, changes in environmental pollution will be reduced to 4.31%. Therefore, given the effectiveness of population growth on the behavior of the energy system and pollution, the adoption of energy management policies should be considered by policy makers.

Keywords: Energy, Food production, Air pollution, System dynamics, Population growth.

Article type: Research Article

INTRODUCTION
Food supply is the most basic need of human societies, and governments are always looking for ways to provide sustainable food security. The World Bank has defined food security as access to adequate food for all individuals to have a healthy life at all times, which was emphasized by experts at the Rome Conference (Esfandiari *et al.* 2016). Food security, due to its important role in providing social health and economic development and maintaining national security, has always been widely considered by policymakers, among which price plays an important role in supply (Shabanzadeh *et al.* 2014). The World Bank has identified food security as an important index of development and equated it with per capita income, equitable income distribution, employment rate,

Caspian Journal of Environmental Sciences, Vol. 19 No. 4 pp. 601-618
DOI:
Received: Mar. 30, 2021 Accepted: Aug. 17, 2021

Publisher: University of Guilan, Iran

environmental protection, and respect for human rights (Esfandiari *et al.* 2016, Masoudi *et al.* 2020; Zeinali Ghasemi *et al.* 2020; Asayesh 2021). Food security is affected not only by production facilities but also by the political, economic, social and cultural space of society. Food security is closely linked to agricultural production and its food distribution system. On the other hand, it is related to the choice of food and the type of diet that consumers choose (Ranjbarpoor *et al.* 2014). The food industry is one of the major consumers of energy in the industry of all countries. In addition to providing a high level of employment, this industry plays a significant role in meeting the basic and primary demands of societies, which is food. Also, since energy as an important factor of production can play an effective role in economic growth and development, it is very essential to analyze how the energy-related decisions and policies can affect various economic sectors and factors (Farajzadeh & Bakhshoodeh 2015). From the production of crops and livestock, to the processing, packaging, distributing, storing, preparing, serving and disposing of food products, energy plays an important and necessary role for every stage of the food industry. In the Iran, the food industry takes a 5.2% share of the Iran's GDP (Statistical Centre of Iran 2018). Although the food industry is neither energy nor emission intensive compared with other industries such as iron or steel, it is still an important energy consumer due to its massive scale. Overall, the industria sector accounts for approximately 23.90% of the total primary energy consumed in Iran, and food sector requires nearly 7.23% of Total energy demanded in the industrial sector (Iran energy balance sheet, 2018). Iran's per capita final energy use during 2011-2016 was 14.21, 14.05, 14.85, 14.59, and 14.79 barrels of crude oil, respectively. In 2016, the per capita final energy use index compared to the previous year had an upward trend of 1.3% (Energy Balance Sheet, 2016). The contribution of different energy carriers to the energy supply of the agricultural sector in recent years shows different trends so that the share of natural gas and electricity since 2005-2011 had an upward trend, but in this period the contribution of petroleum products has reduced from 71.29 to 53.01% (Energy Balance Sheet, 2011). This downward trend in the consumption of petroleum products in recent years has been due to the policy of changing the fuel of irrigation pumps in agricultural fields from oil and gas to electricity.

Global energy consumption is dramatically increasing due to our quest for a higher standard of living and the increasing world population. Most of the world's energy resources come from fossil fuels, and burning these fuels causes' environmental problems, and in particular, the global warming problem. Pollution derived from energy sector affects air, water, soil, agriculture, animal habitat and human health (Alvarez-Herranz *et al.* 2017). These environmental impacts are experienced locally, nationally and globally (Yuan & Zuo 2011). Furthermore, energy is still mainly dependent on fossil fuels such as coal, oil, petroleum and natural gas products, which emit carbon dioxide (CO_2). Many researchers evident that CO_2 emissions have contributed the most to climate change between 1750 and 2005 (Luo & Wu 2016). Kargar and Esmaeili (2018) established a link between energy use, air pollution and public health impacts and found that there are large health benefits to be gained by setting stricter air quality standards for the future in Iran. Since energy is one of the most important factors of production and as one of the goods and services required in final consumption (Zhang *et al.* 2010), it has significant economic effects. Moreover, the energy sector is considered as the main foundation of development and the amount of energy carrier consumption plays an important role in the activity of industrial workshops. Nowadays energy regulation measures have taken on special relevance in environmental correction processes; they are necessary to correct the global warming process and help to ensure sustainable economic growth (Dooley 1998; Mendiluce *et al.* 2010; Costantini & Martini 2010; Dogan & Seker 2016). In addition, because of market-driven technological progress or government regulation, economic sectors may adopt less polluting technologies (Cole *et al.* 2005). Due to changes in population growth in Iran, demand for food is expected to increase. Increasing food and the need for more production requires more energy consumption in the country. As energy consumption increases, pollution emissions are expected to change (Kargar & Esmaeily 2018). Meanwhile, oil and oil derivatives are still the most important suppliers of energy in the world, and in our country, especially after the plan of targeted subsidies, special attention has been paid to how energy is consumed in various sectors. Since the industrial sector is one of the most important energy consumers in the country, the energy group of the Office of Industry, Mining and Infrastructure, Statistics Center of Iran has summarized and prepared a time series of energy use in industrial workshops of 10 employees and more. Therefore, it is important to investigate the changing behavior of energy demand over time to manage this vital resource (Farajzadeh & Bakhshoodeh 2015).

There are two kinds of view exist in the literatures, first, a neo-classical view that is, the economic growth of a country can be 'neutral' to the energy consumption, therefore, the country can set energy conservation policy to

Caspian Journal of Environmental Sciences, Vol. 19 No. 4 pp. 601-618 Received: Mar. 30, 2021 Accepted: Aug. 17, 2021
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reduce CO_2 emissions for saving environmental degradation without compromising the pace of the economic growth which is defined as a 'neutrality hypothesis'. Second, the country's economic growth can be highly associated with the energy consumption; therefore, like any other factors of production, the energy consumption can be a limiting factor to the economic growth (Alam *et al.* 2012). There is a growing concern of scarce energy sources in one hand, and a new paradigm of a green economy on the other as because of the global warming problem. The causality relationship between economic growth and environmental damage because of CO_2 emissions is also much more intense debated over the past decades. The emission of CO_2 is a core cause of global warming.

Therefore, it is also much important and utmost necessary to investigate whether higher economic growth and energy consumption lead to higher environmental damage (Ang 2007; Elif *et al.* 2009). Various studies have shown that increasing energy consumption (Franco *et al.* 2017; Menyah & Rufael 2010), especially in developing countries, leads to increased pollution emissions. Although energy is the driving force of any country's economy, managing this resource can play a significant role in reducing pollution emissions (Mirzaei & Bekri 2017). Effective energy management plays an important role in the necessary increase of energy efficiency in industry (Javied *et al.* 2015). Effective decision-making and learning in an increasingly complex world require systematic thinking. Systematic thinking provides a deeper understanding of problems and considers the whole system and the interactions between system components (Senge 1997).

Systematic thinking provides methods and techniques for planning and solving complex problems by applying nonlinear causal thinking. In general, systematic thinking solves problems through forming subsystems and considering related components so that finally all these components are considered as a unit and a whole (Simonovic 2009). Simonovic & Fahmi (1999) introduced a systemic approach to investigate problems with complex structures. Today, systematic thinking in engineering fields is used to understand the complexities of the system (Forrester 1994; Bahill & Gissing 1998; Frank 2000). The system dynamic is a method of modeling and simulation using systems thinking (Forrester 1994; Assaraf & Orion 2005). System dynamic is a method for studying and managing complex and feedback systems. System simulation usually leads to a new understanding of the structure and behavior of the system, which in the next period will allow the development of more complete models (Kotir *et al.* 2016). This approach has been developed primarily aimed to facilitate interactions between managers' subjective models and analysts' contractual models (Levin *et al.* 2013).

