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A sustainable biomass network design model for bioenergy production by anaerobic digestion technology: using agricultural residues and livestock manure

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Abstract

Scarcity of fossil fuels and their emissions have led energy policymakers to look for alternative renewable and clean energy sources. In line with this target, biomass is a promising alternative source for the generation of clean energy and the development of a sustainable society. The use of animal and agricultural wastes is one of the very promising renewable energy alternatives paving the way for a more sustainable energy network. Animal and agricultural wastes as biomass sources do not endanger food security and mitigate environmental impacts and may therefore considerably contribute to an appropriate waste management. As a result, converting animal and agricultural wastes to energy is a challenging issue that has attracted the attention of academic and industrial researchers. A multi-echelon multi-objective model is developed to design a sustainable supply chain for bioenergy generation through the anaerobic digestion process. The model maximizes economic and social objective functions, representing direct economic profits and positive social externalities such as job creation and economic development, respectively. Factors affecting the international supply chain include imports of intermediate production equipment, exports of a final product, international business terms applied, customs duties, and foreign exchange rates. Bioenergy and fertilizers are outputs considered in this study; the former to be converted to electricity in a biogas plant to meet domestic demands, and the latter to be exported. A case study for the Golestan province is used to evaluate the efficiency of the proposed model. The results support the potential for three biogas power plants in Gonbad-e-Kavoos, with an annual production capacity of about 1000 tons of fertilizer and an electricity supply for 101,556 households per month. There is still a broad field of promising avenues for future research. Studying uncertainty in different supply chain parameters and using robust optimization to deal with uncertainties are recommended approaches.

Keywords: Sustainability, Bioenergy, Anaerobic digestion, Animal and agricultural waste, Biogas

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Background

Scarcity of fossil fuels, together with emission of fossil fuel pollutants, such as carbon dioxide, into the atmosphere, and the resulting consequences, have led energy policy-makers and planners to look for alternative renewable and clean energy sources. Bioenergy is a renewable energy generated from biomass. In general, different types of biomass may be categorized into three generations: the first generation is mainly composed of feed materials such as corn grain, sugar cane, soybeans, and oilseeds; the second generation includes such materials as agricultural wastes [1] such as corn pods, post-felling wastes, or non-edible energy specific products like switchgrass, miscanthus, and jatropha; and finally, the third generation described as aquatic biomass, includes a diverse group of photosynthetic algae and cyanobacteria, sized from microscopic (microalgae and cyanobacteria) to large seaweeds [2]. The importance of design, implementation, and management of renewable energy supply chains has been rapidly growing in recent years. In order to efficiently transform biomass into energy, all supply chain network steps and activities should be designed in a way that guarantees the efficient flow of materials, information, and finance. Such activities include planting, harvesting, collecting, storing, and transporting the biomass, as well as converting biomass to energy, and finally, the distribution and consumption of energy. To carry out these activities, there should be a supply chain configuration along with an efficient transportation network, an optimum spatial and capacity formulation of power plants and warehouses, a supply and management of resources, waste management, and operational scheduling.

For this purpose, a multi-objective and multi-period mixed-integer linear programming approach is proposed to design the biomass-to-bioenergy supply chain model for the transformation of biomass into biogas using an anaerobic digestion process. The model utilizes a second-generation biomass such as animal excreta and agricultural wastes for producing biogas and fertilizer, the former to be exported abroad, and the latter to be converted into electricity in a biogas power plant that meets the domestic demand needs. As the model considers an export of final products and an import of capital equipment, international factors such as a foreign exchange rate and international business terms are included in the model. There are also some factors that take social considerations into account. The developed model designs a global supply chain network for the transformation of waste biomass to energy, indigenizing the necessary international supply chain factors. Compared with the literature regarding the existing biomass supply chain, the model provides policy-makers with instruments to enhance environmental health, deal with waste management difficulties, create a decisive value-add out of biomass wastes, and a control

for social side effects of this supply chain network. A case study for the Golestan province has been conducted, which was a first attempt at designing a supply management chain of second-generation biomass in Iran.

The “Literature of review” section of the paper reviews the literature on a biomass supply chain network, followed by the problem statement in the “Methods” section. A mathematical programming model is developed to formulate the global sustainable biomass supply chain using anaerobic digestion. The “Methods” section describes the methodology of dealing with this problem. In the “Results and discussion” section, a model is implemented for a real-world case using an epsilon constraint approach, whereas the “Conclusion” section wraps up with concluding results and suggestions for future research.

Literature review

Energy is like a bloodstream in the growing body of today's industrial world. On the other hand, the supply and distribution network of energy carriers is indivisible and interconnected across different countries of the globe. A change in the price of crude oil in the Persian Gulf, for instance, will instantaneously result in changes in the price of other energy sources such as aviation fuel around the world. The supply chain of energy carriers must, therefore, be considered as a global supply chain network on an international scale.

Despite the international nature of the supply network of energy carriers, there seems to be a lack in theoretical and empirical literature with regard to the energy supply chain. Heever et al. [3] developed a long-term mathematical model for designing and planning the infrastructure of offshore oil fields, taking into account such commercial terms as customs tariff, tax, and property. Jiao et al. [4] presented an optimization model to minimize the overall cost of the Chinese oil supply chain. They include such international factors as the import of petroleum and the exchange rate in their model. As a clear result, there is no study that investigates global factors that impact the supply chain of the proposed biomass-to-bioenergy network addressed in this paper.

Three generations of bioethanol can be defined: the first generation of bioethanol is produced from sugary raw materials such as beet and sugarcane molasses or starch raw materials such as cereals, potatoes, and cassava. Bioethanol from plants or plant waste and lignocellulosic second-generation bioethanol and bioethanol production plants or waste and municipal solid wastes and industrial plant consisting of sugar and starch and cellulose are called third-generation bioethanol Gilani and Sahebi [5]. Today, the use of first-generation biomass is a threat to the food supply, and its use is limited.

Besides the necessity of studying the components of global trade to optimize economic performance, the environmental and social aspects of energy supply network management decisions are also a serious challenge to be met. Osmani et al. [6] presented a multi-purpose design of a bioethanol supply chain network based on different types of cellulosic biomass, including the environmental debate in terms of the amount of carbon dioxide entering the environment. There are a few articles that address all economic, environmental, and social dimensions of sustainable development. Fengqi You et al. [7] presented a definite model for designing a network of biofuels from cellulosic biomass, considering all aspects of sustainable development. Their model includes three objective functions for minimizing costs, minimizing greenhouse gases, and maximizing the number of jobs created in order to take care of economic, environmental, and social developments, respectively. Miret et al. [8] formulated a three-objective model to deal with sustainable development objectives by minimizing total annual costs through a life-cycle assessment and cost estimation method and employing two social factors, namely, the number of employment opportunities as well as the competition between food and energy.

Most studies, with regard to a bioethanol supply chain, have only considered cellulosic biomass as a source of energy. Zhang et al. [9], for example, introduced an optimization model for a bioethanol supply chain with switchgrass as the raw material. Balaman et al. [10], however, developed a deterministic model for an electricity production supply chain sourced from animal waste and energy seeds in an anaerobic digestion process. Ullah et al. [11] studied wheat straw and okra stalk to evaluate their potential use for integrated lignocellulosic biorefining. Arumugan et al. [12] assessed a non-edible renewable resource, i.e., *Calophyllum inophyllum* oil, to produce biodiesel. A kinetic analysis has been carried out for biodiesel production to identify the rate equation and to estimate the model kinetic parameters.

