Designing a Sustainable Biofuel Supply Chain by Considering Carbon Policies: A Case Study in Iran

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Designing a sustainable biofuel supply chain by considering carbon policies: A case study in Iran

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Abstract

Background: Population growth and increasing the utilization of fossil fuels have increased carbon emissions and the global warming phenomenon with detrimental impacts on the human life and the environment. Therefore, finding a sustainable substitution for fossil fuels becomes a great challenge for all societies from all over the world. Renewable energies such as biofuels are the appropriate alternative to decrease environmental concerns.

Methods: This study develops a multi-objective multi-period multi-echelon biofuel supply chain (BSC) from switch grass regarding economic, environmental and social aspects of the sustainability. For considering the environmental aspect, four carbon policies are taken into account; namely the carbon cap, the carbon tax, the carbon trade and the carbon offset. The fuzzy interactive programming method is implemented to solve the multi-objective model and the fuzzy best-worst method (FMWM) is applied for weighting social objective components.

Results: To illustrate the applicability of the model, an actual case study in Iran is considered. It is revealed that different solutions are obtained for the location of switch grass resources, preprocessing centers, and bio-refineries under different carbon policies. Numerical results also demonstrate that biofuel production and transportation activities have a great share in carbon emissions and BSC costs. Applying the carbon cap policy in the proposed case study decreases the carbon emission over 14% in comparison to the basic situation. Moreover, implementing the carbon trade policy increases the total BSC profit about 11% in comparison to the basic situation. The carbon offset policy plays a significant role in improving social considerations compared with other policies. Overall, since three aspects of sustainability have appropriate values under the carbon trade policy, it can be concluded that this policy is the most appropriate policy.

Conclusions: The proposed model can aid policy makers and governments to optimize the profitability of the BSC, the carbon emission reduction, and the social consideration, simultaneously.

Keywords: Renewable energy, Biofuel supply chain design, Economic growth, Social consideration, Carbon policies

Background

In recent years, the population growth, the urban development and the industrialization of countries have led to increase the usage of fossil fuels, generate incalculable greenhouse gas emissions and accelerate global warming [1]. It is reported that by continuing on using fossil fuels, their limited resources will be depleted in the next 40-60 years [2]. Nowadays, most of the countries in the world are attempting to find a sustainable substitution for fossil fuels [3]. Renewable energies are the best alternatives for this purpose. Biofuel is one kind of renewable energies that produces from renewable resources and it develops in four generations. The first generation of biofuel is produced from edible products like sugar cane, corn grains and animal fats. The second generation uses nonedible products like agricultural residual, switch grass and biomass. The third generation mostly uses algae to produce biofuels, and the fourth generation concentrates on using materials with less carbon emissions [4-6]. The first generation has been mostly used, because it does not need modern and complicated technologies in comparison to other generations, but social problems like food shortage occurs by continuity on producing this generation of biofuel [7, 8]. The second generation handles this problem by using nonedible products. Todays, most populated and developed countries use the second generation of biofuel, because it emits less carbon in comparison to the first generation and protects the society against food shortage problems [9, 10].

The transportation sector has a big share in the fuel consumption, greenhouse gas emissions and the increase in supply chain costs [11-13]. It is reported that in 2012, the ratios of the fuel consumption and carbon emissions of the transportation sector were about 25% [14] and 22% [15], respectively. To maintain the global livable and sustainable, it is necessary to control carbon emissions [16]. Regarding environmental concerns such as the global warming and the climate change, [17-18] governments and legislators are focused on developing different carbon emission policies, including the carbon cap, the carbon tax, the carbon trade and the carbon offset [19]. The carbon cap policy limits the carbon allowance for companies. The carbon tax policy determines a penalty for emitting each unit of carbon. In the context of the carbon trade, a trading market can be established in which companies can sell/ purchase the additional/ shortage amounts of carbon allowance to keep their production activities. Under the carbon offset policy, the companies only can purchase the additional amounts of the carbon allowance to keep their production processes. The proposed policies by different structures must be applied to decrease carbon emissions in supply chains. Recent studies show that these policies have notable impacts on the carbon emission reduction, the environmental improvement and also the economic profitability in supply chains [20].

According to the importance of the sustainable development in last decade [21], all aspects of sustainability must be considered to design an efficient and effective biofuel supply chain (BSC). The most considerable aspect of sustainability of BSCs is the economic aspect, because designing BSCs requires high investment and operating costs [22]. For supporting the biofuel production, the Renewable Fuel Standard (RFS) was established by the US Congress in 2007.

The RFS determined that the amount of produced biofuels will reach 36 billion gallons per year by 2022 and it must include 21 billion gallons of the second generation of biofuels. In addition, only 15 billion gallons of biofuels can be produced from the first generation [23]. Although environmental and social aspects of BSC designs have not received much attention in the literature, some researches showed that countries which implemented nonedible feedstock for producing biofuels, can achieve the economic growth, reduce greenhouse gas emissions, and enhance job opportunities, especially in rural regions [24, 25].

Choosing an appropriate biofuel feedstock is a strategic decision [26]. There are different kinds of biofuel feedstocks, including animal fat, sugarcane, corn grain, forest wood, micro algae and agricultural residual. Switch grass is known as an appropriate and reasonable resource for producing biofuels. It can grow in various soil with different level of nutrient and it needs low water consumption and low production cost. Other benefits of switch grass include decreasing carbon emissions, developing the economic condition of rural regions and obtaining high energy from one unit of it [27, 28].

Regarding the importance of designing the BSC, this study proposes a multi-objective network design for a BSC which produces biofuels from switch grass resources. The model considers all aspects of the sustainable development paradigm, simultaneously. The economic aspect considers the maximization of the total profit. For investigating the environmental aspect of sustainability, the proposed model evaluates the impacts of carbon policies on the economic growth, the social improvement and carbon emissions reduction. These policies include the carbon cap, the carbon tax, the carbon trade and the carbon offset. The social aspect of sustainability considers job opportunities, the regional development, employee's welfare, employee's laid-off and lost days due to occupational accidents. To solve the model, a fuzzy interactive programming method is developed. To determine the appropriate weight for social components, a fuzzy best-worst method (FBWM) is considered. A practical case study is presented to illustrate the efficiency of the proposed model.

This study is structured as follows: The "Literature review" section reviews the literature on BSCs. The "Method" section formulates the multi-objective sustainable BSC model and develops the mathematical model under different carbon policies. The "Case study" section presents a real case study and numerical results. The "Sensitivity analysis" section evaluates the effect of key parameters on the proposed model. Finally the "Conclusions" section presents results and future research outlines.

Literature review

This section reviews the relevant literature in the context of designing and optimizing BSCs. Zamboni et al. [29] developed an optimization bioethanol supply chain from biomass in which the economic and environmental aspects of the sustainability are considered. Their proposed mixed integer linear programming (MILP) model are applied in Italy and the results showed that using biomass can improve the market sales and reduce environmental effects. Corsano et al. [30] presented a sustainable bioethanol supply chain from sugar cane in which the profit of selling bioethanol is maximized. You and Wang [31] designed the BSC from biomass to minimize the total cost and greenhouse gas emissions during installing facilities and operating activities. Then, You et al. [32] developed the model of You and Wang [31] by considering the social aspect of the sustainability in terms of created job opportunities. Azadeh et al. [33] presented a multi-period model for improving BSC profitability in which the facility location, production/distribution system and material flows are considered. Cambero and Sowlati [34] presented a multi-objective BSC in which forest and wood residual are used for producing biofuels. Hombach et al. [10] proposed a mathematical model to design the second-generation BSC by considering greenhouse gas emissions with the objective of maximization of the net present value in Germany. Fattahi and Kannan [35] designed a sustainable multi-echelon BSC from biomass under the uncertainty in order to minimize costs. They considered greenhouse gas emissions and implemented the model in a real case study to show its applicability. Xie and Yongxi [36] developed a multi-echelon BSC under the uncertainty to minimize supply chain costs. They performed the proposed model in South Colombia and observed that producing ethanol is more profitable than other biofuels. Kesharwani et al. [8] considered both centralized and distributed preprocessing centers in a second-generation BSC from corn residual in which minimizing BSC costs and carbon emissions are considered as objectives. Ghosh et al. [37] designed a BSC to concentrate on reducing harmful effects of algal blooms on the water in the nature. Their objectives are minimizing supply chain costs and harmful runoffs during biofuel production activities. Nugroho and Zhu [38] developed a mathematical model for planning and optimizing a BSC by considering economic, environmental and social aspects of sustainability to reduce BSC costs, reduce carbon dioxide emissions and increase the gross domestic product. They showed that producing biodiesel is more proper than ethanol. Haji Esmaeili et al. [39] proposed a first-generation BSC design by considering the financial aspect which maximizes the profit of the bioethanol supply chain.

There are some studies in the literature that applied different carbon policies in the supply chain configuration to consider the environmental aspects of the sustainability. As a first study in the context of carbon policies, Ramudhin et al. [40] proposed an MILP model for designing a supply chain and solve it by the goal programming. Marufuzzaman et al. [41] studied the effect of carbon polices on a biodiesel supply chain. Agrali et al. [42] addressed a mathematical model for a fossil-fired power industry. The proposed model is implemented to choose a preferable policy from several policies, including the carbon capture and storage, the carbon capture and utilization and the carbon trading. It is revealed that the carbon capture and utilization is the more preferable policy. Li et al. [43] introduced a stochastic programming model in product configuration under carbon policies. The experimental analysis illustrates that carbon policies can reduce products configuration costs. Gonela [19] presented an electricity supply chain model under carbon policies. They illustrated that the carbon trade policy can improve economic and environmental aspects of the electricity supply chain. Waqas and Biswajit [44] addressed a sustainable model for the second-generation biofuel by considering the carbon emission tax. The results showed that the considerable amounts of carbon emitted during transportation activities and the notable numbers of jobs are created in rural areas. Li et al. [11] considered different carbon policies for a sustainable coal supply chain design under carbon policies and showed that implementing the carbon trade policy can reduce carbon emissions significantly. He et al. [45] addressed a supply chain network design by considering carbon policies. They concluded that intermediate amounts of carbon cap rather than tighter amounts are more profitable since they can control carbon emissions. Bijarchiyan et al. [46] developed a sustainable BSC network by considering economic and social aspects of sustainability. They showed that the presented model can increase the BSC profit, job creation and economic development through a practical case study. Rezaei et al. [47] presented a scenario-based robust optimization to design a biodiesel supply chain by considering economic and environmental aspects of sustainability.