The objectives of the existing system dynamic models among previous studies can be summarized in four groups: evaluating energy management strategies, evaluating investment strategies to make industries more desired, simulating energy demand and supply, and explaining stakeholder participation. Most dynamical system models have been developed to evaluate the factors affecting energy investment. Due to the effect of energy on economic development and climate, the energy sector has attracted global attention (Jacobsen 2009; Ombach 2010; Jacobsen & Delucchi 2011; Zhang 2015). To find sustainable solutions, a comprehensive view of energy management is needed to investigate the potential effects of different energy management options and their relationship to stakeholders. System dynamics is one of the modeling tools to facilitate the development of such a comprehensive view to consider the relationship between different stakeholders in modeling (Steve 2002; Mirchi *et al.* 2012).

The use of system dynamics in energy resource management with global modeling projects that began at MIT University in the early 1970s (Ford 1997). To date, we have two comprehensive studies on global energy resource management modeling (Ford 1997; Kiani *et al.* 2010). Kiani *et al.* (2010) and Ford (1997) conducted a comprehensive study using system dynamic models in the field of fossil fuels and planning in the field of electrical energy. Only a study has been conducted for educational purposes, which aims to teach the risks associated with energy trade and has been used for undergraduate and graduate students (Franco *et al.* 2000). Xu & Szmerekovsky (2017) used the system dynamic method to manage energy consumption in US. In this study, the amount of energy consumption in the food sector has been considered. A review of previous studies showed that this study is one of the few studies that has modeled the energy system. The results of the study showed that the policy of increasing energy efficiency and reducing food waste can be an effective policy in managing energy consumption. Including the assistance provided in the development of the model presented in Xu and Szmerekovsky (2017) study add a pollution section to the model. Mutingi *et al.* (2017) used a system dynamics approach to energy policy modeling and simulation. The purpose of this research is to present a taxonomic analysis of system dynamics approaches to energy modelling and simulation. Pasqualino *et al.* (2019) used a systemic approach to study energy security and

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global food demand that presented scenario analysis of the impact of an exogenous price, production, and subsidies shock in the food and/or energy dimensions on the economic system, understanding the sources of potential cascade effects, thus providing a systemic risk assessment tool to informglobal food security policies. In the present study, an attempt was made to develop the model presented in Xu & Szmerekovsky (2017) study according to the conditions of Iran. In this study, an attempt was made to model the structure of the energy system in the food and agriculture sectors, considering the importance of energy consumption in the country. Next, the effects of population growth on energy demand and pollution emissions will be evaluated. This paper is organized as follows. The case study and SD model features are presented in the next section. Then, the applied data are described. The simulation results of the model are presented in Section 3 and the conclusions are provided in Section 4.

MATERIALS AND METHODS

System Dynamic

A system dynamic is a method for examining and managing complex and feedback systems (Kotir *et al.* 2016). The concept of feedback plays a key role in the system dynamic approach. This method is suitable for showing behavioral patterns and analyzing them in complex systems and makes it possible to build a model close to the real world in order to better understand the processes affecting the system (Sterman 2000). What distinguishes this method from other methods using a systemic approach is considering feedback, stock-flow and time delay concepts (Ford, 1999). The system dynamic has many capabilities including a) considering the interactions between different components within a system and understanding the interactions of different and at the same time related subsystems, b) considering the endogenous structure of the system, c) identifying delays and effects on system behavior, d) building a model close to the real world and simulating the structure and behavior of the system, e) analyzing the behavior created in the system, flexibility and usability of quantitative and qualitative variables (Forrester, 1994; Sterman, 2000; Girard *et al.* 2015).

Food production systems and energy demand involve the interaction between various factors, and uncertainty in the linear and nonlinear relationships between these factors complicates investigation and evaluation of energy resource problems and challenges (Hassanzadeh *et al.* 2014). A system dynamic with a comprehensive approach to problems is able to express the relationships and feedback of natural processes with the socio-economic aspects of energy resource systems using stock and flow structures (Sterman 2000). A four-stage process for system dynamic modeling was introduced by Sterman (2000) and Ford (1999). These stages include problem definition, composition, evaluation and testing the model, and using the model for analyzing the effects of different scenarios. Problem statement is the most important stage of system dynamic modeling and the next three stages are related to problem definition. Clearly identifying and defining problem-based model objectives can increase the usefulness and effectiveness of system dynamic modeling. This stage includes a) defining the problem, b) identifying important variables related to the problem as stock, flow, endogenous and exogenous variables, and c) determining the time and place interval (Sterman 2000). The formulation of the model aims to show the structure of the problem defined in the first part. Causal loop and stock-flow diagrams are the two basic tools used in combining system structure. Causal loop diagram, although a good tool for showing system feedback structure and endogenous variables, is not able to represent stock-flow concepts (Ford 1999).

In stock-flow diagram, stock variables, also known as surface or cumulative variables, are the memory of a dynamic system, and when they change over time, they determine the state of a system at any point in time. Once the system dynamic model has been developed and the various principles have been reviewed, it should be tested and validated. In this process, the model may be revised and even redesigned. Validation of models related to social systems is an ambiguous concept, which has always been criticized. The structural and behavioral tests are among validation tests of the system dynamic model. The structural test is performed by comparing the model structure with the existing knowledge about the actual system presented in the subject literature, organizations' reports, and evaluated reviews.

The behavioral test also investigates and compares the behavior of a system with historical data (Sterman 2000). After validating the model, the designed system can finally be used to predict the effects of different policies and investigate the behavior of the system over time.

Caspian Journal of Environmental Sciences, Vol. 19 No. 4 pp. 601-618 Received: Mar. 30, 2021 Accepted: Aug. 17, 2021
DOI:

Publisher: University of Guilan, Iran

Modeling food demand system and energy resources

The first and most important step in modeling is to identify the purpose, main variables and time period for modeling. This study is aimed at analyzing the effects of population growth on the food and energy demand and air pollution. The main variables used include population, food consumption, energy consumption, CO_2 emissions, GDP, value added and so on. GDP and population are two important variables in the designed system that directly affect food demand (Ansari & Seifi 2012, 2013).

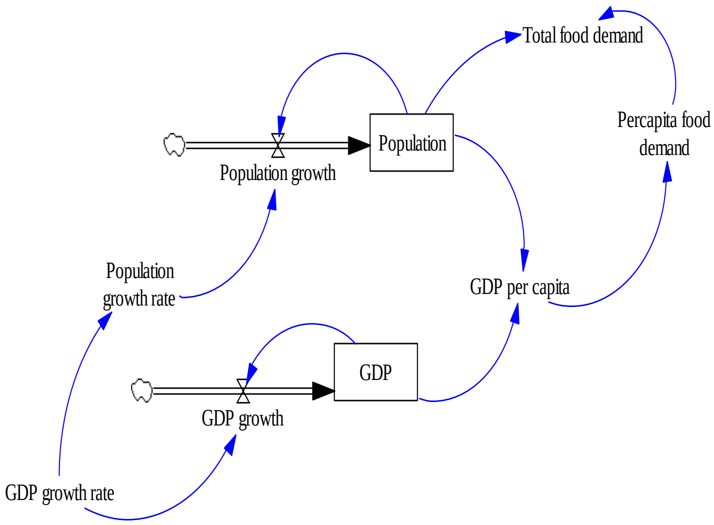

Fig. 1. The stock and flow of food demand.