It is critically important to conduct a case study in order to test for the accuracy of biomass supply chain models. Huang et al. [13] applied a biofuel supply chain design in California to examine the economic potential of the model, the structure requirements, and the risk of bioethanol production from waste. Sharma et al. [14] considered an uncertain model with several scenarios for the design of a biomass supply chain system and implemented their model in Kansas.

Literature shortcomings

When browsing for literature, it is evident that articles examining global trade factors in detail are scarce. Therefore, the present article is an effort to indigenize production equipment and final product export within the model and to include such factors

as incoterms and foreign exchange rates as well as various types of customs duties (to understand its importance, interested readers are referred to [15]). It also introduces a new approach for calculating the export costs (see Eqs. 11 and 12) of this global biomass-to-bioenergy supply chain. Moreover, social decision-making factors have not been sufficiently regarded in the existing literature. A limited number of studies focus just on job creation as the sole social target [16, 17]. This study therefore examines a number of social dimensions of the supply chain by employing the Guidelines for the Social Life Cycle Assessment of a Product (GSLCAP) approach [18], which is one of the most comprehensive methods widely used for evaluating such social impacts that are based on life period concepts. Job creation and economic development measures are chosen to evaluate the social dimensions of the supply chain.

The most efficient way to generate energy in rural and other remote areas, where both agriculture production and animal husbandry are dominant activities, is the conversion of agricultural and animal waste into energy [19, 20]. This study therefore formulates the supply chain of energy production from both agricultural and animal waste sources, alone. According to our studies, no practical study has been conducted for the management of the second-generation biomass supply chain in Iran. From this point of view, the Golestan province is selected to serve as a case study in this article.

As a clear result, the existing literature suffers from a number of essential shortcomings, including (a) designing a bioenergy network for the conversion of second-generation biomass to bioenergy through an anaerobic digestion process, which is a very suitable method to develop rural and other remote areas [21]; (b) providing the required biomass feedstock from both animal and agricultural wastes to obtain a more sustainable supply network; (c) including the social dimensions of the supply chain in terms of job creation and economic development attainments by using GSLCAP technique; (d) globalizing this supply chain network by studying the incoterms and foreign exchange rates; and (e) a practical examination of the model by conducting a real-world case study.

Methods

Anaerobic digestion process

Biomass can be converted into various forms of bioenergy such as ethanol, butanol, methane, hydrogen, electricity, and biofuels through various processes [22]. A process available to convert biomass to energy is anaerobic digestion, which is in fact a microbial decomposition of organic materials in the absence of oxygen. Under favorable conditions, organic material will become fermented and release biogas. Some

important factors which affect the production of biogas include the type, density, and compositions of raw materials, pH, the absence of oxygen in the interaction environment, and the time required to stop the fluid inside the reservoir [23–25]. Biogas can be used to generate electricity and heat. For the conversion of biogas to electricity, it is possible to use electricity and heat units simultaneously or use a combined heat and power (CHP) unit.

The process of generating electricity through an anaerobic digestion at CHP biogas power plants is as follows: first, the usable raw materials (organic waste or animal waste and plant residues) are discharged in an appropriate space, then crushed and mixed with liquid at a specific rate, and moved into the pre-digestive reservoir. Then, it enters into the digestive process, and the operation of biogas production begins. About 50 to 70 percent of the biogas is methane, to be used as a fuel for producing heat and power in generators. By the end of biogas production, the remaining fluid is transferred to the storage tanks, capable of being used as a fertilizer in liquid or dry forms. The produced biogas is transferred to the gas purification system, and the resulting energy is directed to generators in order to produce heat and electricity. The electricity produced is connected to the power distribution network [26].

The Bioenergy Supply Chain Network (BSCN)

Based on the production process described, Fig. 1 shows the energy generation supply chain network diagram of

the model. The chain covers all activities required to generate energy from supplying raw materials to delivering products to their final markets. It consists of the following layers:

Required raw materials

In general, the performance of the anaerobic digestion process as a biological process depends on several factors. One of the critical factors in the production of biogas is the type and composition of raw materials, and the density of materials in the digester [27].

Type and composition of raw materials The type and composition of raw materials affect the quality and quantity of biogas produced by anaerobic digestion processes [27]. As mentioned earlier, organic materials can be used as a feedstock for the process. There have been many studies conducted with regard to this factor and how it affects the outcome of the process. Part of the research focused on increasing the quality and thus improving the performance of biogas by changing the type of substrate from a single to a hybrid biomass type. Doagoe et al. [28] used mixed digestion by combining rosewater wastes and cattle manure and proved that in the combined digestibility of the biogas, the production rate is higher and has a more stable trend. Kollaee et al. [29] tested the composition of rice straw and animal feces and concluded that the quality of biogas increases by changing the kind of bed type from single to a hybrid type. They also used

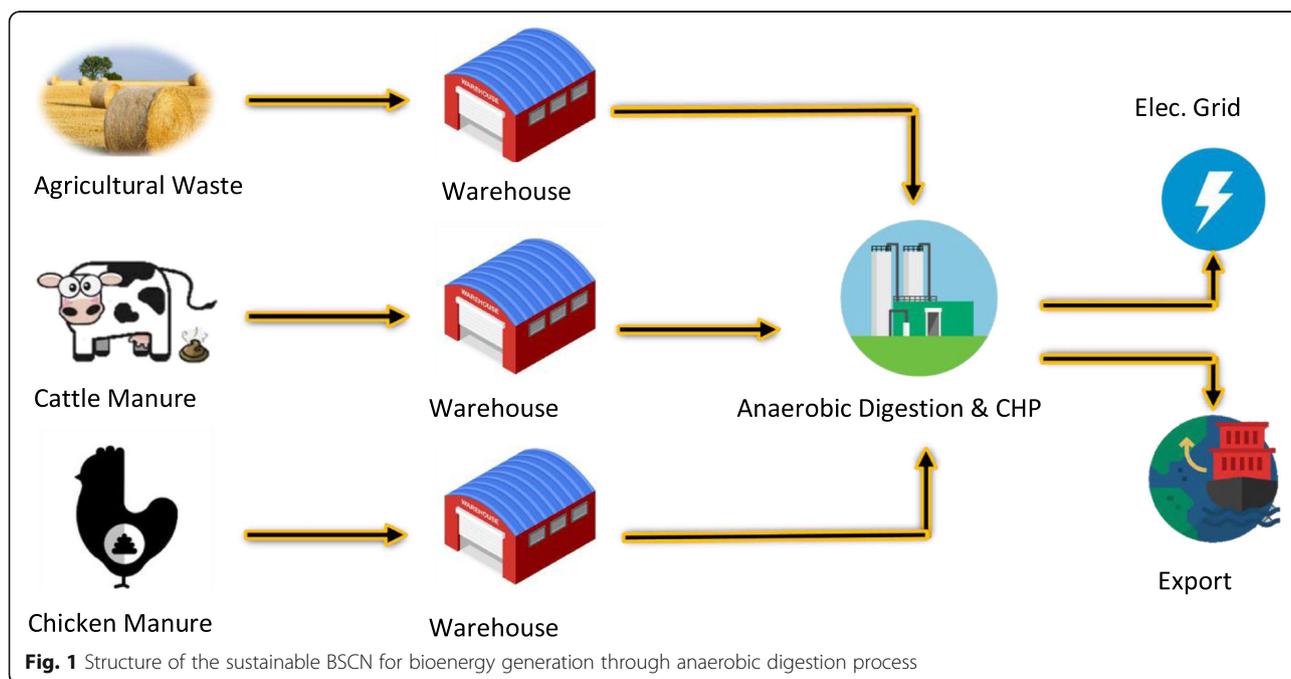


Fig. 1 Structure of the sustainable BSCN for bioenergy generation through anaerobic digestion process