Most of previous studies in the context of designing the BSC investigate the economic aspect of sustainability. Although some papers consider environmental issues in terms of carbon emissions, carbon-related policies rarely are taken into account. Among these researches, only Waqas and Biswajit [44] evaluated carbon policies in designing the BSC. Moreover, social issues have not received great attention. Thus, this study presents a multi-objective BSC design considering the sustainable development paradigm. To control carbon emissions during BSC activities, different carbon policies are considered. The effects of proposed policies on the BSC profitability and social considerations are also evaluated.

Methods

This paper designs a multi-objective multi-period multi-echelon sustainable BSC for producing biofuel from switch grass regarding carbon policies. Fig.1 shows the proposed BSC structure. As it can be seen, the supply chain consists of switch grass resources, preprocessing centers, bio-refineries and markets. Switch grasses are transported from resources to preprocessing centers. The preprocessed switch grasses are transported to bio-refineries and they are converted to biofuels and finally biofuels are transported to markets to satisfy customers' demand. The most attention in designing the BSC is on pre-processing centers and bio-refineries due to the significant effects of their production and transportation processes on the sustainability of the BSC. Two objective functions are considered in the model. The economic objective function maximizes the BSC profit and the social objective function considers the regional development, job opportunities, employee welfare, employees' laid-off and lost days due to occupational accidents. Also, four carbon policies are considered that include the carbon cap, the carbon tax, the carbon offset and the carbon trade. The effects of these policies are evaluated on the BSC profitability, carbon emissions reduction and social sustainability.

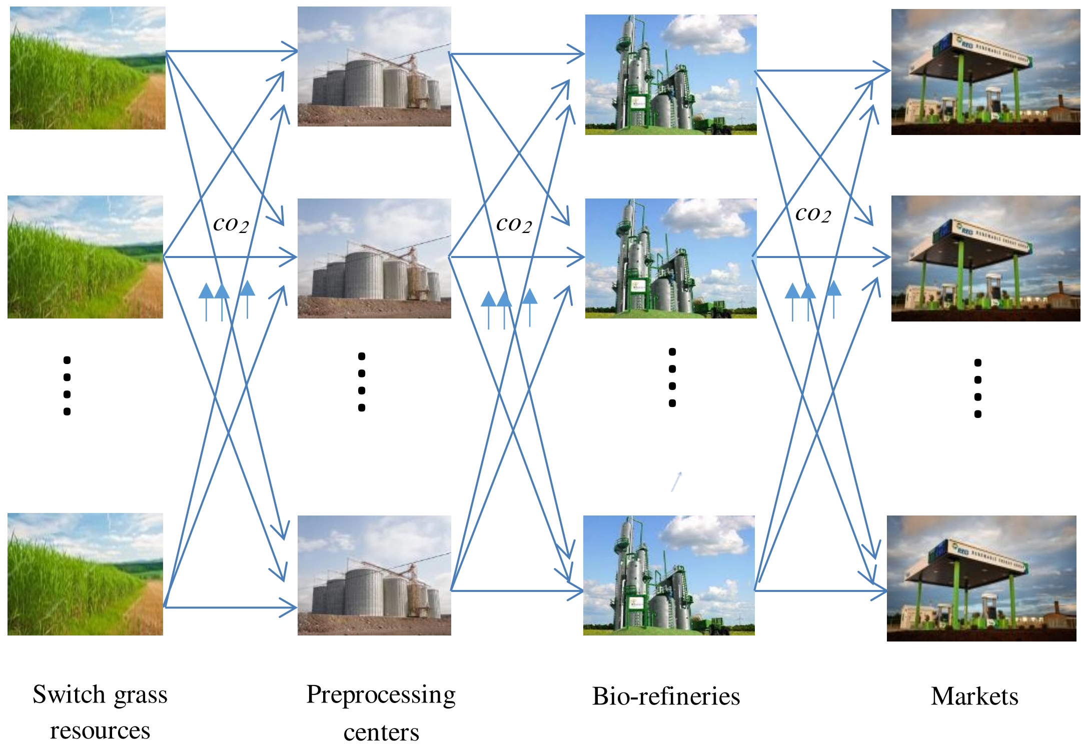


Fig. 1 An illustration of the BSC structure

In the following, sets, parameters and decision variables are defined.

Sets	
i	Set of switch grass resources
j	Set of preprocessing centers
k	Set of bio-refineries
m	Set of markets
t	Set of periods
Parameters	
ϑ	Interest rate
S_i	Supply capacity of resource i (Ton)
R_{kt}	Revenue of bio-refinery k in period t (Rial per Gallon)
F_{jt}	Fixed installation cost of preprocessing center j in period t (Rial)
α	Conversion rate at preprocessing centers
P_j	Capacity of preprocessing center j (Ton)
F_{kt}	Fixed installation cost of bio-refinery k in period t (Rial)
β	Conversion rate at bio-refineries
P_k	Capacity of bio-refinery k (Ton)
D_{mt}	Demand of biofuel in market m in period t (Ton)
C_{it}^{b}	Harvesting, collecting and loading costs of switch grass in resource i in period t (Rial per ton)
C_{it}^{h}	Storage cost of switch grass in resource i in period t (Rial per ton)
C_{ijt}	Transportation cost of switch grass from resource i to preprocessing center j in period t (Rial per ton)
D_{ij}	Distance between resource i and preprocess center j (Km)
E_i	Amounts of carbon emissions during harvesting, collecting and loading of switch grass in resource i (Kg per ton)

E_{ij}	Amounts of carbon emissions during transporting switch grass from resource *i* to preprocessing *j* (Kg per ton).
FC_{jt}	Fixed preprocessing cost in preprocessing center *j* in period *t* (Rial per ton)
VC_{jt}	Variable preprocessing cost in preprocessing center *j* in period *t* (Rial per ton)
E_j	Amounts of carbon emissions during preprocessing switch grass in preprocessing center *j* (Kg per ton)
E_{jk}	Amounts of carbon emissions during transporting preprocessed switch grass from preprocess center *j* to bio-refinery *k* (Kg per ton)
C_{jkt}	Transportation cost of preprocessed switch grass from preprocessing center *j* to bio-refinery *k* in period *t* (Rial per ton)
D_{jk}	Distance between preprocess center *j* and bio-refinery *k* (Km)
FC_{kt}	Fixed operating cost in bio-refinery *k* in period *t* (Rial)
VC_{kt}	Variable operating cost in bio-refinery *k* in period *t* (Rial per ton)
E_k	Amounts of carbon emissions during producing biofuel in bio-refinery *k* (Kg per ton)
E_{km}	Amounts of carbon emissions during transporting biofuels from bio-refinery *k* to market *m* (Kg per ton)
C_{kmt}	Transportation cost of biofuel from bio-refinery *k* to market *m* in period *t* (Rial per Ton)
D_{km}	Distance between bio-refinery *k* and market *m* (Km)
J_j	The number of created job opportunities in preprocessing center *j*
J_{jk}	The number of created job opportunities in transporting preprocessed switch grass from preprocessing center *j* to bio-refinery *k*
J_k	The number of created job opportunities in bio-refinery *k*
J_{km}	The number of created job opportunities in transporting biofuels from bio-refinery *k* to market *m*
L_j	The number of lost days due to occupational accidents in preprocessing center *j*
L_k	The number of lost days due to occupational accidents in bio-refinery *k*
Fr_j	The number of employees' laid-off in preprocessing center *j*
Fr_k	The number of employees' laid-off in bio-refinery *k*
S_{jt}	Employees' job satisfaction in preprocessing center *j* in period *t*
S_{kt}	Employees' job satisfaction in bio-refinery *k* in period *t*
Wa_{jt}	Employees' welfare cost in preprocessing center *j* in period *t* (Rial)
Wa_{kt}	Employees' welfare cost in bio-refinery *k* in period *t* (Rial)
W_1	The weight of work opportunity in the social objective
W_2	The weight of regional development in the social objective
W_3	The weight of employees' welfare in the social objective
W_4	The weight of employees' laid-off in the social objective
W_5	The weight of lost days in the social objective
b_j	Regional development level of preprocessing center *j*
b_k	Regional development level of bio-refinery *k*
va_j	Economic value of installing preprocessing center *j*
va_k	Economic value of installing bio-refinery *k*
C_{1t}^{cap}	Maximum amounts of carbon emissions in switch grass resources in period *t*
C_{2t}^{cap}	Maximum amounts of carbon emissions in preprocessing centers in period *t*
C_{3t}^{cap}	Maximum amounts of carbon emissions in bio-refineries in period *t*
Tx_t	Tax rate on emitting carbon in period *t*
ρ	Carbon selling price (Rial per kg)
Θ	Carbon purchasing price (Rial per kg)
Variables	
Binary variables	
Y_{jt}	1 If preprocessing center *j* is installed,0 otherwise
Y_{kt}	1 If bio-refinery *k* is installed, 0 otherwise
Continuos variables	
X_{ijt}	Amounts of transported switch grass from resource *i* to preprocessing center *j* in period *t* (Ton)
X_{jkt}	Amounts of transported preprocessed switch grass from preprocessing center *j* to bio-refinery *k* in period *t* (Ton)
X_{kmt}	Amounts of transported biofuel from bio-refinery *k* to market *m* in period *t* (Ton)

Model formulation

In the following, the mathematical formulation of the basic model is presented:

$$\begin{aligned} Max\ z_1 = \sum_t \frac{1}{(1+\vartheta)^{t-1}} \Bigg[& \sum_k \sum_t R_{kt} X_{kmt} - \sum_j \sum_t F_{jt} Y_{jt} - \sum_k \sum_t F_{kt} Y_{kt} \\ & - \sum_i \sum_j \sum_t (C_{it}^b + C_{it}^h) X_{ijt} - \sum_i \sum_j \sum_t D_{ij} C_{ijt} X_{ijt} \\ & - \sum_i \sum_j \sum_t (FC_{jt} + VC_{jt}) X_{ijt} - \sum_j \sum_k \sum_t D_{jk} C_{jkt} X_{jkt} \\ & - \sum_j \sum_k \sum_t (FC_{kt} + VC_{kt}) X_{jkt} - \sum_k \sum_m \sum_t D_{km} C_{kmt} X_{kmt} \\ & - \sum_j \sum_t Wa_{jt} Y_{jt} - \sum_k \sum_t Wa_{kt} Y_{kt} \Bigg] \end{aligned} \tag{1}$$

$$\begin{aligned} Max\ z_2 = W_1 & \left(\sum_j \sum_k \sum_t (J_j + J_{jk}) Y_{jt} + \sum_k \sum_m \sum_t (J_k + J_{km}) Y_{kt} \right) \\ & + W_2 \left(\sum_j \sum_t \mathrm{va}_j \,(1 - \mathrm{b}_j) Y_{jt} + \sum_k \sum_t \mathrm{va}_k \,(1 - \mathrm{b}_k) Y_{kt} \right) \\ & + W_3 \left(\sum_j \sum_t S_{jt} Y_{jt} + \sum_k \sum_t S_{kt} Y_{kt} \right) \\ & - W_4 \left(\sum_i \sum_j \sum_t Fr_j Y_{jt} + \sum_j \sum_k \sum_t Fr_k Y_{kt} \right) \\ & - W_5 \left(\sum_j \sum_t L_j Y_{jt} + \sum_k \sum_t L_k Y_{kt} \right) \end{aligned} \tag{2}$$