GDP directly reflects the country's economic development. Population growth is also closely related to increased demand for food. On the other hand, economic growth rate in turn can affect the population growth rate. The average population growth rate of Iran for the calibration period was equal to 1.25% and GDP growth rate was considered 8% (Energy Balance Sheet 2011).

In the designed system, the variable of food need is the amount of food needed to meet the demand ahead, taking into account the percentage of waste. Equilibrium is established when food supply in the market is exactly equal to demand. The hypothesis of the present study is that food waste occupies a large part of food supply that can not be ignored. According to various studies including Buzby *et al.* (2014) and Xu and Szmerekovsky (2017) Food waste accounts for about 30-40% of the total food supplied by the food industry. Thus, food need is calculated as the sum of total food demand and waste (Xu & Szmerekovsky 2017).

Agricultural production measures the amount of crop produced in a particular period (one year) (Xu & Szmerekovsky 2017). Correlation and regression analysis between food needs and agricultural production were performed in this study. The results of correlation analysis indicate a strong correlation between these two variables. The results of linear regression estimation were also considered in system dynamic modeling.

In order to calculate the total energy use in agriculture sector, the amount of direct energy use, fuel use for irrigation, machinery and the use of chemicals, as well as indirect energy use were considered. The idea of using agricultural energy intensity and GDP to measure energy use in agriculture sector was proposed by Feng *et al.* (2013). The intensity of agricultural energy is mainly affected by the agricultural budget and production of this sector (Suh 2015). Therefore, a regression model was constructed using the intensity of agricultural energy and the products of this sector. The relevant results indicate a significant relationship between the two variables. The contribution of agriculture to GDP also measures the contribution of this sector to the national economy. Energy productivity is defined as the ratio of food output divided by energy input. Thus, energy use equals food output of processing and packaging divided by energy productivity (Xu & Szmerekovsky 2017).

The total energy consumption of the food system is also used from the sum of energy use in agriculture sector and during the process of packaging, processing and transfer. The total energy demand increases with population growth and per capita demand for food. Per capita food demand is associated with increased GDP growth.

The equations used in the designed system are presented below:

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$$\text{Population(t)} = \text{Population(0)} + \int (\text{Population growth})\, dt \quad (1)$$

$$\text{Population growth} = \text{Population} \times \text{Growth rate} \quad (2)$$

$$\text{GDP} = \text{GDP(0)} + \int (\text{GDP Growth})\, dt \quad (3)$$

$$\text{GDP Growth} = \text{GDP} \times \text{GDP growth rate} \quad (4)$$

$$\text{Total food demand} = \text{Percapita food demand} \times \text{Population} \quad (5)$$

$$\text{Food requierment} = \text{Total food demand} / (1 - \text{Food waste percentage}) \quad (6)$$

$$\text{Agricultural output} = \alpha + \beta \times \text{Food requierment} \quad (7)$$

$$\text{Agricultural GDP} = \text{GDP} \times \text{Agricultural share} \quad (8)$$

$$\text{GDP growt rate} = \text{LOOKUP (GDP growth rate)} \quad (9)$$

$$\text{Population growth rate} = \text{LOOKUP (GDP growth rate)} \quad (10)$$

$$\text{Food system energy consumption(t)} = \text{Initial energy use} + \int (\text{Total energy use}).dt \quad (11)$$

$$\text{Food industry energy use} = \text{Packaging and processing} / \text{Productivity} \quad (12)$$

The pollution emission variable was considered as the storage variable. By changing the rate of change in the emission of pollution, the amount of pollution caused by carbon dioxide changes. The rate of change in pollution emissions depends on changes in population, changes in GDP, and changes in energy consumption (Kargar & Esmaeili 2018). In this study, the elasticities related to population, GDP and energy from previous studies were used (Falahi & Hekmati Farid 2013; Meidani & Zabihi 2014; Zamani 2007).

$$CO_2 \text{ emission(t)} = \text{Initial emission} + \int (CO_2 \text{ emission change}).dt \quad (13)$$

$$CO_2 \text{ emission change} = \text{Effect of GDP on } CO_2 + \text{Effect of population on } CO_2 + \text{Effect of energy on } CO_2 \quad (14)$$

$$\text{Effect of GDP on } CO_2 = \%\Delta \text{ GDP} \times \text{Elasticity of GDP} \quad (15)$$

$$\text{Effect of population on } CO_2 = \%\Delta \text{ GDP} \times \text{Elasticity of population} \quad (16)$$

$$\text{Effect of GDP on energy} = \%\Delta \text{ Energy} \times \text{Elasticity of energy} \quad (17)$$

Model testing begins as the first equation is written and it is a critical step in SD modeling (Sterman 2001). Behavior test is to run the model and compare the results to the reference mode (Historical or observed data). When the simulation results match the reference mode, you have reached a major milestone in the modeling process (Ford & Ford 1999). In this study coefficient of determination (R^2) were applied to evaluate the performance of the model.

$$R^2 = 1 - \frac{\sum (Y_i - \hat{Y}_i)^2}{\sum (Y_i - \bar{Y}_i)^2} = 1 - \frac{\sum (e_i)^2}{\sum (y_i)^2} \quad (18)$$

In this study, the time period of the model or the time interval of simulating the demand for food and energy resources for a period of 26 years (2004-2030) was considered. A review of previous studies showed that the time period in various studies in the field of resource management varies from a period of 10 years (Zarghami & Akbariyeh 2012) to 100 years (Naill 1976; Rehan *et al.* 2011). Part of the period is used to compare the results of the designed model and the observational data. In this study, the data observed over a period of 10 years (2004-2014) were used to validate the designed system dynamic model. The other part is related to evaluating the behavior of future designed system variables. According to the available data on the demand for food and energy, for the development of the system dynamic model, time steps were considered annually. Vensim Professional 5

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(Ventana Systems 2009), one of the several software packages available for SD modeling, is applied to develop and run the energy model. Also, Eviews9 software was used to estimate the regressions in the study. Some key parameters and stock variables used in the model and their corresponding values are describe in Table 1.

Table 1. Main variables and parameters of SD model.

Variable type	Variable name	Initial value	Unit
Stock Variable	Population	68122936	Person
	GDP	1073070	Milliard rial
	Energy consumption	13722	Barrels of crude oil
	CO_2 Emission	447480	Killoton
Exogenous variable	Food waste	0.35	%
	Agricultural share	8.53	%
	Price spread	1.02	-
	Population elasticity of emission	0.56	%
	GDP elasticity of emission	0.95	%
	Energy elasticity of emission	0.82	%
	Variable name	**Equation**	
Endogenous variable	Population	INTEG (populationgrowth,6.81229e + 007)	
	Population growth	Population × population growth rate	
	GDP	INTEG (GDPgrowth,1.07307e + 006)	
	GDP growth	GDP × GDP growth rate	
	GDP growth rate	WITH LOOKUP (Energy consumption change)	
	GDP per capita	GDP/Population	
	Food requierment	Total food demand/(1-food waste)	
	Total food demand	Per capita food demand × Population	
	Total energy use	Agricultural energy use + Food industrial energy use	
	Agricultural energy use	Agricultural energy intensity × Agricultural GDP	
	Agricultural GDP	Agricultural share × GDP	
	Agricultural output	-1.46424e+006+23.96 × Food requirement ($R^2 = 0.85$, p- value = 0.00)	
	CO_2 emission of Iran	INTEG (Emission change, 447480)	
	Effect of energy on emission	Energy consumption change × Energyemision elastisity	
	Effect of GDP on emission	GDP growth rate × GDP emission elastisity	
	Effect of populatiom on emission	Population emission elastisity × Population growth rate	
	Emission change	CO_2 emission of Iran × Totoal percent change of emission	
	Food industrial energy use	Processing and packaging food product / Energy productivity	
	Per capita food demand	0.254 × Smoothed lag per food demand + 0.0073 × GDP per capita + 0.00038 ($R^2 = 0.90$, p-value = 0.00)	
	Processing and packaging food product	Agricultural output × price spread	

RESULTS

After designing the model and entering the mathematical relationships and desired values for the variables in the designed system, at the beginning, the model's ability to simulate system behavior was evaluated. In other words, one of the evaluation tests of the designed model is to compare historical data with simulated data. For this purpose, the simulated behavior for the variable of water stored in the dam was compared with its historical data and R^2 statistic was calculated. The model was validated using observational data during 2004-2015. A comparison of the trend of the amount of energy demand during the studied years and the behavior simulated by the system indicates good agreement of the model output with historical data. The calculated value of R^2 is equal to 0.92. Therefore, the model designed can be used to investigate and simulate the effects of different scenarios. The structure of food-energy interactions was tested by comparing the causal and mathematical relationships between variables with the available knowledge about real system.