cow, poultry feces, and straw wastes to reach the same result. However, as mentioned earlier, to work effectively, the appropriate conditions for the digestion process should be chosen for the respective digestible organic materials to allow fermentation to be carried out properly and to produce biogas. Ratio procurement of carbon to nitrogen (C/N) which is proper for the solution inside the digestives is among the conditions of digestion. The C/N ratio of the raw material is very important for the activity of anaerobic bacteria, the speed of fermentation, and therefore the production of methane gas. The ideal ratio for a solution inside the digestion is about 25 to 30. Hashimoto [30] shows that poultry manure alone cannot be digested because of the high ammonia levels. Therefore, high-carbon waste should be used to boost digestibility. For this reason, in order to provide a C/N ratio, it should be co-digested with other high-carbon and cellulose wastes such as vegetable and other agricultural wastes. Hashimoto used straw as a carbon source along with poultry waste. Having information on the C/N ratio of available materials in the region, a suitable mixture of wastes, can be selected to feed the biogas plant [31]. According to the literature [28, 30, 31], the entry of the substances into the digestive process would be a proportion of the poultry feces, the straw, and the cow feces, which would allow the C/N ratio in the digestive solution to be adjusted at an ideal ratio.

The density of materials in the digestion system The materials used in digestion systems should be soluble. Two digestion systems are distinguished in terms of the proportion of solid content: a wet digestion process with a solid content of less than 15 percent and a dry digestion process with a latter of more than 15 percent. While both freshwater and wastewater may be used to supply water, there are some limitations in using the wastewater. Therefore, the model developed here considers a wet digestion process using freshwater.

Warehouses

In order to store materials, a collection of potential sites is allocated for the construction of three types of warehouses for agricultural wastes, liquid or semi-solid animal wastes, and solid animal wastes. High-solid wastes (poultry feces) are considered as solid animal feces, and low-solid ones (cow feces) are considered as liquid or semi-solid feces.

Biogas power plants with different capacities

The required amounts of wastes stored are transferred from the warehouses to biogas plants in

appropriate time intervals. The model considers three levels of capacity for the digestion process and CHP power plants. The production equipment was purchased in Germany and imported into the country through seaports.

Product supply areas

The supply areas are located at the bottom line of the supply chain. Due to the scarcity of electric power in the northern cities of Iran, the electricity produced is transferred to the national electricity grid to meet domestic demands. The fertilizers produced are exported, mainly due to higher international prices compared with prices in domestic markets. Fertilizers are exported through seaports.

Transportation

Roads are considered the only transportation mode that connect the different supply chain layers. As road transportation is heavily affected by climate conditions and road quality, transportation costs are higher in the second half of the year compared with the first half.

Mathematical model for supply chain network design

Model symbols

The variables and parameters used in the model are listed below:

Sets		
p	Candidate locations for power plant	$(p \in P)$
d	Candidate locations for warehouses	$(d \in D)$
r	Biosupply places	$(r \in R)$
c	Power plant capacity levels	$(c \in C)$
o	Export destination countries	$(o \in O)$
s	Available currency	$(s \in S)$
t	Time periods	$(t \in T)$
Technical parameters		
pc_c	Monthly loading capacity for the digestion process at the capacity level c	
pec_c	Power generation capacity for the co-production unit of electricity and heat at the capacity level c	
h	Monthly working hours of a power plant	
$g/g'/g''$	Conversion rate of cow feces/poultry feces/straw to fertilizer	
$e/e'/e''$	Conversion rate of cow feces/poultry feces/straw to biogas	
v_{be}	Conversion rate of biogas to energy	
ee	Electricity efficiency of combined heat and power plants	
$ts/ts'/ts''$	Total solid cow feces/poultry feces/straw	
\underline{ts}	Minimum density of biomass solution in the digestion process	

Methods (Continued)

Technical parameters	
\bar{t}_s	Maximum density of biomass solution in the digestion process
nc_r	The number of cows producing feces in place r
nh_r	The number of laying hens producing feces in place r
wc	The amount of feces per cow over a period of time
wh	The amount of feces per laying hen in a period of time
tca_r	The cultivated area in the place r
pr	Percentage of agricultural waste (straw) per metric tons of crops
ac_t	The amount of agricultural crops per hectare at time period t
po	Percentage annual investment allocated for operational costs
d_{ot}	Demand for fertilizer in country o at time period t
dr	Import rates
r_{st}	Free market exchange rate of foreign currency s against local currency at time t
r'_{st}	Fixed exchange rate of foreign currency s against local currency at time t
d_p	Road distance from Anzali (international port of northern Iran) to power plant in place p
d_{rd}	Road distance from supply district r to warehouse in place d
d_{dp}	Road distance from warehouse in place d to power plant in location p

Economic parameters

tcc_t	Transportation cost of cow feces at time t
tcl_t	Transportation cost of poultry feces at time t
tcs_t	Transportation cost of straws at time t
tcf_t	Transportation cost of fertilizers at time t
tcp	Local transportation cost of imported equipment from seaport to selected location for the power plant
ic_c	Purchasing cost of equipment for power plant with capacity level c
ulc_d	Purchasing cost of land for construction of a warehouse in place d for each ton of biomass
ulc_{cp}	Purchasing cost of land for construction of a power plant with capacity level c in power plant p site
ulf_p	Purchasing cost of land for construction of a warehouse at location p per ton of surplus fertilizer on demand
ucc	Construction cost of warehouses for cow feces
ucl	Construction cost of warehouses for poultry feces
usc	Construction cost of warehouses for straws
ucf	Construction cost of warehouses for surplus fertilizer on demand
flc	Production costs of exported fertilizers (independent of inventory stock)
vlc	Production costs of exported fertilizers (dependent on inventory stock)
ep	Price of electricity sold
fp	Price of fertilizers sold

Methods (Continued)

Economic parameters	
wp	Water cost
pcc	Purchasing cost of cow feces
pcl	Purchasing cost of poultry feces
pcs	Purchasing cost of straws
i_c	Insurance cost for capacity level c
tc_c	Cost of abroad transportation for a power plant with a capacity level c

Social parameters

jp	Person-hour of job opportunities created due to the construction of the power plant (with any capacity)
jd	Person-hour of job opportunities created due to storage of each ton of biomass
$s^{ij} = (\sum_p \sum_c jp \cdot Z_{pc}) + (jd \cdot (\sum_r \sum_t \sum_d AC_{rtd} + \sum_r \sum_t \sum_d AL_{rtd} + \sum_r \sum_t \sum_d AS_{rtd} + \sum_d \sum_t RS_{dt} + \sum_p \sum_t \sum_o (F_{pto} - d_{ot})))$	

The amount of social impacts in terms of local employment and migration

$$s^{ed} = (\sum_p \sum_t ep \cdot OE_{pt}) + (\sum_p \sum_t \sum_o fp \cdot r_{s=1,t} \cdot F_{pto})$$

The amount of social impacts in terms of economic development attainments

$s^{ij}_{max}/s^{ij}_{min}$	Maximum/minimum possible amount of social impacts in terms of local employment and migration
$s^{ed}_{max}/s^{ed}_{min}$	Maximum/minimum possible amount of social impacts in terms of economic development attainments
wj	The weight of social impacts in terms of local employment and migration
we	The weight of social impacts in terms of economic development attainments