$s.t.$

$$\sum_j X_{ijt} \le S_i \qquad \forall\, i,t \tag{3}$$

$$\sum_k X_{jkt} \le P_j \qquad \forall\, j,\mathrm{t} \tag{4}$$

$$\sum_m X_{kmt} \le P_k \qquad \forall\, k,t \tag{5}$$

$$\sum_i \alpha X_{ijt} = \sum_k X_{jkt} \qquad \forall\, j,t \tag{6}$$

$$\sum_j \beta X_{jkt} = \sum_m X_{kmt} \qquad \forall\, k,t \tag{7}$$

$$\sum_k X_{kmt} = D_{mt} \qquad \forall\, m,t \tag{8}$$

$$\sum_i X_{ijt} \le M\, Y_{jt} \qquad \forall\, j,t \tag{9}$$

$$\sum_j X_{jkt} \le M\, Y_{kt} \qquad \forall\, k,t \tag{10}$$

$Y_{jt} \geq Y_{jt-1}$ $\quad \forall\, j, t$ (11)

$Y_{kt} \geq Y_{kt-1}$ $\quad \forall\, k, t$ (12)

$X_{ijt}, X_{jkt}, X_{kmt} \geq 0$ $\quad \forall\, i, j, k, t$ (13)

$Y_{jt} \in \{0,1\}$ $\quad \forall\, j, t$ (14)

$Y_{kt} \in \{0,1\}$ $\quad \forall\, k, t$ (15)

Objective function (1) maximizes the profit of selling biofuels. The first term considers the total revenue. The other terms of the first objective include the costs of installation, harvesting, collecting, loading and storage of switch grass, transportation and production. Objective function (2) maximizes job opportunities, the regional development and employee's welfare, and also minimizes the number of employee's laid-off and lost days due to occupational accidents. Constraint (3) ensures that the amount of transported switch grass from each resource to preprocessing centers does not exceed its capacity. Constraints (4) and (5) ensure that amounts of transported switch grass to preprocessing centers and preprocessed switch grass to bio-refineries do not exceed the capacity of preprocessing centers and bio-refineries, respectively. Constraint (6) is considered to balance the amounts of transported switch grass from resources to preprocessing centers and the amounts of preprocessed switch grass to bio-refineries. Constraint (7) specifies the balance between the amounts of the preprocessed switch grass from preprocessing centers to bio-refineries and the amounts of biofuels to markets. Constraint (8) is considered to satisfy market demands. Constraints (9) and (10) indicate that the switch grass and the preprocessed switch grass are transported to installed preprocessing centers and bio-refineries, respectively. Constraints (11) and (12) indicate that each preprocessing center and bio-refinery must be installed in the specific period and remains open in next future periods, respectively. Constraints (13) to (15) determine the type of decision variables.

The extension of the model by considering carbon policies

The proposed model in the previous section is extended under four carbon policies in the following to evaluate the impacts of environmental concerns on the BSC.

The extended model under the carbon cap policy

The carbon cap policy limits the carbon consumption of a company. Under the carbon cap policy, the amount of the carbon consumption for a company is limited to the given value. Therefore, for posing this policy on the BSC, constraints (16) to (18) are added to the proposed model and the following model will be obtained:

$Max\ z_1, Max\ z_3$

$s.t.$ (3)-(15)

$$\sum_i \sum_j \left(E_i + E_{ij}\right) X_{ijt} \leq C_{1t}^{cap} \qquad \forall\, t \qquad (16)$$

$$\sum_j \sum_k \left(E_j + E_{jk}\right) X_{jkt} \leq C_{2t}^{cap} \qquad \forall\, t \qquad (17)$$

$$\sum_{k}\sum_{m}(E_k + E_{km})X_{kmt} \leq C_{3t}^{cap} \qquad \forall\, t \qquad (18)$$

Constraint (16) denotes that the carbon emissions of switch grass resource activities are limited. These activities include harvesting, collecting, loading, storage and transportation of switch grass. Constraints (17) and (18) impose the maximum permissible amount of carbon emissions for preprocessing and producing activities in the BSC, respectively.

The extended model under the carbon tax policy

In the context of the carbon tax policy, a specific tax is considered for each unit of emitted carbon. Unlike the carbon cap policy, there is no limitation for the released carbon in this policy. The proposed model under this policy will be:

$Max\ z_3$

$$\begin{aligned} Max\ z_1 = \sum_t \frac{1}{(1+\vartheta)^{t-1}} \Bigg[& \sum_k \sum_t R_{kt}\, X_{kmt} - \sum_j \sum_t F_{jt}\, Y_{jt} - \sum_k \sum_t F_{kt}\, Y_{kt} \\ & - \sum_i \sum_j \sum_t \left(C_{it}^{b} + C_{it}^{h}\right) X_{ijt} - \sum_i \sum_j \sum_t D_{ij} C_{ijt}\, X_{ijt} \\ & - \sum_i \sum_j \sum_t \left(FC_{jt} + VC_{jt}\right) X_{ijt} - \sum_j \sum_k \sum_t D_{jk}\, C_{jkt}\, X_{jkt} \\ & - \sum_j \sum_k \sum_t \left(FC_{kt} + VC_{kt}\right) X_{jkt} - \sum_k \sum_m \sum_t D_{km}\, C_{kmt} X_{kmt} \Bigg] \\ & - \sum_i \sum_j \sum_t Tx_t\left(E_i + E_{ij}\right) X_{ijt} - \sum_j \sum_k \sum_t Tx_t\left(E_j + E_{jk}\right) X_{jkt} \\ & - \sum_k \sum_m \sum_t Tx_t\left(E_k + E_{km}\right) X_{kmt} \end{aligned} \qquad (19)$$

$s.t.$ (3)-(15)

The extended model under the carbon trade policy

Under the carbon trade policy, a trading market is established for the carbon consumption. If a company needs more carbon allowance to keep its production activities, it can purchase the amounts of the carbon shortage from companies which have more carbon allowance than the determined cap level. Let ρ be the price of each unit of trading carbon. e_{1t}^{+} and e_{1t}^{-} denote the amounts of the purchased carbon and the sold carbon in switch grass resources, respectively. Let e_{2t}^{+} and e_{2t}^{-} show the amounts of the purchased carbon and the sold carbon in preprocessing centers and e_{3t}^{+} and e_{3t}^{-} demonstrate the amounts of the purchased carbon and the sold carbon in bio-refineries. The proposed model under the carbon trade policy is as follows:

$Max\ z_3$

$$
\begin{aligned}
Max\ z_1 = \sum_t \frac{1}{(1+\vartheta)^{t-1}} \Bigg[& \sum_k \sum_t R_{kt} X_{kmt} - \sum_j \sum_t F_{jt} Y_{jt} - \sum_k \sum_t F_{kt} Y_{kt} \\
& - \sum_i \sum_j \sum_t \left(C_{it}^b + C_{it}^h\right) X_{ijt} - \sum_i \sum_j \sum_t D_{ij} C_{ijt} X_{ijt} \\
& - \sum_i \sum_j \sum_t \left(FC_{jt} + VC_{jt}\right) X_{ijt} - \sum_j \sum_k \sum_t D_{jk} C_{jkt} X_{jkt} \\
& - \sum_j \sum_k \sum_t (FC_{kt} + VC_{kt}) X_{jkt} - \sum_k \sum_m \sum_t D_{km} C_{kmt} X_{kmt} \Bigg] \\
& - \sum_t \rho(e_{1t}^+ - e_{1t}^-) - \sum_t \rho(e_{2t}^+ - e_{2t}^-) - \sum_t \rho(e_{3t}^+ - e_{3t}^-)
\end{aligned} \tag{20}
$$

$s.t.$ (3)-(15)

$$\sum_i \sum_j \left(E_i + E_{ij}\right) X_{ijt} + e_{1t}^- \leq C_{1t}^{cap} + e_{1t}^+ \qquad \forall\, t \tag{21}$$

$$\sum_j \sum_k (E_j + E_{jk}) X_{jkt} + e_{2t}^- \leq C_{2t}^{cap} + e_{2t}^+ \qquad \forall\, t \tag{22}$$

$$\sum_k \sum_m (E_k + E_{km}) X_{kmt} + e_{3t}^- \leq C_{3t}^{cap} + e_{3t}^+ \qquad \forall\, t \tag{23}$$

$$e_{1t}^+ \,.\, e_{1t}^- \,.\, e_{2t}^+ \,.\, e_{2t}^- .\; e_{3t}^+ \,.\, e_{3t}^- \geq 0 \qquad \forall t \tag{24}$$

According to constraints (21) to (23), switch grass resources, preprocessing centers and bio-refineries can purchase the amounts of the carbon shortage or sell the amounts of additional carbon allowance to keep their activities, respectively. Constraint (24) defines the decision variables type.