After validating the model, the behavior of the key variables of the model based on the base scenario was simulated for 2014-2031. A graphical view and description of the behavioral pattern of the variables of energy and food demand in Iran are reported in Fig. 4.

The results show that under the base scenario, energy use in the food industry has an increasing trend so that this variable is expected to increase from 15038 barrels of crude oil in 2014 to 26153 barrels of crude oil in 2031. Under these conditions, the average annual growth of this variable during the period is calculated equal to 3.31%.

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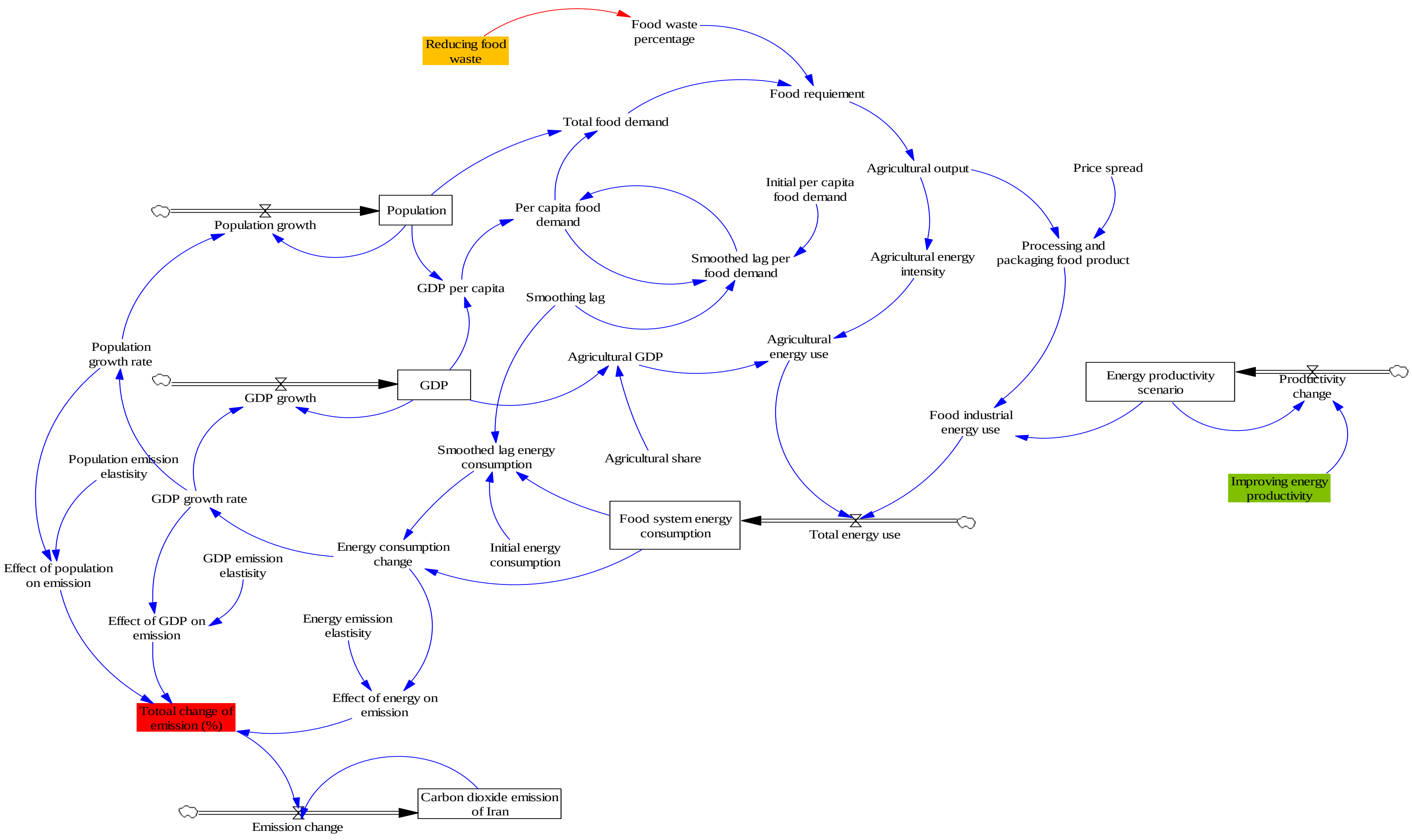

Fig. 2. Stock and flow of food production system and energy demand.

Caspian Journal of Environmental Sciences, Vol. 19 No. 4 pp. 601-618
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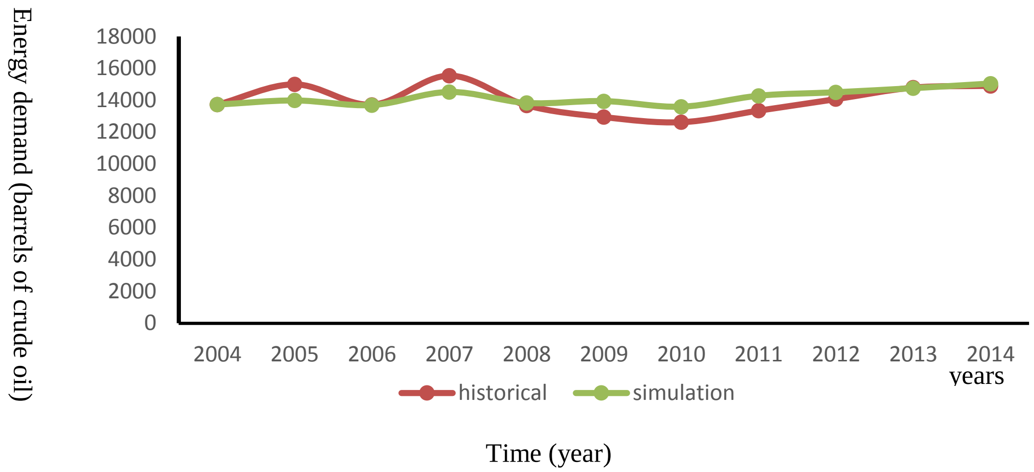


Fig. 3. Comparison of historical and simulated data behavior of the variable energy demand.