Decision variables

Z_{pc}	The number of factories with capacity level c to be built at location p
AC_{rtd}	The amount of cow feces transferred from place r to the warehouse at place d over time period t
AL_{rtd}	The amount of poultry feces transferred from place r to the warehouse at place d over time period t
AS_{rtd}	The amount of straw transferred from place r to the warehouse at place d over time period t
BC_{dtp}	The amount of cow feces transferred from warehouse at place d to power plant in place p over the time period t
BL_{dtp}	The amount of poultry feces transferred from warehouse at place d to power plant in place p over the time period t
BS_{dtp}	The amount of straw transferred from warehouse at place d to power plant in place p over the time period t
CL_d	The storage capacity of liquid and semi-solid biofuels (cow feces) at place d
CS_d	The storage capacity of solid biomass (poultry feces) at place d

Methods (Continued)

Decision variables	
CSS_d	The storage capacity of straws at place d
CF_p	The storage capacity of fertilizer at place p
RS_{dt}	The amount of straw inventory stock in warehouse at place d over time period t
W_{pt}	The amount of water used at power plant at place p over time period t
OB_{pt}	The amount of biogas produced by in the power plant at place p over time period t
F_{pto}	The amount of fertilizer produced in the power plant at place p over time period t to be exported to destination country o
OE_{pt}	The amount of electrical energy generated in the power plant at place p over time period t

Objective functions

The first objective function that maximizes total profit consists of two segments, namely, total revenue and total cost. As potential places for the implementation of the project in Golestan province are defined as deprived areas, the project will be fully tax exempted for 10 years, according to Article 132 of the Tax Law code. Therefore, there is no parameter to take tax calculations into account.

Total income Total income is made up of two parts as well: income from fertilizer exports and income from electricity sales. Note that fertilizer is sold in USD.

$$\text{Income from electricity sales} = \left(ep \cdot \sum_p \sum_t OE_{pt} \right) \quad (1)$$

$$\text{Income from fertilizer exports} = \left(fp \cdot \sum_p \sum_t \sum_o r_{s=1,t} \cdot F_{pto} \right) \quad (2)$$

$$\text{Total income} = \left(ep \cdot \sum_p \sum_t OE_{pt} \right) + \left(fp \cdot \sum_p \sum_t \sum_o r_{s=1,t} \cdot F_{pto} \right) \quad (3)$$

Capital cost The cost of capital is also composed of two elements: capital cost for the power plant and that of the warehouse. As cost, insurance, and freight (CIF) is chosen as the basis for international price bids, the cost of capital for the power plant includes purchasing costs, the cost of equipment import into the country, and the cost of transporting the equipment from the seaport to the power plant. It also includes the costs of purchasing land for the

construction of the power plant as well as the warehouse. In addition to raw materials, warehouses are also built for surplus fertilizer on demand.

The capital cost of a warehouse

$$\begin{aligned} &= \sum_d (ucc \cdot CL_d) + \sum_d (ucl \cdot CS_d) + \sum_d (ucs \cdot CSS_d) \\ &+ \sum_d ulc_d \cdot (CS_d + CL_d + CSS_d) + \sum_p (ucf \cdot CF_p) \\ &+ \sum_p (CF_p \cdot ulf_p) \end{aligned} \quad (4)$$

The capital cost of a power plant

$$\begin{aligned} &= \left(\sum_p \sum_c ic_c \cdot r_{s=2,t=0} \cdot Z_{pc} \right) \\ &+ \left(\sum_p \sum_c 1/005 (ic_c + tc_c + i_c) \cdot dr \cdot r'_{s=2,t=0} \cdot Z_{pc} \right) \\ &+ \left(\sum_p \sum_c 0/09 (ic_c + tc_c + i_c) \cdot (1 + dr) \cdot r'_{s=2,t=0} \cdot Z_{pc} \right) \\ &+ \left(\sum_p \sum_c tcp \cdot d_p \cdot Z_{pc} \right) + \left(\sum_p \sum_c ulc_{cp} \cdot Z_{pc} \right) \end{aligned} \quad (5)$$

Operational costs It is also comprised of power plant and warehouse components, both of which are assumed to be a percentage (PO) of the total capital cost. Equation (8) also takes the cost of water used in the digestion process into account.

$$\begin{aligned} \text{Annual operational costs of a factory} \\ &= po \cdot (\text{cost of the power plant}) \end{aligned} \quad (6)$$

$$\begin{aligned} \text{Annual operational costs of a warehouse} \\ &= po \cdot (\text{capital cost of warehouse}) \end{aligned} \quad (7)$$

$$\text{Costs of the water} = \sum_p \sum_t wp \cdot w_{pt} \quad (8)$$

Transportation costs Transportation costs include the cost of transporting biomass from supply areas to the warehouse and from the warehouse to the biogas plant. Also, since Free on Board (FOB) is chosen as the commercial term for the export of fertilizers, the cost of carrying fertilizer from the power plant to the port is assumed to be imposed on the seller.

$$\begin{aligned}
 \text{Transportation cost} = & \left(\sum_r \sum_t \sum_d tcc_t \cdot d_{rd} \cdot AC_{rtd} \right) \\
 & + \left(\sum_r \sum_t \sum_d tcl_t \cdot d_{rd} \cdot AL_{rtd} \right) \\
 & + \left(\sum_r \sum_t \sum_d tcs_t \cdot d_{rd} \cdot AS_{rtd} \right) \\
 & + \left(\sum_d \sum_t \sum_p tcc_t \cdot d_{dp} \cdot BC_{dtp} \right) \\
 & + \left(\sum_d \sum_t \sum_p tcl_t \cdot d_{dp} \cdot BL_{dtp} \right) \\
 & + \left(\sum_d \sum_t \sum_p tcs_t \cdot d_{dp} \cdot BS_{dtp} \right) \\
 & + \left(\sum_p \sum_t \sum_o tcf_t \cdot d_p \cdot F_{pto} \right) \tag{9}
 \end{aligned}$$

Purchase costs of biomass:

$$\begin{aligned}
 \text{Purchasing cost of biomass} \\
 = & \left(\sum_r \sum_t \sum_d pcc \cdot AC_{rtd} \right) \\
 & + \left(\sum_r \sum_t \sum_d pcl \cdot AL_{rtd} \right) \\
 & + \left(\sum_r \sum_t \sum_d pcs \cdot AS_{rtd} \right) \tag{10}
 \end{aligned}$$

Procurement costs The costs of procurement include the expenses with regard to all necessary actions for the export of fertilizers, which are divided into those independent of inventory and those dependent on the amount of inventory. Since export deals are assumed to be based on FOB terms, the cost of packing goods, landing the cargo at the exporting port, loading it on board a ship, and storage in destination customs, all depending on the number of goods exported, is considered to be the seller’s responsibility. Besides, the export of commodities results in costs due to marketing, issuing pro forma invoice, price negotiations, export permit grants from relevant institutions, transferring goods to customs, issuing a final purchase invoice, obtaining a certificate of origin, signing transportation contracts, etc. All such costs are included as the procurement cost that is independent of the amount of inventory.