The extended model under the carbon offset policy

The carbon offset and the carbon trade policies have the same mechanism, but a company cannot sell the additional carbon allowance to other companies under this policy. The model formulation under this policy will be:

$Max\ z_3$

$$
\begin{aligned}
Max\ z_1 = \sum_t \frac{1}{(1+\vartheta)^{t-1}} \Bigg[& \sum_k \sum_t R_{kt} X_{kmt} - \sum_j \sum_t F_{jt} Y_{jt} - \sum_k \sum_t F_{kt} Y_{kt} \\
& - \sum_i \sum_j \sum_t \left(C_{it}^{b} + C_{it}^{h}\right) X_{ijt} - \sum_i \sum_j \sum_t D_{ij} C_{ijt} X_{ijt} \\
& - \sum_i \sum_j \sum_t \left(FC_{jt} + VC_{jt}\right) X_{ijt} - \sum_j \sum_k \sum_t D_{jk} C_{jkt} X_{jkt} \\
& - \sum_j \sum_k \sum_t \left(FC_{kt} + VC_{kt}\right) X_{jkt} - \sum_k \sum_m \sum_t D_{km} C_{kmt} X_{kmt} \Bigg] \\
& - \sum_t \Theta e_{1t}^{+} - \sum_t \Theta e_{2t}^{+} - \sum_t \Theta e_{3t}^{+}
\end{aligned} \tag{25}
$$

$s.t.$ (3)-(15)

$$\sum_i \sum_j \sum_t \left(E_i + E_{ij}\right) X_{ijt} \leq C_{1t}^{cap} + e_{1t}^{+} \qquad \forall t \tag{26}$$

$$\sum_j \sum_k \sum_t \left(E_j + E_{jk}\right) X_{jkt} \leq C_{2t}^{cap} + e_{2t}^{+} \qquad \forall t \tag{27}$$

$$\sum_k \sum_m \sum_t \left(E_k + E_{km}\right) X_{kmt} \leq C_{3t}^{cap} + e_{3t}^{+} \qquad \forall t \tag{28}$$

$$e_{1t}^{+}\ .\ e_{2t}^{+}\ .\ e_{3t}^{+} \geq 0 \qquad \forall t \tag{29}$$

Note that θ shows the price of each unit of the purchased carbon. Constraints (26) to (28) denote that switch grass resources, preprocessing centers and bio-refineries can purchase the shortage amounts of the carbon allowance to keep production activities, respectively. Constraint (29) shows the type of decision variables.

Solution approach

To solve the proposed model, a two-stage solution approach is developed. A fuzzy interactive programming approach is considered to solve the multi-objective model in the first stage. The FBWM is applied to determine the weight of social components in the second stage.

The fuzzy interactive programming approach

Fuzzy approaches have been mostly applied in recent researches for solving multi-objective models [20, 47]. Fuzzy approaches are known as strong approaches due to the ability of determining the satisfaction level of objective functions [48]. According to this capability, decision makers can choose an efficient solution. In this paper, an attractive fuzzy programming approach developed by Torabi and Hassini [48] is applied for solving the presented multi-objective model. This method is described below.

Step 1. Specify positive and negative ideal solutions for each objective as follows:

$$
\begin{aligned}
& Z_1^{PIS} = max\ Z_1\ , Z_1^{NIS} = min\ Z_1 \\
& Z_2^{PIS} = max\ Z_2\ , Z_2^{NIS} = min\ Z_2
\end{aligned} \tag{30}
$$

Step 2. Define a linear membership function for each objective as:

$$\mu_k(z) = \begin{cases} 1 & if\ \ Z_k < Z_k^{PIS} \\ \dfrac{Z_k^{NIS} - Z_k}{Z_k^{NIS} - Z_k^{PIS}} & if\ \ Z_k^{PIS} \le Z_k \le Z_k^{NIS} \\ 0 & if\ \ Z_k > Z_k^{NIS} \end{cases} \tag{31}$$

Step 3. Transform the multi-objective model into a single-objective one according as:

$$\begin{aligned} &\max\ \ Z = \gamma\lambda_0 + (1-\gamma)\sum_k \theta_k \mu_k \\ &s.t. \\ &\lambda_0 \le \mu_k \qquad\qquad k = 1, 2 \\ &v \in F(v) \\ &\gamma \in [0,1] \end{aligned} \tag{32}$$

Note that $F(v)$ shows the feasible region. γ and θ_k denote the coefficient of the compensation and the importance of objective k, respectively. θ_k values are defined by decision makers according to their importance, and also $\sum_k \theta_k = 1$, $\theta_k > 0$. μ_k denotes the satisfaction degree of objective k and $\lambda_0 = min_k\{\mu_k\}$ is the minimum satisfaction degree of objectives.

The fuzzy best-worst method

The best-worst method (BWM) is presented by Rezaei [49] to determine the weight of criteria based on the pairwise comparison. In this method, a decision maker determines the best and the worst criterion and then evaluates the preference of the best criterion over others and other criteria over the worst criterion [49, 50]. According to the uncertainty of real world problems and the ambiguity of decision makers' judgments, Guo and Zhao [51] developed the fuzzy BWM (FBWM). Due to the capability of the FBWM in dealing with the actual situation vague, this method is applied for weighting social objective components. The steps of this method can be presented as follows:

Step 1. Determine a set of related criteria.

Step 2. Specify the best (C_B) and the worst (C_W) criterion by a decision maker.

Step 3. Specify the fuzzy preference of the best criteria over others according to linguistic variables presented in Table 1. The fuzzy best evaluation vector is as $\tilde{A}_B = (\tilde{a}_{B1}, \tilde{a}_{B2}, \dots, \tilde{a}_{Bn})$. Note that $\tilde{a}_{Bj}$ presents the fuzzy preference of the best criterion over criterion j and $\tilde{a}_{BB} = (1,1,1)$.

Step 4. Assign the fuzzy preference of other criteria over the worst criterion, using linguistic variables in Table 1. The fuzzy vector of others to the worst criterion is as $\tilde{A}_W = (\tilde{a}_{1W}, \tilde{a}_{2W}, \dots, \tilde{a}_{nW})$. Note that $\tilde{a}_{jW}$ is the fuzzy preference of criteria j over the worst criterion and $\tilde{a}_{WW} = (1,1,1)$.

Step 5. Compute the optimal fuzzy weights $(\widetilde{W}_1^*, \widetilde{W}_2^*, \ldots, \widetilde{W}_n^*)$.

The fuzzy weights are obtained if the absolute difference of $\left|\frac{\widetilde{W}_B}{\widetilde{W}_j} - \tilde{a}_{Bj}\right|$ and $\left|\frac{\widetilde{W}_j}{\widetilde{W}_W} - \tilde{a}_{jW}\right|$ for all j can be minimized. Note that $\widetilde{W}_B$, $\widetilde{W}_j$ and $\widetilde{W}_W$ are triangle fuzzy numbers. The obtained $\widetilde{W}_j = (l_j^w, m_j^w, u_j^w)$ must be converted to its equivalent crisp value. The FBWM formulation is presented as follows:

$$\begin{aligned}
&\min \max_j \left\{ \left|\frac{\widetilde{W}_B}{\widetilde{W}_j} - \tilde{a}_{Bj}\right|, \left|\frac{\widetilde{W}_j}{\widetilde{W}_W} - \tilde{a}_{jW}\right| \right\} \\
&s.t. \\
&\sum_{j=1}^{n} R(\widetilde{w}_j) = 1 \\
&l_j^w \le m_j^w \le u_j^w \\
&l_j^w \ge 0 \\
&j = 1,2,\ldots,n
\end{aligned} \tag{33}$$

In equation (33), $\widetilde{w}_B = (l_B^w, m_B^w, u_B^w)$, $\widetilde{w}_j = (l_j^w, m_j^w, u_j^w)$, $\widetilde{w}_W = (l_W^w, m_W^w, u_W^w)$, $\tilde{a}_{Bj} = (l_{Bj}, m_{Bj}, u_{Bj})$, $\tilde{a}_{jW} = (l_{jW}, m_{jW}, u_{jW})$.

The above model can be stated as follow:

$$\begin{aligned}
&\min \xi \\
&s.t. \\
&\left|\frac{\widetilde{W}_B}{\widetilde{W}_j} - \tilde{a}_{Bj}\right| \le \xi \\
&\left|\frac{\widetilde{W}_j}{\widetilde{W}_W} - \tilde{a}_{jW}\right| \le \xi \\
&\sum_{j=1}^{n} R(\widetilde{w}_j) = 1 \\
&l_j^w \le m_j^w \le u_j^w \\
&l_j^w \ge 0 \\
&j = 1,2,\ldots,n
\end{aligned} \tag{34}$$

where $\tilde{\xi} = (l^\xi, m^\xi, u^\xi)$. By considering $l^\xi \le m^\xi \le u^\xi$and $\tilde{\xi}^* = (k^*, k^*, k^*), k^* \le l^\xi$, model (34) is reformulated as follows:

$$\begin{aligned}
&\min \xi \\
&s.t. \\
&\left|\frac{(l_B^w, m_B^w, u_B^w)}{(l_j^w, m_j^w, u_j^w)} - (l_{Bj}, m_{Bj}, u_{Bj})\right| \le (k^*, k^*, k^*) \\
&\left|\frac{(l_j^w, m_j^w, u_j^w)}{(l_W^w, m_W^w, u_W^w)} - (l_{jW}, m_{jW}, u_{jW})\right| \le (k^*, k^*, k^*) \\
&\sum_{j=1}^{n} R(\widetilde{w}_j) = 1 \\
&l_j^w \le m_j^w \le u_j^w
\end{aligned}$$

$$l_j^w \geq 0 \tag{35}$$
$$j = 1,2, \ldots, n$$

The optimal fuzzy weights will be obtained by solving the presented model (35). Then equation (36) is used to convert them to the equivalent crisp value.

$$R(\widetilde{w_j}) = \frac{l_j^w + 4m_j^w + u_j^w}{6} \tag{36}$$

Table1 Linguistic variables and the equivalent fuzzy number [51]

Linguistic variables	Membership function
Equally importance (EI)	(1,1,1)
Weakly importance (WI)	(2/3,1,3/2)
Fairly importance (FI)	(3/2,2,5/2)
Very importance (VI)	(5/2,3,7/2)
Absolutely importance (AI)	(7/2,4,9/2)

Results and discussion

Case study description

In this section, the proposed models are applied to a practical case study in Iran. The population growth, environmental concerns and increasing the fossil fuel consumption are the most significant motivation for developing biofuels in Iran [52]. Iran has a great capability for producing different biofuel feedstocks such as corn, sunflower and switch grass [53]. Also it has the potential agricultural zones and the great climatic geography for growing switch grass [54]. As mentioned before, switch grass is a nonedible feedstock. It is known as an appropriate and profitable feedstock for producing biofuel in comparison with edible feedstocks [39]. Therefore, in this study, Iran is selected to illustrate the applicability of presented models. A 4-year planning horizon is considered. Fig. 2 shows a geographic map of Iran.