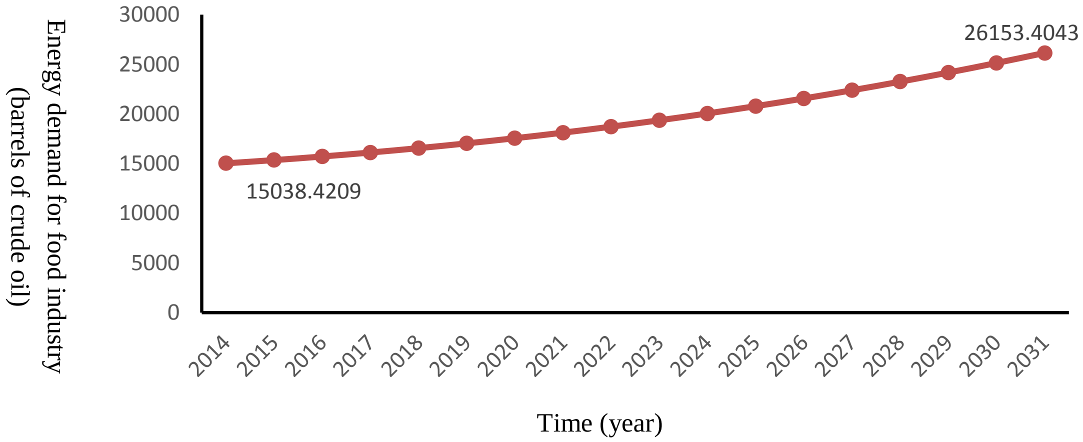
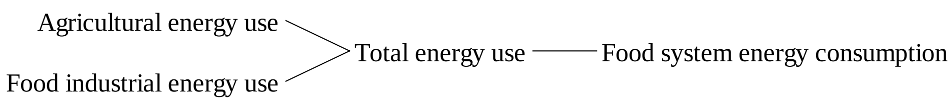
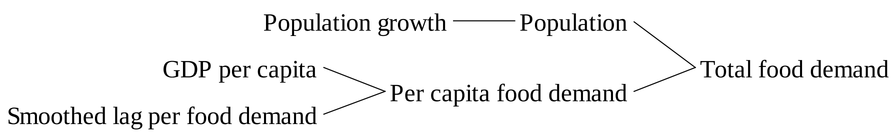


Fig. 4. Simulation of the variable behavior of energy use in the food industry.

According to the stock-flow diagram designed in this study, total change in energy consumption depends on the behavior of energy demand in agriculture sector and food industry. The amount of energy consumed in the agricultural sector depends on the demand for food and thus population growth.



In other words, the behavior of food demand in the country can be attributed to the behavior of the population and per capita food consumption. These two variables are also affected by population growth rate and per capita GDP. Therefore, it is expected that with increasing population in the country, the demand for food and consequently the demand for energy in agriculture sector and food industry will increase.



Received: Mar. 30, 2021 Accepted: Aug. 17, 2021

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Therefore, Fig. 5 presents the trend of the behavior of food demand. As shown in this table, this variable experiences an increasing trend during the studied period. So that it increased from 51384 thousand tons in 2014 to 64658 thousand tons in 2031. The average annual growth of this variable is estimated to be 1.35%. Fig. 6 shows the trend in the amount of pollution emissions (carbon dioxide emissions-kiloton). As shown in this table, increased energy consumption, population growth and economic growth lead to increased greenhouse gas emissions. Based on the results, the amount of pollution emission in 2021 was equal to 706834 kilotons, which with an average growth of 4% per year at the end of the period will reach 1132570 kilotons. Therefore, it seems that the change in government policies regarding population growth and energy consumption will have a significant effect on the spread of pollution and consequently the cost of health in the country.

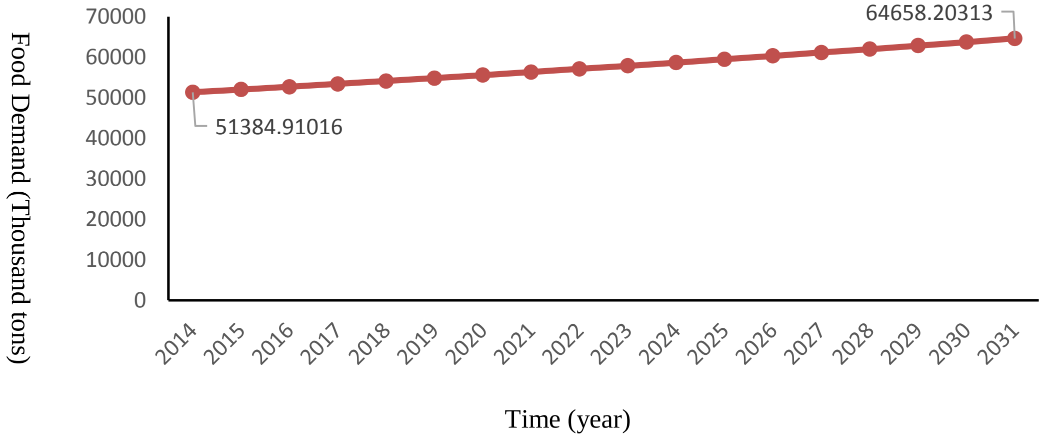

Fig. 5. Simulation of the variable demand behavior for food (thousand tons).

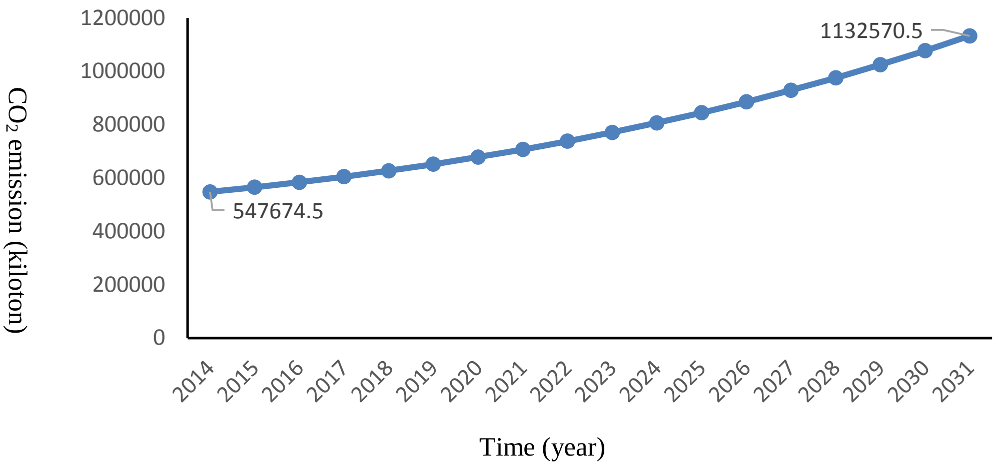

Fig. 6. Simulation of the variable CO_2 emission (kiloton).

Given that according to the stock-flow diagram, the variable population is considered as one of the main variables and determinants of system behavior, so two population scenarios were considered based on the report of the Statistics Center of Iran and the World Bank to evaluate the effects of population growth rate changes on the behavior of key variables of the system. In the first scenario, the population growth rate is assumed to be increasing. In more detail, according to reports of the Statistics Center of Iran, three levels are predicted for the population growth rate as expected reduction during 2017-2012 equal to 1.59%, during 2020-2026 equal to 1.87% and at the end of the period considered about 1.38%. The second scenario defined is consistent with the population growth rate predicted by the World Bank as shown in Fig. 8. As shown, under this scenario, the population growth rate has reduced from 1.46% in 2018 to 0.74% in 2031. In other words, under this scenario, the country's population is assumed to increase at a decreasing rate. The variable population of the whole country is the result of a change in the population growth rate. Therefore, it is expected that with the increase after the change in the

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DOI:
Received: Mar. 30, 2021 Accepted: Aug. 17, 2021

Publisher: University of Guilan, Iran

population growth rate according to the prediction of the Statistics Center of Iran and the World Bank, the population in the country will also change.