The procurement cost independent of the inventory amount

$$= \sum_p \sum_t \sum_o vlc \cdot F_{pto} \tag{11}$$

The procurement cost dependent on the inventory amount

$$= \sum_p \sum_c flc \cdot Z_{pc} \tag{12}$$

Second objective function

The second objective has optimized positive social effects using the proposed model. Measuring social responsibility is a complicated and multidimensional problem due to the wide range and complex nature of social issues. ISO has recently published the International Standard of Social Responsibility (ISO 26000), which divides social responsibility into seven main areas: (1) institutional domination, (2) human rights, (3) labor affairs, (4) environment, (5) fair work, (6) consumer rights, and (7) participation in local development. Many researchers have developed methods to simplify the measurement and use of social responsibility. Among the existing methods, this article employs the “Guidelines for Social Life Cycle Assessment of Products” (GSLCAP), with the following advantages over other proposed methods for assessing social impacts:

- (1) GSLCAP is product-oriented and based on the life-cycle approach. Therefore, it is more consistent with supply chain logic and environmental impact assessment methods that account for life cycle of the product. Thus, it helps to reduce the complexity of designing and formulating the model.
- (2) This method is one of the latest developed approaches that takes advantage of most recent social assessment knowledge [18].

The steps to implement GSLCAP method are as follows:
 Step 1: Defining the goal and scope of the lifecycle social assessment

Step 2: Setting up of the lifecycle steps and decisions with respect to each phase of the lifecycle

Step 3: Clarifying the impact of decision variables on the basis of the GSLCAP social performance categories

Step 4: Establishing an appropriate index to measure the effectiveness of problem decision variables on the social performance categories

Step 5: Normalizing the indices and weighting them to calculate total social impact [18]

Accordingly, local employment and economic development factors have been used to study the social effectiveness of the project. According to Pishvee et al. [18], new job opportunities and the number of products produced are among the best variables to measure social and economic development. Two types of employment in

power plant activities and storage of waste and straw are considered here. A panel of experts is identified, and by using the Delphi method, all the employment information is provided. The economic value of maximum capacity of production is supposed to equal total revenue from export of fertilizers as well as the value of electricity sales.

$$w_j \cdot si_{nor}^j + w_e \cdot si_{nor}^{ed} = w_j \cdot \frac{\left(\sum_p \sum_c jp \cdot Z_{pc} \right) + \left(jd \cdot \left(\sum_r \sum_t \sum_d AC_{rtd} + \sum_r \sum_t \sum_d AL_{rtd} + \sum_r \sum_t \sum_d AS_{rtd} + \sum_d \sum_t RS_{dt} + \sum_p \sum_t \sum_o (F_{pto} - d_{ot}) \right) \right) \cdot -si_{min}^j}{\left(ep \cdot \sum_p \sum_t OE_{pt} \right) + \left(fp \cdot \sum_p \sum_t \sum_o r_{s=1,t} \cdot F_{pto} \right) \cdot -si_{min}^{ed} - si_{min}^j} + w_e \cdot \frac{si_{max}^{ed} - si_{min}^{ed}}{si_{max}^{ed} - si_{min}^{ed}} \tag{13}$$

Constraints

Biomass supply Constraints (14) to (16) ensure that the amount of biomass collected from each area does not exceed the total amount of biomass in that area.

$$\sum_d AC_{rdt} \leq nc_r \cdot wc \forall r, t \tag{14}$$

$$\sum_d AL_{rdt} \leq nh_r \cdot wh \forall r, t \tag{15}$$

$$\sum_d AS_{rdt} \leq tca_r \cdot ac_t \cdot pr \forall r, t \tag{16}$$

Flow material balancing Constraints (17) and (18) refer to animal wastes, while constraint (19) applies to agricultural wastes. There is only one possibility for agricultural wastes to be stored and transferred into the next period.

$$\sum_r AC_{rtd} = \sum_p BC_{dtp} \forall d, t \tag{17}$$

$$\sum_r AL_{rtd} = \sum_p BL_{dtp} \forall d, t \tag{18}$$

$$\sum_r AS_{rtd} + RS_{d(t-1)} = \sum_p BS_{dtp} + RS_{dt} \forall d, t \tag{19}$$

Capacity constraints Constraints (20) to (23) limit the storage capacity.

$$\sum_r AC_{rdt} \leq CL_d \forall d, t \tag{20}$$

$$\sum_r AL_{rdt} \leq CS_d \forall d, t \tag{21}$$

$$\sum_r AS_{rdt} + RS_{d(t-1)} \leq CSS_d \forall d, t \tag{22}$$

$$\sum_p (F_{ptk} - d_{kt}) \leq CF_d \forall p, t \tag{23}$$

Feedstock of digestion Constraints (24) and (25) illustrate the appropriate proportion of the materials combined in digestion process.

$$\sum_d BC_{dtp} = 3 \sum_d BL_{dtp} \forall p, t \tag{24}$$

$$\sum_d BL_{dtp} = \sum_d BS_{dtp} \forall p, t \tag{25}$$

Constraint (26) ensures that the total amount of monthly waste supply to power plants in location p does not exceed the maximum capacity of that location for loading.

$$\sum_d BL_{dtp} + \sum_d BC_{dtp} + \sum_d BS_{dtp} \leq 30 \left(\sum_c pc_c \cdot Z_{pc} \right) \forall p, t \tag{26}$$

Production limitations Constraint (27) determines the amount of biogas production, while constraint (28) limits the quantity of biogas converted to electricity. Constraint (29) guarantees that total electricity production per month at power plant location p does not exceed the monthly capacity of electricity generation at the plant. Also, constraint (30) states that the total electricity produced per plant and per month should be at least 60 percent of the monthly electricity generation capacity of the plant. Constraint (31) deals with the amount of fertilizer production over each period of time and at each location of the plant p .

$$\sum_d e \cdot BC_{dtp} + \sum_d e' \cdot BL_{dtp} + \sum_d e'' \cdot BS_{dtp} = OB_{pt} \forall p, t \tag{27}$$

$$v_{be} \cdot e \cdot OB_{pt} = OE_{pt} \forall p, t \tag{28}$$

$$OE_{pt} \leq h \cdot \left(\sum_c pec_c \cdot Z_{pc} \right) \forall p, t \tag{29}$$

$$OE_{pt} \geq 0.6 \cdot h \cdot \left(\sum_c pec_c \cdot Z_{pc} \right) \forall p, t \tag{30}$$

$$\sum_d g \cdot BC_{dtp} + \sum_d g' \cdot BL_{dtp} + \sum_d g'' \cdot BS_{dtp} = F_{pto} \forall p, t \tag{31}$$

Constraint (32) refers to the density of aqueous solution in the digestion. It also determines the amount of water required to create a proper density.

$$ts \leq \frac{\sum_d ts \cdot BC_{dtp} + \sum_d ts' \cdot BL_{dtp} + \sum_d ts'' \cdot BS_{dtp}}{\sum_d BC_{dtp} + \sum_d BL_{dtp} + \sum_d BS_{dtp} + w_{pt}} \leq \bar{ts} \forall p, t \tag{32}$$

Distribution Finally, according to constraint (33), the quantity of fertilizers produced per period should be at least as much as the destination country demand.

$$\sum_p F_{pto} \geq d_{ot} \forall t, o \tag{33}$$

Solution method

In general, the literature on multi-objective optimization includes three types of “priori,” “interactive,” and “posterior” methods. The main advantage of a priori method is that it draws a general picture of a set of optimal solutions and provides decision makers with more handy and reliable information on how to choose an optimal solution from such a set. An “Epsilon Constraint” approach, which is a specific type of a priori method, is applied in this article. While the weighting approach, a specific type of an interactive method, converts the objective functions of a multi-objective problem by weighting to a single objective function, the epsilon constraint approach enjoys the following advantages:

- (1) The weighting method produces only very strict efficient responses, while the epsilon constraint method can also produce non-strict efficient responses. As there may be different weight combinations that result in the same efficient identical solutions, there will be some redundant and derivative solutions. By using the epsilon constraint method, however, different solutions are obtained at any time, the model is solved. As a result, it is capable of providing a better image of the efficient response set [32].
 - (2) The epsilon constraint method controls the number of efficiently generated responses by determining the number of milestones per interval of each of the target functions, while this is not easily possible in the weighting method [33].
- The following multi-objective problem is used:

$$\text{Min } \{f_1(x) \cdot f_2(x) \dots f_p(x)\}$$

$$\begin{aligned} \text{s.t. :} \\ x \in S \end{aligned}$$

where x is the vector of decision variables and $f_i(x)$ represents the i^{th} objective function. p denotes the number of objective functions and s represents the space of response to the problem. x is an efficient solution, the corresponding function of which is called non-dominated, if and only if there is no solution such as x' that $f_i(x') \leq f_i(x) \forall i = 1, 2, \dots, p$. In the epsilon constraint method, we first select one of the target functions as the main objective function and then limit the rest of the target functions as follows:

$$\text{Min } f_1(x)$$

$$\text{s.t. :}$$

$$f_2(x) \leq \varepsilon_2$$

$$f_3(x) \leq \varepsilon_3$$

...

$$f_p(x) \leq \varepsilon_p$$

$$x \in S$$

ε_i denotes the level of satisfaction of the objective function and i denotes the different systematic changes which result in different solutions. If some of the objective functions are of maximizing types, the associated constraints are written as $f_i(x) \geq \varepsilon_i$

Different steps to implement the epsilon constraint method are [34]:

Step one: Solve the single-objective problem like the following problem (SOP_i) P-1 times and find the optimum solution and the value of the corresponding objective function for each single solution.

$$SOP_i : \text{Min } f_i(x)$$

$$\text{s.t. : } (x_i^*, f_i(x_i^*))$$

$$x \in X$$

Step two: Create an equilibrium table, any i^{th} row of which representing the value of other objective functions given the i^{th} equation's solution as derived in step 1 above. Then, determine the maximum and minimum values of each target function at any column (for instance, y_i^{min} and y_i^{max} for the objective function). Table 1 depicts the structure of the equilibrium table.

Table 1 The structure of the equilibrium table in the epsilon constraint method

SOP_i	$f_2(x_i)$	...	$f_p(x_i)$
x_2^*	$f_2(x_2^*)$	...	$f_p(x_2^*)$
\vdots	\vdots		\vdots
x_p^*	$f_2(x_p^*)$	...	$f_p(x_p^*)$
y_i^{min}	$f_2(x_2^*)$	...	$f_p(x_p^*)$
y_i^{max}	$\max(f_2(x_i))$	...	$\max(f_p(x_i))$

Step three: The value of any ε lies in a range of the values of the corresponding target function in the equilibrium table:

$$y_i^{\text{min}} \leq \varepsilon_i \leq y_i^{\text{max}}$$

The resulting intervals are usually divided into equal parts, and the recursive points are used as values for ε .

Step four: Stop solving the problem if the desired solution is achieved from one of the optimal points; otherwise, divide the range of ε into more intervals and change ε values in new ranges to achieve the final Pareto optimum.

Results and discussion

In this section, the performance of the proposed model is evaluated and analyzed using a case study to design a transformation supply chain network of biomass to energy. For this purpose, the Golestan province has been selected for the following reasons: (1) according to the reports, a high potential capacity of biogas production from biomass energy sources (animal wastes) in Golestan is proven; (2) agriculture is the dominant economic sector in Golestan, a province that is home to production of many important and strategic products as well as animal husbandry products, due to the existence of susceptible agricultural waste; (3) due to the lack of enough infrastructures for transmission of electricity to the northern cities of the country and electricity imports from neighboring countries currently meet the power demand; (4) The Golestan province is geographically close to the international ports of northern Iran, paving the way for quick and easy equipment import and product export. The port of Anzali, among the most international ports of northern Iran, has been selected here; (5) According to Article 132 of the Direct Tax Law, production in deprived areas (such as those in Golestan province) are exempted from tax for 10 years, resulting in greater profitability of the supply chain; and (6) implementation of such a project helps the creation of more jobs and enhancement of economic development, in which Golestan has unfortunately no proper records.

Figure 2 represents the map of Golestan province and its districts, with proposed project sites marked with a

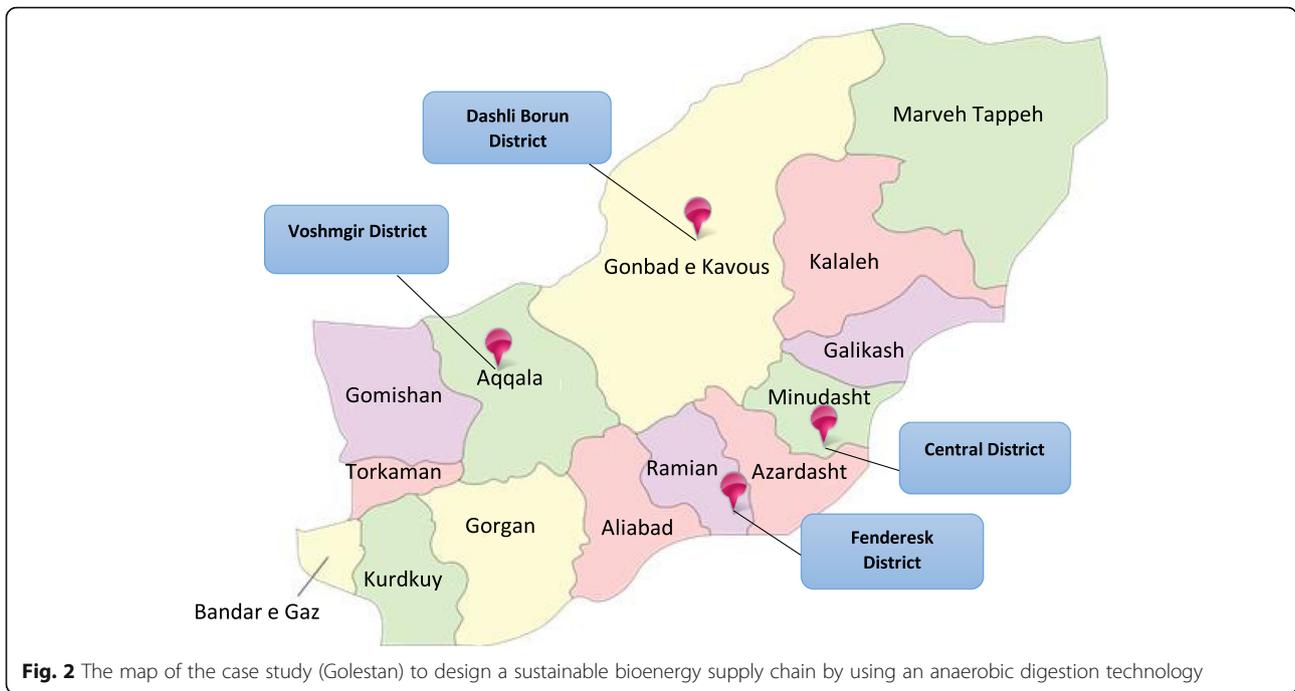


Fig. 2 The map of the case study (Golestan) to design a sustainable bioenergy supply chain by using an anaerobic digestion technology

cursor. The statistical database at Arya Parto Pars Company is the primary reference to access the required data with regard to critical parameters of the model, such as the rate of conversion of biomass to biogas, the rate of conversion of biomass to fertilizer, and the rate of conversion of biogas to energy.