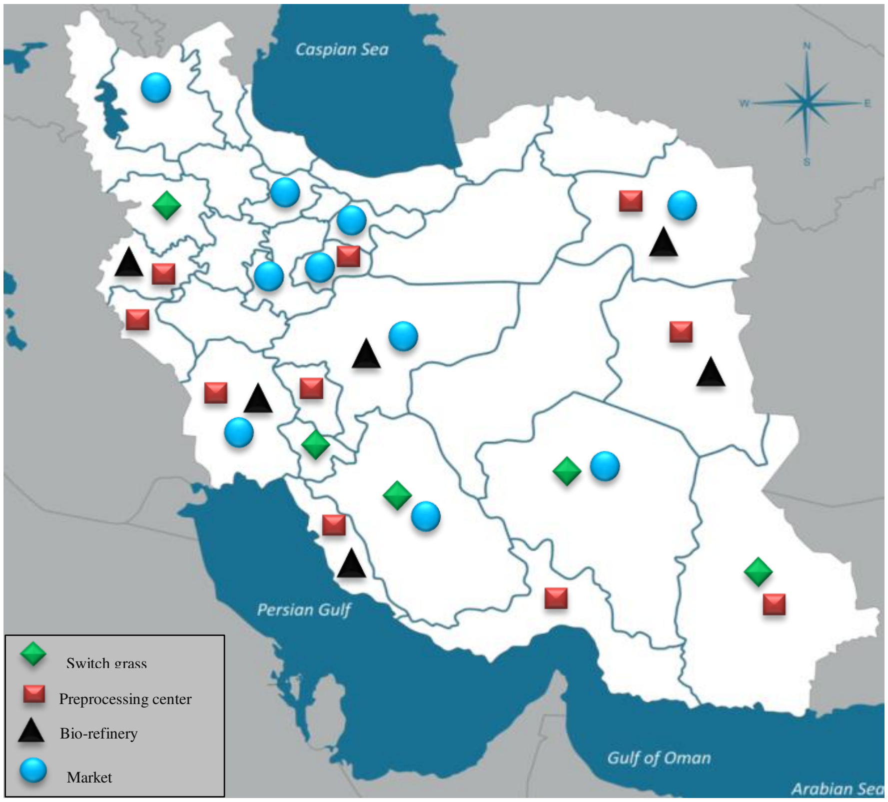


Fig. 2 A geographic map of Iran and potential locations for facilities

As it can be seen, five potential provinces are considered as switch grass resources. Ten and six provinces are selected for installing preprocessing centers and bio-refineries, respectively. Note that these provinces are selected based on geographical and climatic conditions, distances from human societies, communication channels and faults. Ten bigger and the more populated provinces are selected as locations for the biofuel consumption.

Numerical results based on the case study are presented. The proposed models are coded in GAMS 24.1.2 software. All experiments are executed on an Intel Core i5 5200U CPU (2.20 GH) laptop with 4.00 GB of RAM and 64-bit operating system. Table 2 illustrates the range of the case study parameters. Tables 3 and 4 demonstrate the fuzzy preferences of the decision maker for the best social component over other components and other social components over the worst component, respectively. Table 5 gives the optimal weight of social objective components obtained by the FBWM.

Table 2 The range of parameters

Parameter	Range	Parameters	Range	Parameter	Range
ϑ	0.15	C_{jkt}	$[0, 15200]$	Fr_j	$[0.000003, 0.0000053]$
S_i	$[500{,}000, 700{,}000]$	D_{jk}	$[0, 1581]$	Fr_k	$[0.000003, 0.000008]$
R_{kt}	$[76 \times 10^7, 79 \times 10^7]$	FC_{kt}	$[5 \times 10^7, 5.4 \times 10^7]$	S_{jt}	$[50\%, 87\%]$
F_{jt}	$[50 \times 10^9, 72 \times 10^9]$	VC_{kt}	$[2 \times 10^7, 5 \times 10^7]$	S_{kt}	$[57\%, 87\%]$
A	0.45	E_k	$[2055.6, 2065.6]$	Wa_{jt}	$[180000, 206000]$
P_j	$[300{,}000, 400{,}000]$	E_{km}	$[0.2022, 0.2033]$	Wa_{kt}	$[190000, 208000]$
F_{kt}	$[400 \times 10^9, 680 \times 10^9]$	C_{kmt}	$[0, 15200]$	b_j	$[60\%, 90\%]$
B	0.80	D_{km}	$[0, 1754]$	b_k	$[60\%, 85\%]$
P_k	$[300{,}000, 340{,}000]$	J_i	$[0.000898, 0.000899]$	va_j	$[13, 19]$
D_{mt}	$[35000, 70000]$	J_{ij}	$[0.000013, 0.000014]$	va_k	$[14, 19]$
C_{it}^{b}	$[8000000, 12000000]$	J_j	$[0.000042, 0.000053]$	C_{1t}^{cap}	$[52 \times 10^6, 63 \times 10^6]$
C_{it}^{h}	$[500000, 600000]$	J_{jk}	$[0.000010, 0.000012]$	C_{2t}^{cap}	$[80 \times 10^6, 88 \times 10^6]$
C_{ijt}	$[0, 17200]$	J_k	$[0.000043, 0.000053]$	C_{3t}^{cap}	$[12 \times 10^8, 13 \times 10^8]$
D_{ij}	$[0, 1784]$	J_{km}	$[0.000012, 0.000015]$	Tx_t	$[30\%, 35\%]$
E_i	$[3, 4.5]$	L_j	$[22, 27]$	ρ	30000
E_{ij}	$[0.2002, 0.2005]$	L_k	$[17, 22]$	θ	50000
FC_{jt}	$[40000000, 44000000]$	T_{ij}	$[0, 968]$	E_j	$[14.3, 17.2]$
VC_{jt}	$[10000000, 40000000]$	E_{jk}	$[0.2022, 0.2024]$		

Table 3 The fuzzy preference of the best social component over other components

Social components	Work opportunities	Regional development	Employees' welfare	Employees' laid-off	Lost days
Best component (regional development)	(1.5,2,2.5)	(1,1,1)	(3.5,4,4.5)	(2.5,3,3.5)	(2.5,3,3.5)

Table 4 The fuzzy preference of other social components over the worst component

Social components	Worst component (Employees' welfare)
Work opportunities	(1.5,2,2.5)
Regional development	(3.5,4,4.5)
Employees' welfare	(1,1,1)
Employees' laid-off	(0.66,1,1.5)
Lost days	(1.5,2,2.5)

Table 5 The weight of social objective components

Weight	W_1	W_2	W_3	W_4	W_5
Value	0.2394	0.3765	0.1531	0.1243	0.1067

Fig. 3 graphically shows the optimal locations for installing preprocessing centers and bio-refineries from solving the basic model. As it can be seen, three provinces are selected as switch grass resources, namely Kurdistan, Fars and Sistan and Baluchestan. Three preprocessing centers are installed in Kermanshah, Bushehr and Sistan and Baluchestan. Five bio-refineries are located in Kermanshah, Bushehr, Esfahan, Razavi Khorasan and south Khorasan. Table 6 illustrates the numerical results of solving the basic model.

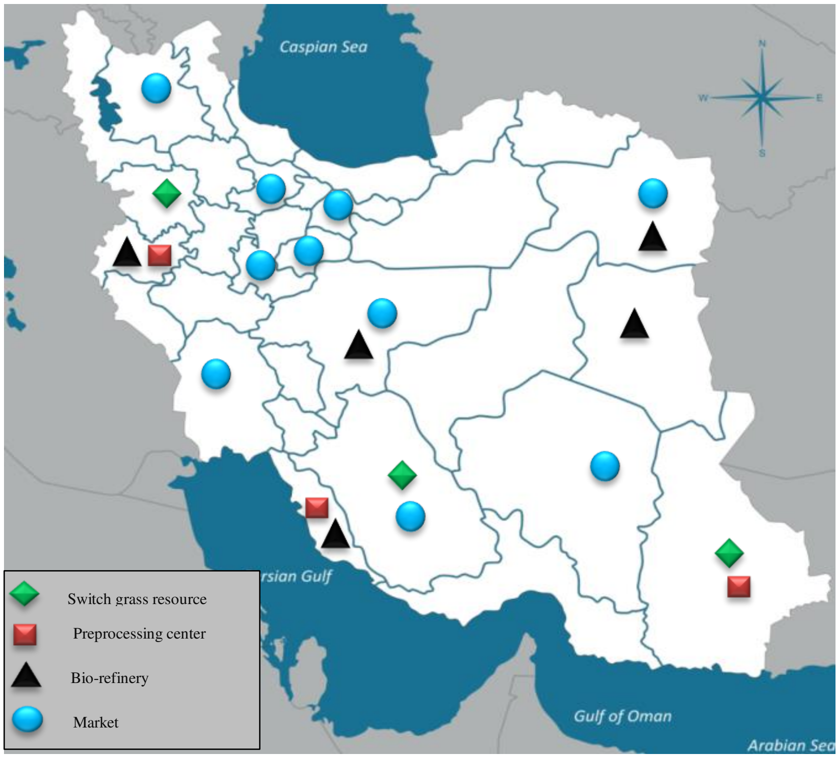


Fig. 3 The optimal design of the basic mode

Table 6 Numerical results of the basic model

μ_1	μ_2	z_1 (Rial)	z_2	Carbon emissions (Kg)
0.860	0.987	1382840000000000	22284.242	1564251000

The amounts of carbon emissions in different BSC sectors of the basic model are shown in Fig. 4. According to this figure, bio-refineries have a great share in the carbon emissions of the entire supply chain. Moreover, 50% of carbon emissions are related to the transportation between different levels of the BSC. In order to decreasing carbon emissions, different carbon policies are considered.

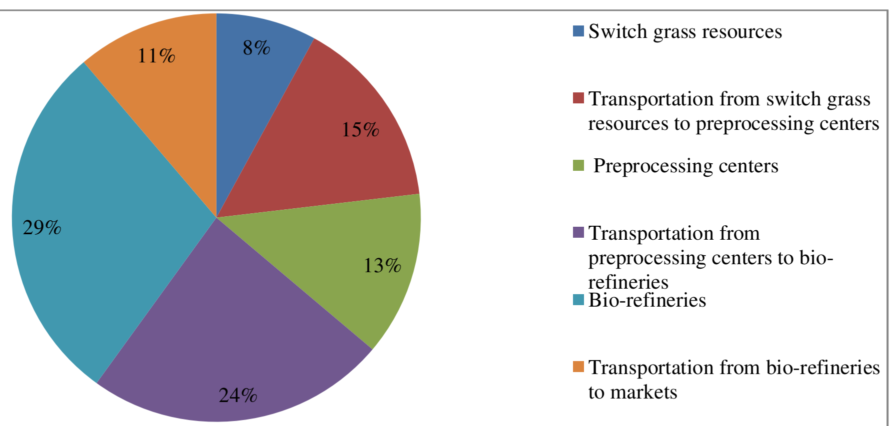


Fig. 4 The total carbon emissions in the basic model

Fig. 5 shows the components of the economic objective. According to this figure, operating activities including harvesting, collecting, preprocessing and producing biofuel have the greatest proportion of the total cost. It is worthy to mention that the higher production cost leads to the higher market price of biofuel. One possible solution for decreasing the total cost of the BSC is to increase the capacity of facilities by implementing advanced technologies.