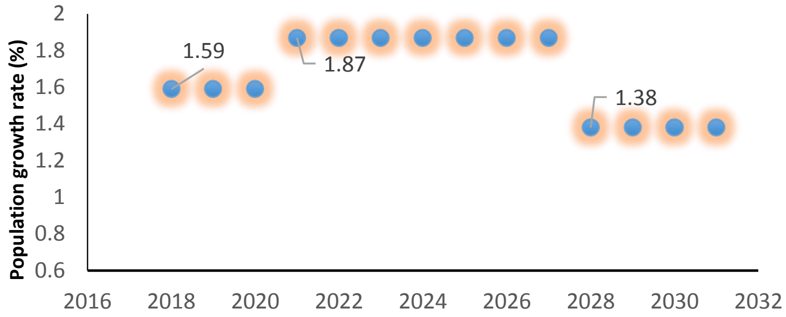

Fig. 7. Population growth rate defined in the first population scenario.

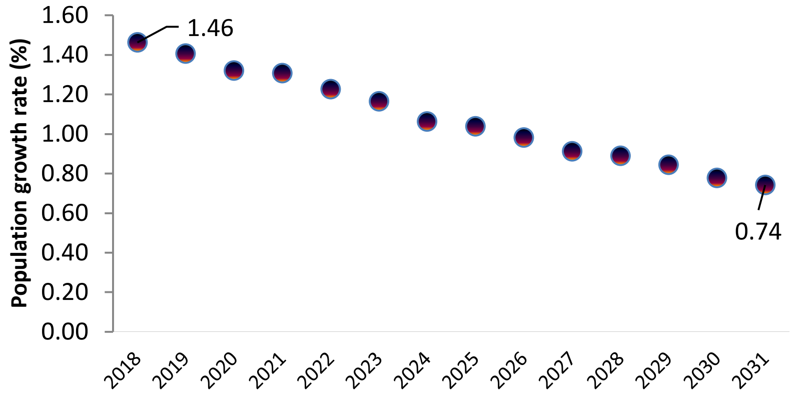

Fig. 8. Population growth rate defined under the second population scenario.

According to Fig. 9, with applying the first population scenario, the variable simulated population is at a higher level than the base scenario. Due to the positive population growth rate in all three scenarios, the population has an increasing trend, but during the application of the second scenario, due to the decreasing population growth rate during the simulation period, the total predicted population compared to the base and the first scenario is at the lower level. Under the third scenario, demand for food and energy consumption in agriculture sector and the food industry are expected to be lower than status quo.

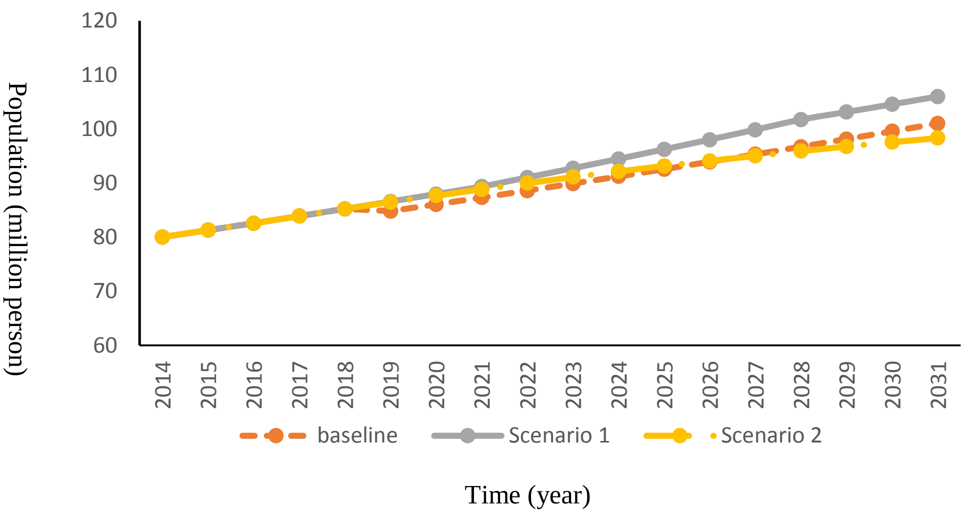

Fig. 9. Population simulation under different scenarios.

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DOI:

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For further analysis, Table 2 presents the effect of changes in population growth rate on the variable population under the base scenario and the first and second demographic scenarios. As shown, population is estimated to be 87.30 million at the beginning of the study period. Under the first scenario, with a population growth rate of 1.59%, the country's population in 2021 is predicted to be 89.33 million individuals, which is higher than the base scenario of 2.33%. At the end of the period, the effectiveness of the scenario of changing the population growth rate, according to the reports of the Statistics Center of Iran, is equal to 4.91%. Under the second scenario, the population in 2021 is equal to 88.82 million individuals, which at the end of the period reaches 98.31 million individuals. Although the population has been increasing under this scenario, in the final years it is 2.68% lower.

Table 2. Effects of population growth rate change on population - million individuals.

Variables	2021	2023	2025	2027	2029	2031
Population baseline	87.30	89.88	92.55	95.29	98.11	101.02
Population (The 1st population scenario)	89.33	92.71	96.21	99.89	103.11	105.97
Percent of change	2.33	3.14	3.95	4.78	5.10	4.91
Population (The 2nd population scenario)	88.82	91.09	93.13	95.02	96.73	98.31
Percent of change	1.75	1.34	0.63	-0.29	-1.40	-2.68

Source: Study results.

Then, the variable behavior of food demand was analyzed. As shown in Fig. 10, with the application of the first demographic scenario, the demand for food will be higher than in the base scenario. However, under the second scenario, with a reduction in population growth rate and consequently the population in the country, the demand for food is lower than the base and the first scenarios of population.

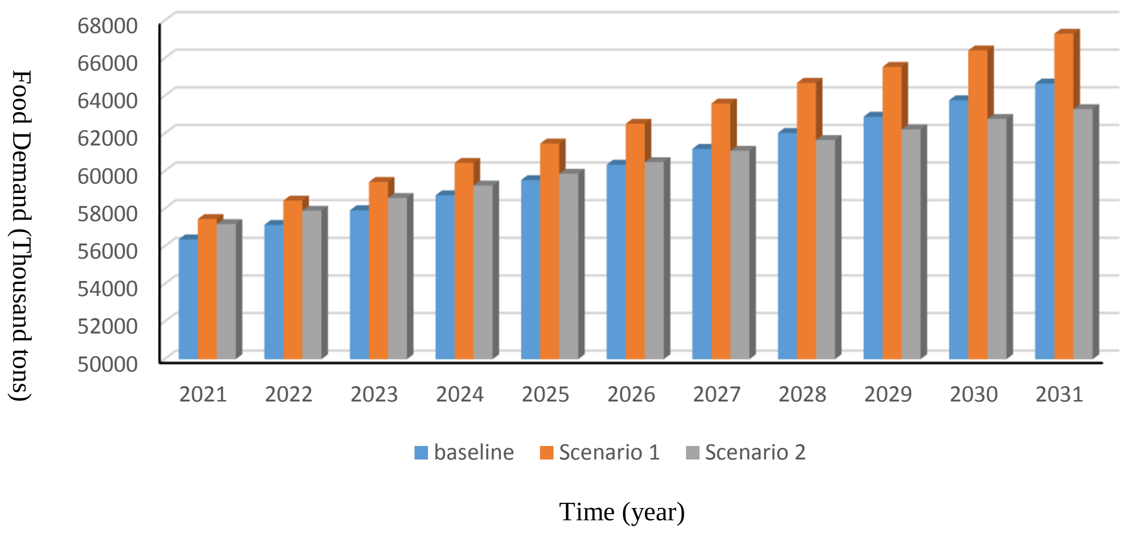

Fig. 10. Effect of population growth rate change on food demand.