Case study assumptions

The following assumptions and data are applied in this study:

- (1) The time horizon is 1 year, divided into 30-day time spans.
- (2) The straw used is the residue of wheat. According to expert views, on average, each hectare of land yields about 2.5 tons of wheat, and 0.25 of it convert to straw. Based on the seasonal timing of wheat cultivation, the required amount of straw is purchased during summer and stored for the whole year. A number of animal husbandries, poultry houses, and agricultural lands in four cities of Gonbad-Kavoos, Agh-ghala, Ramayan, and Minoodasht are considered as the supply points of required biomass. In order to implement the model, four remote areas were selected in four districts of Golestan province. All of these four areas are considered as potential points for the supply of biomass, the location of power plant *x*, and construction of the reservoir.
- (3) The total solid content of a biomass slurry in the digester should vary between 10% and 12%.

The conversion rate of biogas to energy is 5.5 kWh per cubic meter, and the electrical efficiency of combined heat and power generation units is 41%. Three levels of capacity are considered for digestion. These capacities, together with the amounts of electricity produced in respective combined heat and power generation units, is depicted in Table 2.

- (4) There is no limit with regard to the electricity power production capacity due to the national priorities to develop renewable energies. The guaranteed purchasing price of electricity was 0.1 \$ per kilowatt-hour in the year 2016. The annual operating cost of a biogas plant and the repositories are a proportionate of 10 percent of total investment expenditures.
- (5) The fertilizers produced are exported through the Anzali seaport to Azerbaijan and Russia for a price of \$1000 per ton. The demand for fertilizer is expected to be 550 tons by the Republic of Azerbaijan and 500 tons by Russia for each period of time. Besides, the combined heat and power

Table 2 Power plant capacities

Power of CHP (kW)	Digestion capacity (tons/day)	Loading capacity (tons/day)	Capacity levels
1000	1625	1950	1
1250	2000	2400	2
1500	2375	2850	3

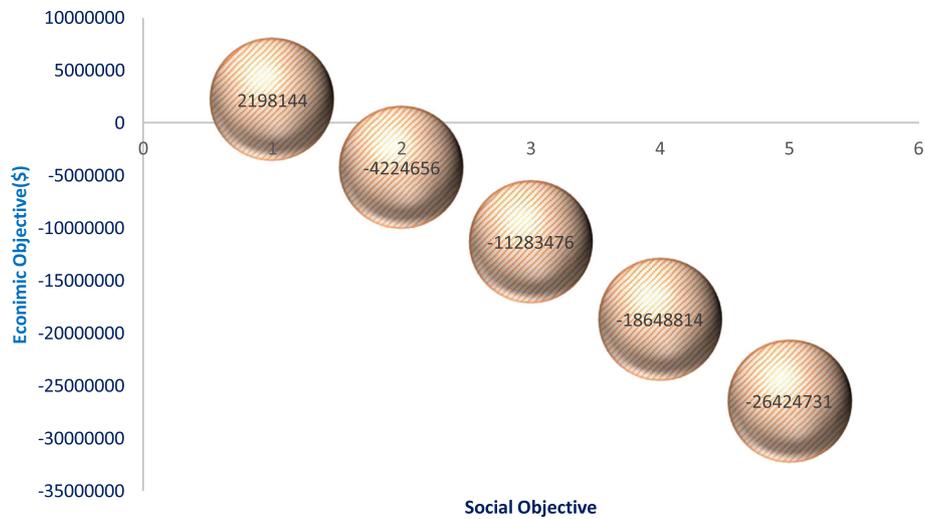


Fig. 3 Pareto solutions the trade-offs between economic objective and social objective

solution from it, as it is accompanied by low profit reductions and significant increases in social objective functions.

Now, the results for $\epsilon_2 = 0.599$ are shown in Fig. 4.

Sensitivity analysis

The effects of biogas plant investment expenditures on the total profitability of the whole project are analyzed in this section, where biogas power plant costs represent

most of the total costs. The former, in real world, mostly depends on the brand, technology, and production procedures of the capital equipment manufacturer. Since, according to “Iran Renewable Energy and Energy Efficiency Organization”, the investment cost of biomass power plants with anaerobic digestion technology ranges from 6104 to \$2574 per kilowatt (41), and the model here assumes a cost value of €2400, inclusive of all charges from purchase origin point to delivery

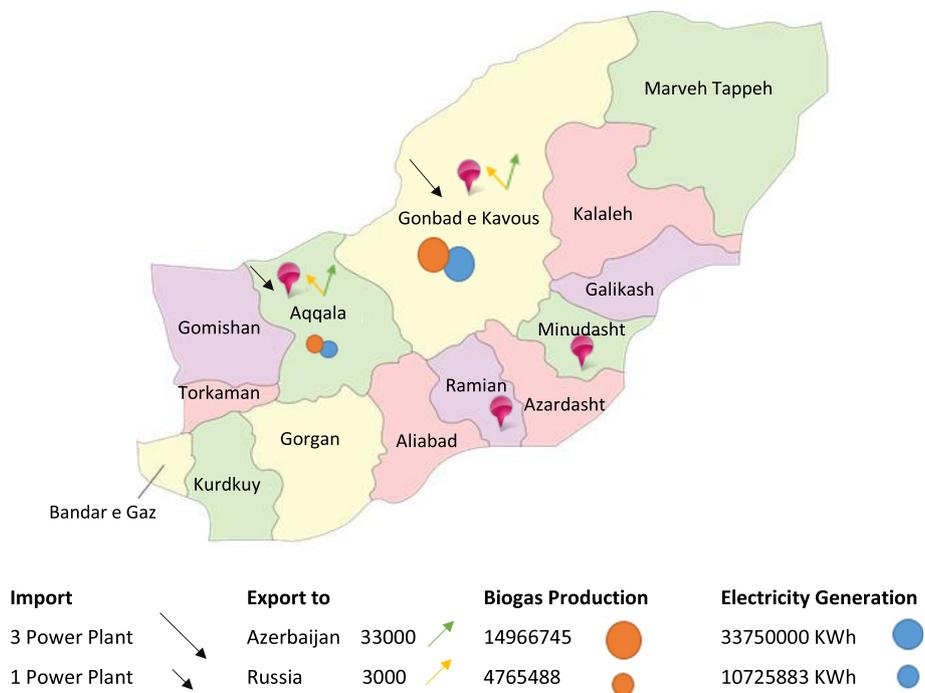
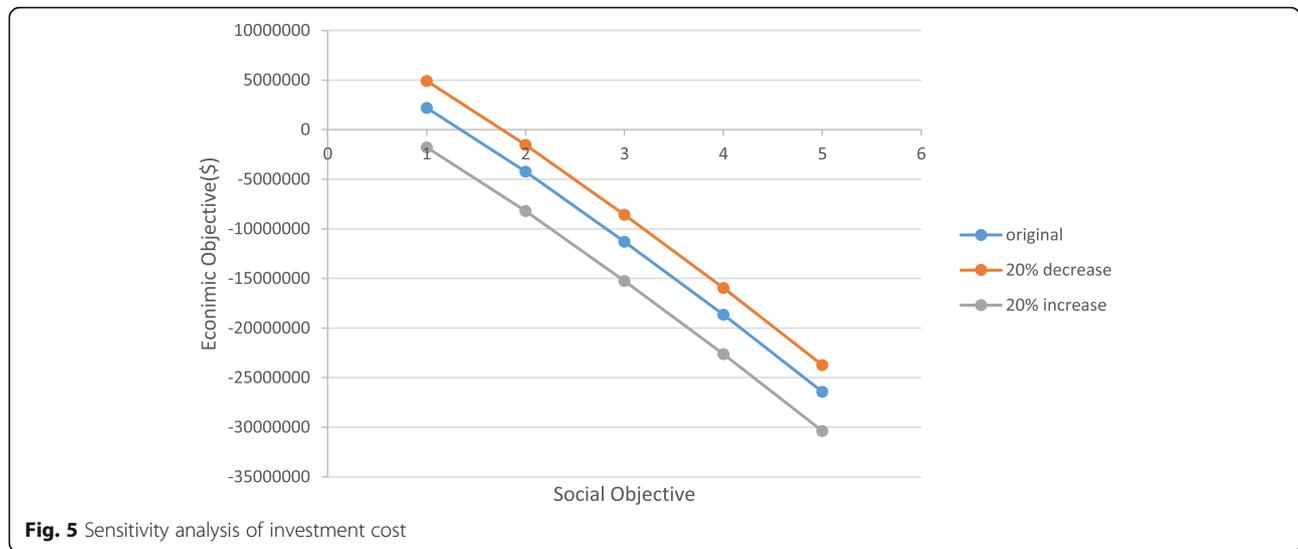