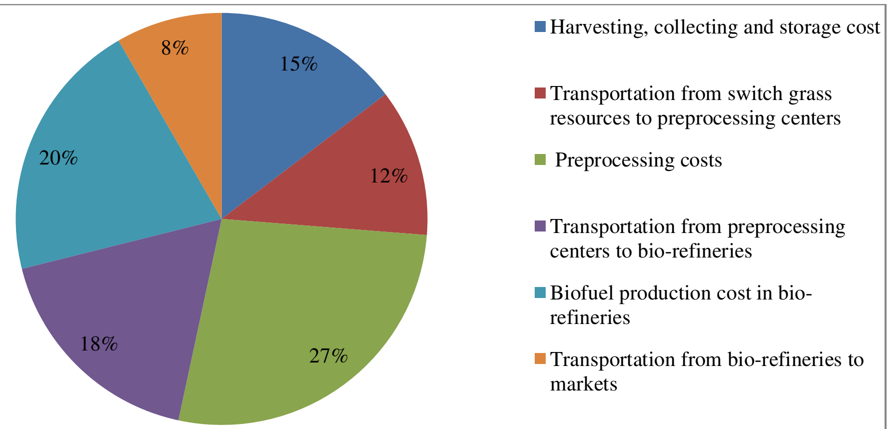


Fig. 5 The components of the economic objective of the basic model

Fig.6 illustrates the components of the social objective. As shown in Fig. 6, a large number of job opportunities is created due to the installation of preprocessing centers and bio-refineries in the basic model. It should be noted that one of the main social concerns in every society is job opportunities, especially in rural regions. This model can improve significantly this requirement of societies.

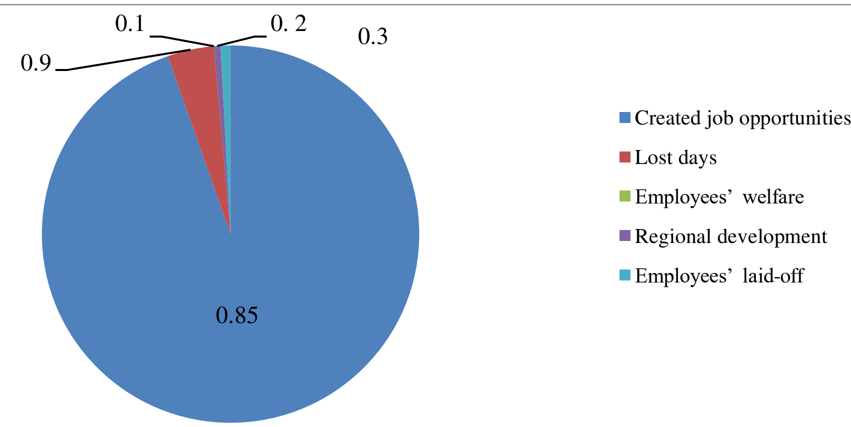
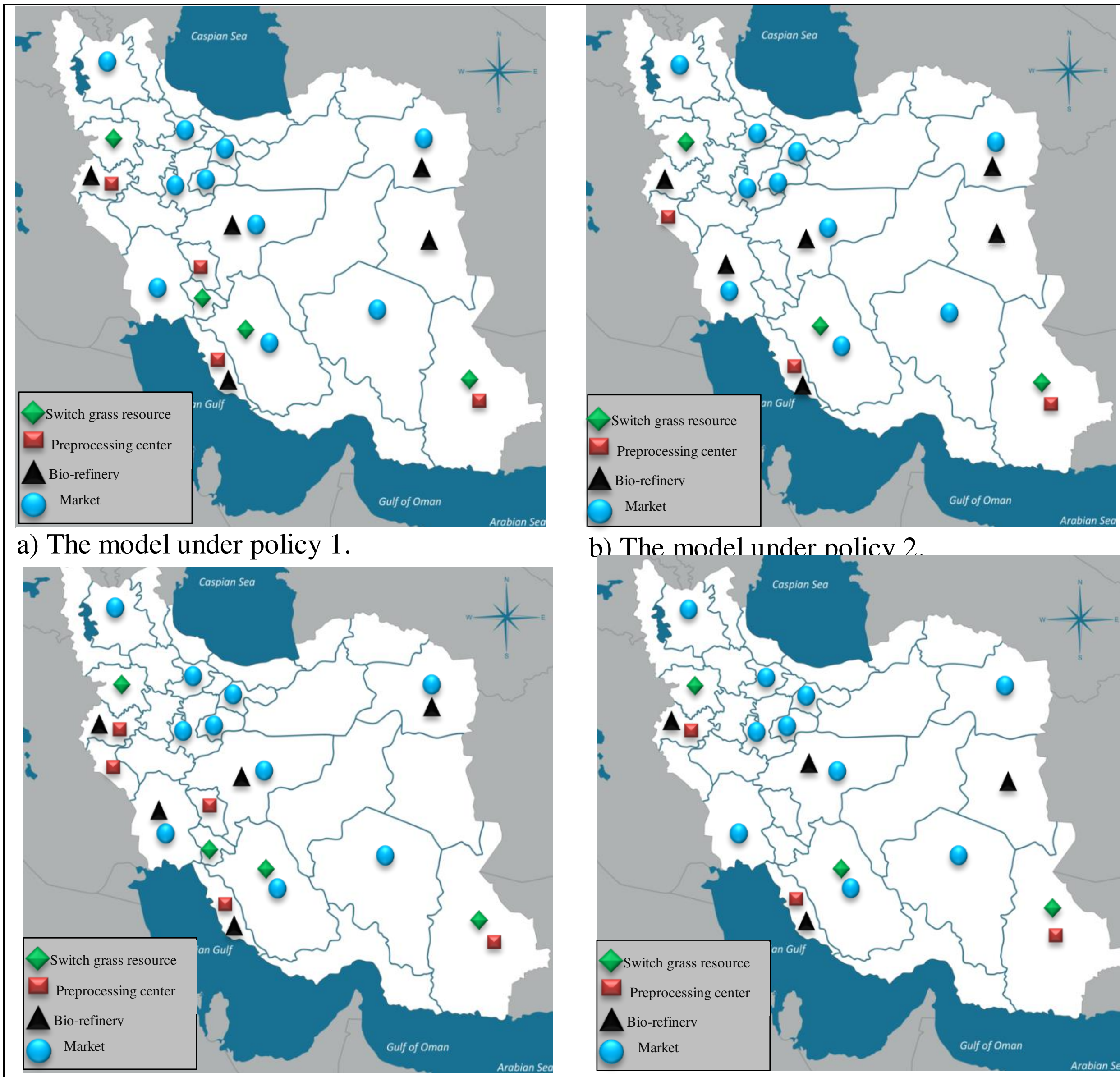


Fig. 6 The social objective components of the basic model

According to the importance of reducing carbon emissions in the BSC, the effects of different carbon policies on the basic model are evaluated. Fig. 7 shows the optimal BSC design under different carbon policies. Note that policy 1 to policy 4 show the carbon cap, the carbon tax, the carbon trade and the carbon offset policy, respectively. It is clear that different solutions are obtained for the location of switch grass resources, preprocessing centers, and bio-refineries. For example, 6 provinces are selected for installing bio-refineries under the carbon tax policy, namely Kermanshah, Esfahan, Bushehr, Khuzestan, Razavi Khorasan and South Khorasan. But 4 provinces are selected for bio-refineries under the carbon offset policy in Kermanshah, Esfahan, Bushehr and South Khorasan.



a) The model under policy 1.

b) The model under policy 2.

c) The model under policy 3.

d) The model under policy 4.

Fig. 7 The optimal design of the BSC under different carbon policies

The optimal results of proposed models are summarized in Table 7. According to this table, among different carbon policies, the carbon trade policy obtains solutions with the highest economic objective value and the carbon offset policy obtains solutions with the highest social objective value. Note that Z shows the objective function of the fuzzy interactive programming method proposed in model (32).

Table 7 Numerical results of objective functions

Model	Z	μ_1	μ_2
Basic	0.880	0.860	0.987
Policy 1	0.836	0.818	0.935
Policy 2	0.895	0.883	0.956
Policy 3	0.948	0.954	0.947
Policy 4	0.883	0.867	0.968

Fig. 8 presents the profit of the BSC under various carbon policies and also the basic model. According to this figure, the BSC under the carbon trade policy gains the highest economic profit. Furthermore, implementing carbon cap policy leads to the least profit because it limits the amounts of carbon allowance for different operational activities.

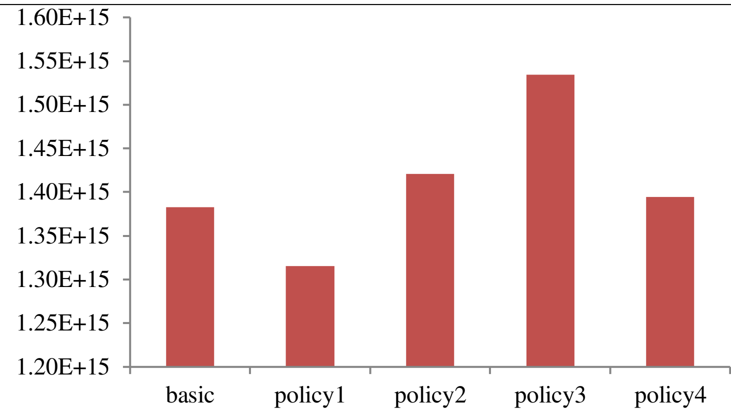


Fig. 8 The economic objective function of different models

The results of the social objective under different carbon policies and the basic model are shown in Fig. 9. It can be concluded that applying carbon policies are not effective for improving the social aspect in this case study. However, the carbon offset policy is the most significant policy in comparison with other policies and the carbon cap policy is the worst one in improving the social considerations.