Table 3 presents the demand for food in more detail. As shown, the demand for food at the beginning of the period under the base scenario is 56372 thousand tons, which in the first and second population scenarios is 57452 and 57182 thousand tons, respectively. In other words, the effectiveness of the first scenario is equal to 1.92% and the effectiveness of the second scenario is equal to 1.44%. Then, in 2023 this amount will increase to 57920 thousand tons at an increasing rate. Under the first scenario, the demand for food has increased by 2.60%, equivalent to 59423 thousand tons, which under the first scenario, with a change of 1.12%, it was predicted equivalent to 58570 thousand tons. At the end of the study period, due to the decreasing rate of population growth under the second scenario, the percentage of changes in food demand compared to the base scenario is negative and is equal to -

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DOI:

Publisher: University of Guilan, Iran

2.11%. In other words, according to the growth rate of 0.75%, the demand for food is equal to 63296 thousand tons, which is equivalent to 2.11% lower than status quo, which was equal to 64658 thousand tons.

Table 3. Effects of population growth rate change on food demand.

Year	2021	2023	2025	2027	2029	2031
Food demand baseline	56372	57920	59522	61180	62892	64658
Food demand The 1st population scenario	57452	59423	61468	62597	65542	67304
Percent of chage	1.92	2.60	3.27	3.95	4.21	4.09
Food demand The 2nd population scenario	57182	58570	59856	61078	62220	63296
Percent of change	1.44	1.12	0.56	0.17	-1.07	-2.11

Source: Study results.

As food demand changes, energy demand is also expected to change. As shown in Fig. 7, under the first demographic scenario, energy demand is at its highest. In the second scenario, although the demand for energy is predicted to be higher than the base conditions, but due to the negative changes in food demand compared to the base scenario, under these conditions, the demand for energy has grown at a lower rate.

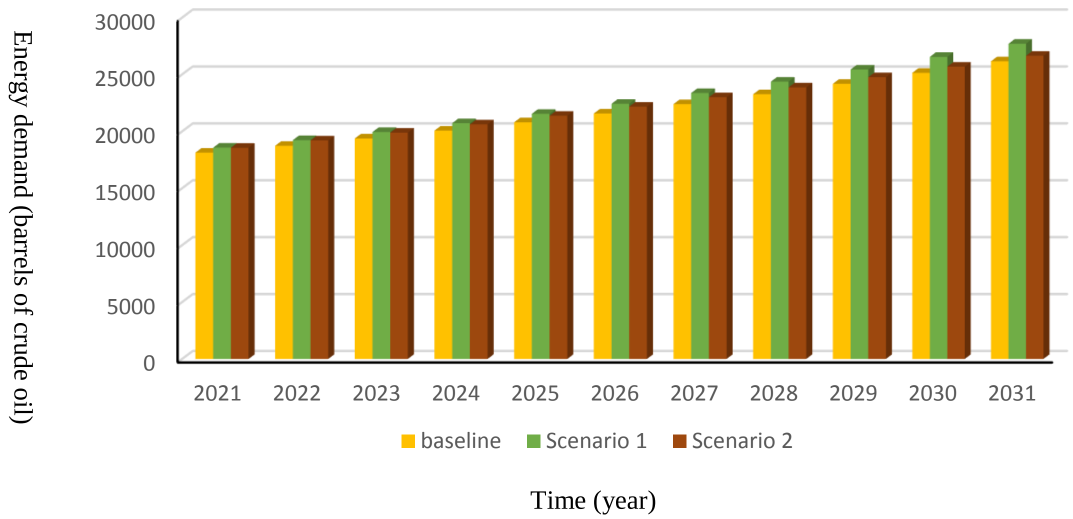

Fig. 11. Effect of different population scenarios on energy demand variable.

In more detail, changes in energy demand under different demographic scenarios are presented in Table 4. As shown in this table, at the beginning of the period, energy demand under the first scenario was equivalent to 18566 barrels of crude oil, which with an annual growth rate of 4% at the end of the period reaches 27699 barrels. Compared to the base scenario, the percentage change in this variable as a result of applying the first scenario in 2021 is predicted equal to 2.41%, and 5.91% in 2031. The effectiveness of the second scenario on the energy demand variable is lower than the first scenario, so that at the end of the period this rate reaches 1.86%. In other words, although energy demand is higher than the base scenario, its rate of change has been evaluated as decreasing. In more detail, the simulated amount of this variable after applying the second scenario in 2029 is equal to 24754 barrels of crude oil and in 2021 is equal to 26638 barrels of crude oil. During 2029-2031, in the base scenario, the amount of energy demand was 24178 and 26153 barrels of crude oil, respectively, which is lower than the values predicted in the second scenario. Table 5 presents the effect of change in population growth rate in the form of two scenarios on the rate of carbon dioxide emissions. As shown in this table, under the baseline scenario, the amount of pollution emission in 2021 is equal to 706834 kilotons, which with the change of population growth rate under the two population scenarios, this amount reaches 729569 kilotons and 727163 kilotons, respectively. At the end of the study period, the rate of pollution emission under the first population

Caspian Journal of Environmental Sciences, Vol. 19 No. 4 pp. 601-618 Received: Mar. 30, 2021 Accepted: Aug. 17, 2021
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scenario with a growth of 7% compared to the baseline scenario will reach 1221660 kilotons, which in the second population scenario is predicted to be 1135553 kilotons. The average annual growth rate of pollution under three different population scenarios is 4.36%, 4.75% and 4.30%, respectively.

Table 4. Effects of population growth rate change on energy demand.

Variables	2021	2023	2025	2027	2029	2031
Energy demand (baseline)	18128.4	19375.2	20795	22393.9	24178	26153.4
Energy demand (The 1st population scenario)	18566	19943.6	21541.2	23367.5	25431.8	27699.5
Percent of chage	2.41	2.93	3.59	4.35	5.19	5.91
Energy demand (The 2nd population scenario)	18554.8	19887.7	21372.2	22996.9	24754.8	26638.6
Percent of change	2.35	2.65	2.78	2.69	2.39	1.86

Source: Study results.

Table 5. Effects of population growth rate change on pollution.

Year	2021	2023	2025	2027	2029	2031	Average annual change
pollution baseline	706834	770929	844693	928959	1024608	1132570	4.36
pollution The 1st population scenario	729569	802573	887852	986909	1098245	1221660	4.75
Percent of chage	3.1	3.9	4.8	5.8	6.7	7.2	-
pollution The 2nd population scenario	727163	793856	868042	949897	1039092	1135553	4.30
Percent of change	2.8	2.9	2.7	2.2	1.4	0.2	-

Source: Study results.