Fig. 4 Optimal designs of a biomass-bioenergy supply chain, obtained from the model for $\epsilon_2 = 0.599$



destination (i.e., customs duties, and transportation costs). Even though recent increases in the foreign exchange rate in our case study might increase the investment and customs costs of the model, it could be offset or significantly compensated by higher export revenues accordingly. Figure 5 presents the investment costs and the resulting profits for the abovementioned range. As it can be seen, for instance, a 16-percent increase of costs from 2574 to \$ 3000 per kilowatt results in a considerable 233 percent decline in total profit. This, in fact, calls for paying enough attention to finding appropriate sources and prices of power plant capital equipment. The project eventually reaches a break-even point at costs above \$3250.

It is also necessary to examine the effect of a change in other costs, such as purchasing biomass, on profits. Animal wastes and straws are sold in different parts of the country, and their price varies according to different factors such as abundance of the materials in the region, the production of agriculture, and animal husbandry products in that region. Table 5 lists the respective parameters and their ranges. Now, based on the range of parameters, an increase in the cost of purchasing materials by 20% and then a decrease of 20% show its effect on the Pareto chart (Fig. 6).

According to the above discussions, the following management decisions are concluded:

Table 5 Fluctuation range of biomass purchasing costs

Extent	Cost per ton (– \$)	Parameter
– 10–18	14	Cow feces
– 21–30	28	poultry feces
– 66–100	93	Straw

- Due to high foreign exchange rates, imports do not seem to be profitable. As there are a variety of local companies manufacturing digestion equipment, with significant differences in operating approaches that result in different equipment prices, it is necessary to choose capable exporters with due care.
- In spite of difficulties in the imports of capital equipment due to high exchange rates, there is still a significant advantage for domestic production using anaerobic processes. While the price of domestic fertilizer is 0.075\$ per kilo on local markets, it is sold for \$1 on world markets, namely, 12 times more expensive. Therefore, exporting fertilizers results in significant profits.

Conclusions

A definite supply chain model to convert biomass to energy through an anaerobic digestion process is developed, with the following implications:

In today’s global economy, the environmental considerations of greenhouse gas emission have become a challenging issue in energy supply chains. That is why renewable energies are the focus of attention for industry and research centers as an appropriate energy source to secure green supply chains. Besides, due to fast population growth and high urbanization rates, waste management is recognized as a major environmental challenge as well. It is therefore necessary to design an appropriate network for waste management systems, both in urban and rural areas. By using anaerobic digestion, in addition to environmental protection from contaminated wastes, it can produce biogas and richer fertilizers.

Therefore, in this study, a deterministic design model of the biomass to bioenergy supply chain is presented using the anaerobic digestion process. The important

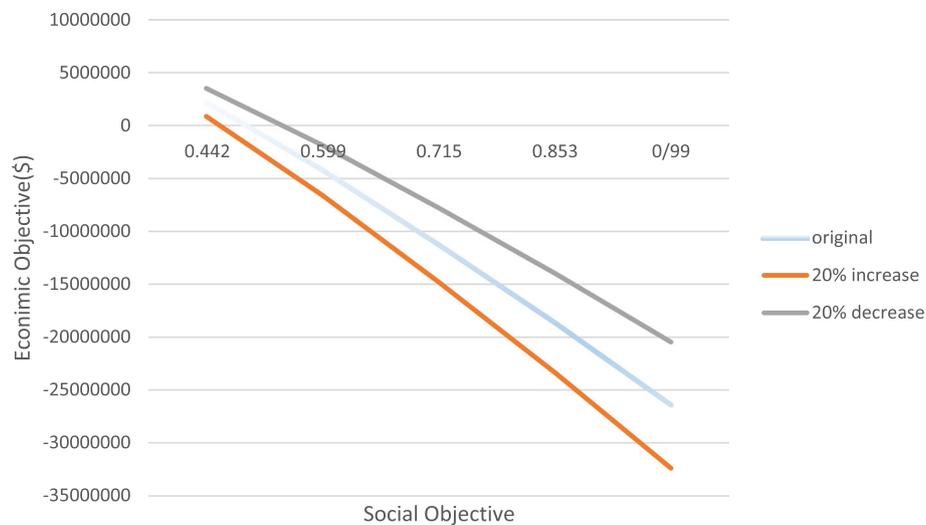


Fig. 6 Sensitivity analysis of biomass purchasing cost

point in this study is the supply of all primary sources of the bioenergy supply chain from only biowaste sources. Due to the rapid growth of globalization, recognition of the international commercial terms and consideration of them in international logistics models are essential for further profits. This renewable energy source is one of the most suitable options for cutting or reducing energy dependence on fossil fuels, which has been developed and implemented economically. In addition, the construction of these power plants from a social perspective can also have many benefits, such as job creation and aid for economic development and desertification.

In a nutshell, the main contributions of this work are (1) designing a bioenergy network for conversion of the second generation of biomass to bioenergy through an anaerobic digestion process, which is the very most efficient and sustainable method to develop rural and other remote areas. (2) Studying the social aspects of a sustainable supply chain design by means of defining sustainable criteria according to the GSLCAP technique. (3) Elaborating a mathematical model for an animal and agricultural waste-to-biofuel supply chain design. (4) Applying incoterms and foreign exchange rates to deal with an international supply chain which consists of importing anaerobic digestion technologies from external suppliers and exporting the final product, fertilizer, to external distribution centers. (5) Validating the developed model through a real case study.

For further research, considering the continued growth of the population and the rise in consumerism and the consequent increasing production of solid municipal waste, the use of these wastes as a source of energy supply requires a more serious study. In addition, the analysis of other environmental, technical, and social

dimensions of similar models might help to render better decisions in this regard. Uncertainty is inevitable in many of the parameters of the model [35], which is also recommended. Upscaling of biogas plants is not a linear function and, on the other hand, in reliable reports, usually, the generation cost per kilowatt of electricity is given. Due to confidentiality issues, more detailed information is not possible to be presented, which is hence the main challenging limitation of this work.

Abbreviations

GSLCAP: Guidelines for Social Life Cycle Assessment of the Product; CHP: Combined heat and power; BSCN: Bioenergy Supply Chain Network; C/N: Ratio of carbon-to-nitrogen ratio; CIF: Cost, insurance, and freight; FOB: Free on Board

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Authors' contributions

MB and HS conceived the proposed idea, developed the model, and carried out the computations. The interpretation of the results is given by MB and SM. All authors provided significant feedback and support to shape the work, the results, and the overall manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The main datasets on which the results of the manuscript based are presented in the main paper.

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Consent for publication

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