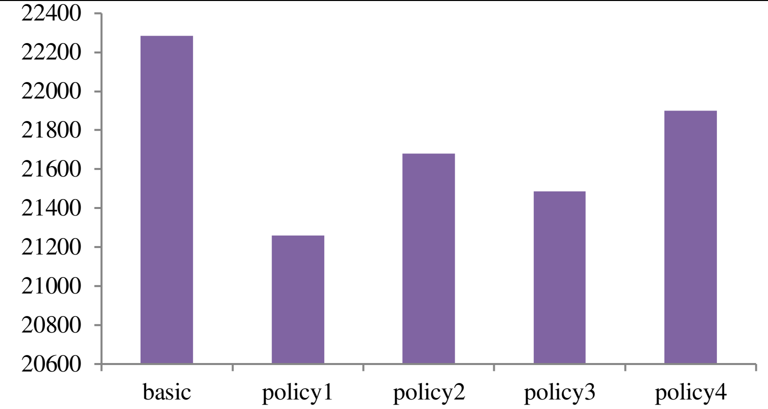


Fig. 9 The social objective function of different models

Fig. 10 shows the total amounts of carbon emissions in the BSC under various carbon policies and the basic model. It is revealed that the BSC under the carbon cap policy has the least amounts of carbon emissions. Moreover, applying carbon cap and carbon trade policies can reduce the carbon emissions of the basic model significantly.

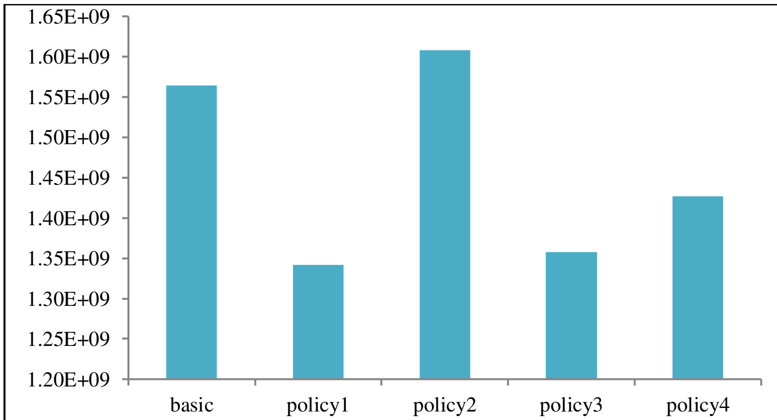


Fig. 10 Total carbon emissions in different models

According to previous results, it can be concluded that implementing carbon policies have significant effects on the supply chain profitability, social factors and carbon emissions reduction. Moreover, the strategic decisions of locating facilities are significantly affected by these policies. Therefore, applying these policies can be the best solution for achieving the sustainable development paradigm in every society, especially in developing countries in which their production is more dependent on fossil fuels.

Sensitivity analysis

In this section, a sensitivity analysis is presented to evaluate the effects of different parameters on economic and social objectives.

Fig.11 represents how the carbon cap affects objective functions. As the amounts of carbon cap increase, the economic value increases unless in the range of 10% variation. However, the social objective does not have a particular trend. Since the increase in the amounts of carbon allowance can lead to the increase in the biofuel production, the economic objective has an increasing trend. Moreover, social factors such as regional development and the number of created job opportunities are not changed more with increasing the biofuel production. Therefore, policy makers must determine the optimal amounts of carbon allowance for enterprises to achieve the economic growth and control the environmental effects of production activities.

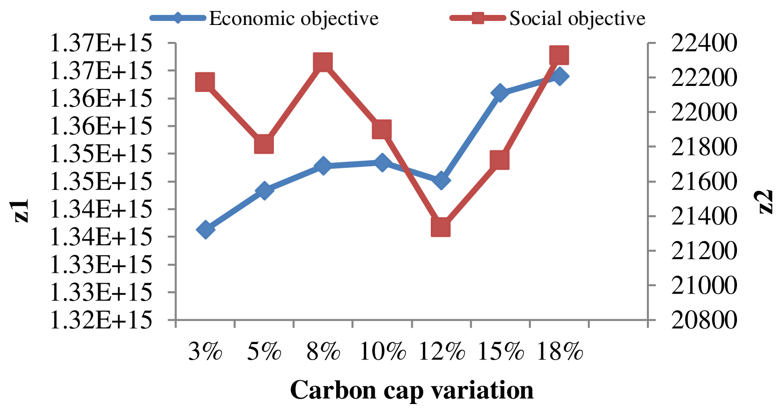


Fig. 11 The effect of the carbon cap on objective functions

Fig. 12 illustrates how objective functions vary with the carbon tax. As the amounts of carbon tax increase, the profit grows while the social objective decreases unless when the amounts of the carbon tax increases 20%. Although the growth of the carbon tax leads to additional costs in the BSC, the biofuel production increases to cancel out this increase. As a result, the profit of the BSC increases due to the selling more biofuels. Moreover, to balance between the cost and the profit, the number of employees decreases and the number of employees' laid-off increases. It can be concluded that when the carbon tax increases, it is essential to increase the biofuel production to achieve more profit.

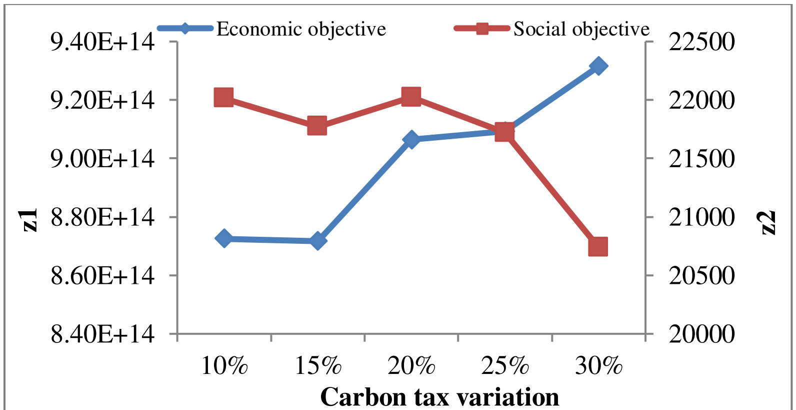


Fig. 12 The effect of the carbon tax on objective functions

Fig. 13 shows that by increasing the amounts of the carbon trade, the BSC profit fluctuates but after point of 10% it starts to increase. The social objective initially decreases and then becomes stable. It can be concluded that BSC facilities have more carbon allowance when the amounts of the carbon trade increase, and as a result, more profit will be obtained by selling more production.

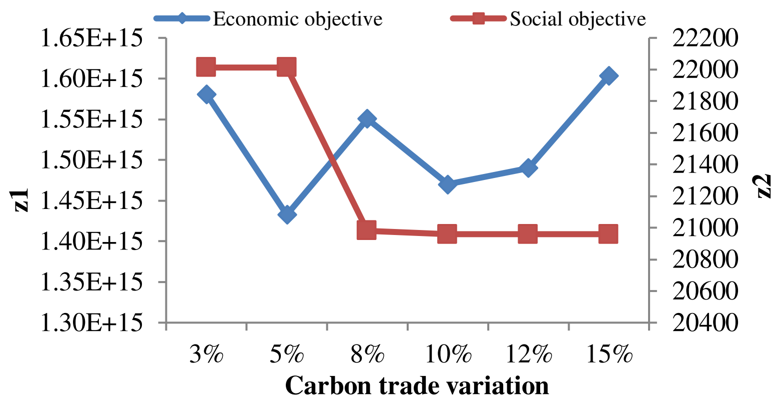


Fig. 13 The effect of the carbon trade on objective functions

Fig. 14 shows that the economic objective fluctuates by increasing the amounts of the carbon offset, but it starts to decrease after point of 12% variation. The social objective initially decreases and then it starts to increase after point of 10%. It can be concluded that by increasing the amounts of the carbon offset, the company's costs increase due to purchasing more carbon allowances, and the profitability decreases after a special point.

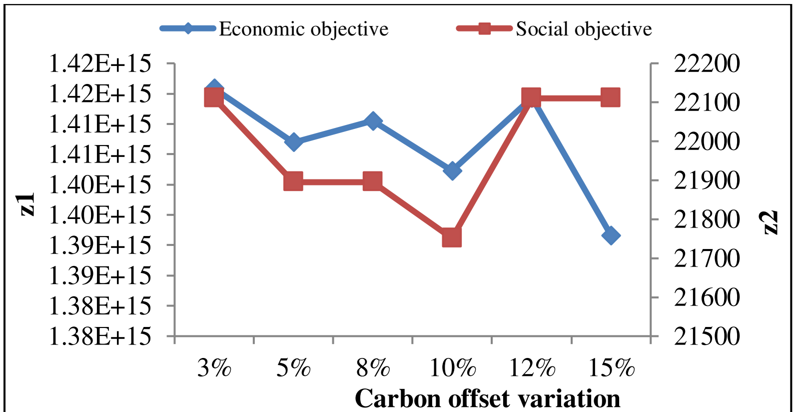


Fig.14 The effect of the carbon offset on objective functions

Conclusions

By emerging the detrimental impacts of fossil fuels and the importance of utilizing renewable energies such as biofuels, this paper develops a sustainable multi-objective multi-period multi-echelon BSC. The supply chain includes switch grass resources, preprocessing centers, bio-refineries and markets. All dimensions of sustainability are considered in this paper, including economic, environmental and social aspects. In the economic aspect, the BSC profit is maximized by considering the revenue and the costs of harvesting, collecting, loading and storage of switch grass, transportation and operating. The social aspect takes into account job opportunities, the regional development, employee's welfare, employee's laid-off, and lost days due to occupational accidents. To consider the environmental aspect, different carbon policies are considered, namely the carbon cap, the carbon tax, the carbon trade and the carbon offset. Finally, a practical case study is applied to demonstrate the performance of the presented model. The results show that the carbon trade policy can lead to more profits. Moreover, the amounts of carbon emissions under this policy are already low. It is necessary to note that the carbon trade policy does not have a notable effect on improving social aspects but it can perform better than the carbon cap policy. Since three aspects of sustainability have appropriate values under the carbon trade policy, policy makers and governments can apply this policy as a good solution to optimize the economic growth, the profitability of the BSC and the carbon emission reduction.

For future research, considering the uncertainty of real world parameters such as the market demand can be a proper direction. Moreover, selecting different feedstocks like sugar cane, corn grain and agricultural residual might be a valuable direction in designing BSCs. Furthermore, implementing different solution approaches for solving the multi-objective model such as meta-heuristic algorithms can be considered as a new contribution for future research.