DISCUSSION

In this study, an attempt was made to investigate the changing behavior of energy demand and pollution due to increased demand for food using a systemic thinking approach. In this regard, the system dynamic method was used. The biggest advantage of the systematic thinking is that it helps to identify highly effective changes and lowly effective changes in complex situations. The art of the systematic thinking is that from within the complexities, the fundamental structures that cause change can be seen. This study developed a SD model for food-energy demand with the incorporation of greenhouse gas emissions and conducted a formal model validation. This study is helpful to understand the implications of food and energy interactions, and recognize the benefits of integrated food and energy management in terms of reducing resource uses and the environmental impacts while meeting the demand for food as a result of population growth. System dynamics is a methodology and mathematical modeling technique to frame, understand, and discuss complex issues and problems. System dynamics is an aspect of systems theory as a method to understand the dynamic behavior of complex systems. The basis of the method is the recognition that the structure of any system, the many circular, interlocking, sometimes time-delayed relationships among its components, is often just as important in determining its behavior as the individual components themselves. It is useful for studying the behavior of complex systems in the environment. System Dynamics models are used to understand and anticipate changes over time in puzzlingly complex systems. It can be used with what are thought to be 'data poor' problems. The information base for the conceptualisation and formulation of System Dynamics models is much broader than the numerical database employed in operations research and statistical modelling. This method can be useful to gain insight and understanding in a messy situation by sketching increasingly sophisticated causal loop diagrams. The food-energy model consists of sectoral energy demand (agriculture and food industry), food demand, population, and

Received: Mar. 30, 2021 Accepted: Aug. 17, 2021

Publisher: University of Guilan, Iran

greenhouse gas (GHG) emissions .The performance of the model is discussed by comparing model outputs for the selected variables to the corresponding historical data. The structure of food-energy interactions was tested by comparing the causal and mathematical relationships between variables with the available knowledge about real system. The study results showed that the population is constantly growing. Due to the per capita consumption of food, which in turn depends on the growth of GDP, the demand for food is increasing, which in turn has led to an increase in demand for energy. The average annual growth of the food demand variable is estimated at 1.35 percent. As a result of population growth and increasing demand for food, the country's energy consumption with an average annual growth of 3.31 percent reaches 26,153 barrels of crude oil. Due to the positive causal relationship between the energy variable and population with the rate of pollution in the designed system, it is expected that the rate of greenhouse gas emissions with a growth rate of 4% will experience an upward trend. So that the pollution at the end of the period is simulated to be equal to 1132570 killo tone. Therefore, the environmental damage by users should be reduced to the lowest level through some policies such as cultural environmental training and energy efficiency increase. The result also showed that the increases in food and energy demands are primarily driven by the population growth and are also contributed by the reinforcing feedback structure between food and energy demands. With increasing demand, there is a need to look for alternative options for renewable energy sources. Because energy consumption in the country has a significant role in the production and spread of pollution (Zhuang 2014). With the growing population of Iran, water, food and energy supply will be one of the most important challenges ahead. In this study, an attempt was made to enter the model of different population growth scenarios defined by the Statistics Center of Iran and the World Bank to investigate the behavior of the energy demand system and food production as a result of population growth changes. The results showed that with reducing population growth rate consistent with expectations, the level of demand for food and energy will be lower. The results showed that by changing the population growth rate according to the first scenario, the demand for energy at the end of the study period is 5.91% higher than the value set in the baseline conditions. However, after the change in the population growth rate according to the second scenario, the demand for energy is 1.86 percent higher than the baseline conditions. Due to the positive population growth rate in the country, the demand for food and energy is experiencing a growing trend. Given that the agricultural sector on the one hand is facing limited production resources and on the other hand is providing food security to the growing population, a balance must be struck between the harvesting of production resources and the amount of agricultural production. According to FAO estimates, the agricultural sector must increase its production by 60% to meet the need for population growth by 2050. According to the International Energy Agency (IEA 2010), energy consumption will increase by about 50% by 2035. Providing food and energy alongside reducing pollution without depleting natural resources is a major challenge facing policymakers. The model designed in this study can be a good guide for evaluating different policies. At the same time, the results of population policies in the country can be followed in this way. Although the model designed in this study is the first study on energy consumption modeling in the food sector in Iran, but it also has some limitations. Given the importance of the agricultural sector, modeling this sector in more detail, and considering the amount of energy in the process of irrigating crops, can increase the accuracy of the model. But we must be careful that a system dynamics diagram can become very complex when actual situations with lots of variables are modelled. Future work can specifically address the difference of energy consumption among different food types into modeling. Also, other influential factors such as household affluence and machinery could be considered as parameters. Although household energy use consumes a large percentage of total food energy, this part is a small part of this model since the focus of this research is on the agricultural sector. Further research can further address the household sector.

CONCLUSION

Currently, energy has a special place in all human production and consumption activities and the largest contribution in world trade. The results of several studies indicate that the accelerating trend of economic and industrial development in countries around the world is highly correlated with the level of efficient consumption of energy carriers. With the beginning of the industrial revolution and the formation of industries, energy carriers are considered as important factors of production. As economic and industrial growth and development continued, the consumption of energy carriers after the 1973 oil crisis was studied and analyzed very seriously. This has led developed countries to adopt policies to make the best use of these institutions. Today, energy carriers as

Received: Mar. 30, 2021 Accepted: Aug. 17, 2021

Publisher: University of Guilan, Iran

production inputs play an important and vital role in all production activities and various economic sectors. This input is the main source of government revenue in Iran and a determinant in economic growth. According to the report of Energy Balance Sheet (2017) during 1991-2017, a significant share of the price of energy carriers has been provided by the government as a subsidy. Not only has the price of these carriers not risen over the years, but for some, such as oil, gas, gasoline and electricity, even real prices have fallen. Of course, in the case of other carriers, the real price increase has been very limited. In agriculture sector, fuel inputs are used both directly and indirectly. The most important part of fuel use in agriculture is related to the extraction of water from groundwater sources for irrigation and the use of agricultural machinery at the stages of planting, maturity and harvesting. Also, the contribution of different energy carriers to the energy supply of agriculture sector in recent years shows different trends, so that the contribution of natural gas and electricity since 2005-2016 had an upward trend, but in this period the contribution of petroleum products has reduced from 71.29 to 53.01% (Energy Balance, 2017). This downward trend in the consumption of petroleum products in recent years has been due to the policy of changing the fuel of irrigation pumps in agricultural fields from oil and gas to electricity. Cheap energy carriers, but along with low energy use technology, has led to excessive use of energy carriers and reduced energy efficiency in various economic sectors, including agriculture sector in the country. During 1976-2016, the value added of the country's agricultural sector has grown by an average of 4.12% annually.

Meanwhile, during the same period, energy use in this sector has grown by an average of 4.77%. In other words, the growth of energy use has been greater than the growth of value added of agriculture sector. This situation has led to a reduction in energy efficiency. Generally, changes in energy demand are expected in the future as a result of several factors, including population growth, and social and economic development.

Therefore, the energy system can be vulnerable due to an imbalance in the supply and demand. Considering the critical role that energy plays in food production, any shock in energy availability will have great effects on food production process, and through the food markets, these impacts will reach the economy as a whole, with economy-wide consequences. In this regard, Understanding the impact of different parameters such as population growth, and another government program about food production under the different scenarios, is essential for ensuring the sustainability of future energy resources management and also controlling environmental pollution. So, to achieve a better result in studies, it is necessary to consider factors affecting energy resource system, in terms of the interaction between them. Although system dynamics models have been built for food system in other parts of the word, our study is the first application in food system in Iran. Using the system dynamics model and engaging stakeholders in model development, we have implemented a process compatible with improving stakeholder understanding of the dynamic behaviour of the energy-food-pollution over time, and more importantly, the interactions between the variables that determine this behaviour. The designed system can be used by policymakers to determine the effectiveness of various policies for energy management, food security and pollution control in Iran.

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Received: Mar. 30, 2021 Accepted: Aug. 17, 2021

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Bibliographic information of this paper for citing:

Mobaseri, M, Mousavi, S.N, Mousavi Haghighi, M.H 2021, Causal effects of population growth on energy utilization and environmental pollution: A system dynamics approach. Caspian Journal of Environmental Sciences, 19: 601-618

Caspian Journal of Environmental Sciences, Vol. 19 No. 4 pp. 601-618
DOI:

Received: Mar. 30, 2021 Accepted: Aug. 17, 2021

Publisher: University of Guilan, Iran