Abbreviations
BSC: Biofuel Supply Chain; BWM: Best-Worst Method; FMWM: Fuzzy Best-Worst Method; MILP: Mixed Integer Linear Programming

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Authors' contributions
The first author proposed the main idea of this study. All authors proposed models, finding up the required data, carried out computations, analyzed results and approved the final manuscript.

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Availability of data and material
The range of parameters and used material are presented in the proposed paper.

Competing interests
The authors declare that they have no competing interests.

References

1. Asadi E, Habibi F, Nickel S, Sahebi H (2018) A bi-objective stochastic location-inventory-routing model for microalgae-based BSC. Applied energy. 228, 2235-61
2. EIA (2009): World proved reserves of oil and natural gas, most recent estimates
3. Lee K.H (2011) Integrating carbon footprint into supply chain management: the case of Hyundai Motor Company (HMC) in the automobile industry. Journal of cleaner production. 19, 1216-23

4. Apergis N, Payne J.E (2014) Renewable energy, output, CO2 emissions, and fossil fuel prices in Central America: Evidence from a nonlinear panel smooth transition vector error correction model, Energy Economics. 42, 226-32
5. Chisti, Y (2007) Biodiesel from microalgae. Biotechnology advances. 25, 294-306
6. Gray D, White C, Tomlinson G (2007) Increasing security and reducing carbon emissions of the US transportation sector: a transformational role for coal with biomass. National Energy Technology Laboratory.
7. Wang M, Han J, Dunn J.B, Cai H, Elgowainy A (2012) Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use. Environmental research letters. 7, 045905
8. Kesharwani R, Zeyi S, Cihan D, Haoyi X (2019) Moving second generation biofuel manufacturing forward: Investigating economic viability and environmental sustainability considering two strategies for supply chain restructuring. Applied energy. 242, 1467-96
9. Edwards Rachel S, Dixon S, Jian X (2004) Enhancement of the Rayleigh wave signal at surface defects. Physics D: Applied Physics. 3716, 2291.
10. Hombach L.E, Cambero C, Sowlati T, Walther G (2016) Optimal design of supply chains for second generation biofuels incorporating European biofuel regulations. Cleaner production. 133, 565-75
11. Li Y, Kesharwani R, Sun Z, Qin R, Dagli C, Zhang M, Wang D (2019) Economic viability and environmental impact investigation for the BSC using co-fermentation technology. Applied energy. 114235
12. Kesieme U, Pazouki K, Murphy A, Chrysanthou A (2019) Attributional life cycle assessment of biofuels for shipping: Addressing alternative geographical locations and cultivation systems. Environmental management. 235, 96-104
13. Palak G, Ekşioğlu SD, Geunes J (2014) Analyzing the impacts of carbon regulatory mechanisms on supplier and mode selection decisions: An application to a biofuel supply chain. Production Economics. 154,198-216
14. EIA (2013) US Energy Information Administration. Report Number: DOE/EIA-0484
15. Brennan L, Owende P (2010) Biofuels from microalgae a review of technologies for production, processing, and extractions of biofuels and co-products. Renewable and sustainable energy reviews. 142, 557-77
16. Labib S. M, Neema M. N, Rahaman Z, Patwary S. H, Shakil S. H (2018) Carbon dioxide emission and bio-capacity indexing for transportation activities: A methodological development in determining the sustainability of vehicular transportation systems. Environmental management. 223, 57-73
17. Yang B, Wang Y, Qian PY (2016) Sensitivity and correlation of hypervariable regions in 16S r RNA genes in phylogenetic analysis. BMC bioinformatics. 171,135
18. Benjaafar S, Li Y, Daskin M (2012) Carbon footprint and the management of supply chains: Insights from simple models. IEEE transactions on automation science and engineering. 101, 99-116
19. Gonela V (2018) Stochastic optimization of hybrid electricity supply chain considering carbon emission schemes. Sustainable Production and Consumption. 14, 136-151
20. Mohammadi M, Torabi S. A, Tavakkoli-Moghaddam R (2014) Sustainable hub location under mixed uncertainty. Transportation Research Part E: Logistics and Transportation Review. 62, 89-115
21. Buyukozkan G, Yagmur K (2018) Sustainability performance evaluation: Literature review and future directions. Environmental management. 217, 253-267
22. Dansereau L.P, El-Halwagi M, Mansoornejad B, Stuart P (2014) Framework for margins-based planning: Forest bio-refinery case study. Computers & Chemical Engineering 63, 34-50
23. Luo Y, Shelie (2013) M A game theory analysis of market incentives for US switch grass ethanol. Ecological economics. 93, 42-56
24. FPAC (2011) The new face of the Canadian forest industry. Forest Products Association of Canada.
25. Natural Resources Canada (2015) Forest bio economy, bioenergy and bio products. October 27, 2015 2015, doi: http://www.nrcan.gc.ca/forests/industry/
26. Gitinavard H, Shirazi M.A, Zarandi M.H.F (2020) Sustainable feed stocks selection and renewable products allocation: A new hybrid adaptive utility-based consensus model. Environmental Management. 264, 110428

27. McLaughlin S.B, Walsh M.E (1998) Evaluating environmental consequences of producing herbaceous crops for bioenergy. Biomass and Bioenergy. 14, 317-324
28. Khanjarpanah H, Pishvaee M.S, Seyedhosseini S.M (2017) A risk averse cross-efficiency data envelopment analysis model for sustainable switch grass cultivation location optimization. Industrial Crops and Products. 109, 514-522
29. Zamboni A, Fabrizio B, Nilay S (2009) Spatially explicit static model for the strategic design of future bioethanol production systems. 2|. Multi-objective environmental optimization. Energy & Fuels. 23, 5134-43
30. Corsano G, Vecchietti A.R, Montagna J.M (2011) Optimal design for sustainable bioethanol supply chain considering detailed plant performance model. Computers & Chemical Engineering. 35: 1384-98
31. You F, Wang B (2011) Life cycle optimization of biomass-to-liquid supply chains with distributed–centralized processing networks. Industrial & Engineering Chemistry Research. 50, 10102-27
32. You F, Tao L, Graziano D.J, Snyder S.W (2012) Optimal design of sustainable cellulosic biofuel supply chains: multiobjective optimization coupled with life cycle assessment and input–output analysis. AIChE Journal. 584, 1157-1180
33. Azadeh A, Arani H.V, Dashti H (2014) A stochastic programming approach towards optimization of BSC. Energy. 76, 513-25
34. Cambero C, Sowlati T (2016) Incorporating social benefits in multi-objective optimization of forest-based bioenergy and BSCs. Applied energy. 178, 721-35
35. Fattahi M, Kannan G (2018) A multi-echelons stochastic program for the sustainable design of BSC networks under biomass supply uncertainty and disruption risk: A real-life case study. Transportation Research Part E: Logistics and Transportation Review. 118, 534-67
36. Xie F, Yongxi H (2018) A multi-echelons stochastic programming model for a multi-period strategic expansion of BSC under evolving uncertainties. Transportation Research Part E: Logistics and Transportation Review. 111, 130-48
37. Ghosh T, Bakshi B.R (2019) Designing BSCs while mitigating harmful algal blooms with treatment wetlands. Computers & Chemical Engineering. 126, 113-27
38. Nugroho Y. K, Zhu L (2019) Platforms planning and process optimization for biofuels supply chain. Renewable energy. 140 ,563-579
39. Haji Esmaeili S.A, Szmerekovsky J, Sobhani A, Dybing A, Peterson T.O (2020) Sustainable biomass supply chain network design with biomass switching incentives for first-generation bioethanol producers. Energy policy. 111222
40. Ramudhin A, Amin C, Marc P (2010) Carbon market sensitive sustainable supply chain network design. Management Science and Engineering Management. 5.1, 30-38
41. Marufuzzaman M, Sandra D, Eksioglu Y, Eric H (2014) Two-stage stochastic programming supply chain model for biodiesel production via wastewater treatment. Computers & Operations Research 49, 1-17.
42. Ağralı S, Üçtuğ FG, Türkmen BA (2018)An optimization model for carbon capture & storage/utilization vs. carbon trading: A case study of fossil-fired power plants in Turkey. Environmental management. 215,305-315
43. Li X, Dong Y, Mengqi H (2018) A scenario-based stochastic programming approach for the product configuration problem under uncertainties and carbon emission regulations. Transportation Research Part E: Logistics and Transportation Review. 115, 126-46
44. Waqas A, Biswajit S (2018) Impact of carbon emissions in a sustainable supply chain management for a second generation biofuel. Journal of cleaner production. 186, 807-20
45. He L, Zhaoguang X, Niu Z (2014) Joint optimal production planning for complex supply chains constrained by carbon emission abatement policies. Discrete Dynamics in Nature and Society
46. Bijarchiyan M, Sahebi H, Mirzamohammadi S (2020) A sustainable biomass network design model for bioenergy production by anaerobic digestion technology: using agricultural residues and livestock manure. Energy, Sustainability and Society. 10:1-7

47. Rezaei M, Chaharsooghi S.K, Kashan A.H, Babazadeh R. (2020) Optimal design and planning of biodiesel supply chain network: a scenario-based robust optimization approach. International Journal of Energy and Environmental Engineering. 11.1, 111-128
48. Torabi S.A, Hassini E (2008) An interactive possibilistic programming approach for multiple objective supply chain master planning. Fuzzy sets and systems. 159, 193-214
49. Rezaei J (2015) Best-worst multi-criteria decision-making method. Omega. 53, 49-57
50. Omrani H, Alizadeh A, Emrouznejad (2018) A Finding the optimal combination of power plants alternatives: A multi response Taguchi-neural network using TOPSIS and fuzzy best-worst method. Cleaner Production 203, 210-23
51. Guo S, Haoran Zh (2017) Fuzzy best-worst multi-criteria decision-making method and its applications. Knowledge-Based Systems. 121, 23-31
52. Mohseni Sh, Pishvaee M.S (2019) Supply Chain Management Models for the Development of Green Fuel Production from Microalgae in Iran. 189-210
53. Babazadeh R, Ghaderi H, Pishvaee M.S (2019) A benders-local branching algorithm for second-generation biodiesel supply chain network design under epistemic uncertainty. Computers & Chemical Engineering 124, 364-380.
54. Babazadeh R, Razmi J, Rabbani M, Pishvaee M.S (2017) An integrated data envelopment analysis–mathematical programming approach to strategic biodiesel supply chain network design problem. Cleaner Production. 147, 694-707

Figures

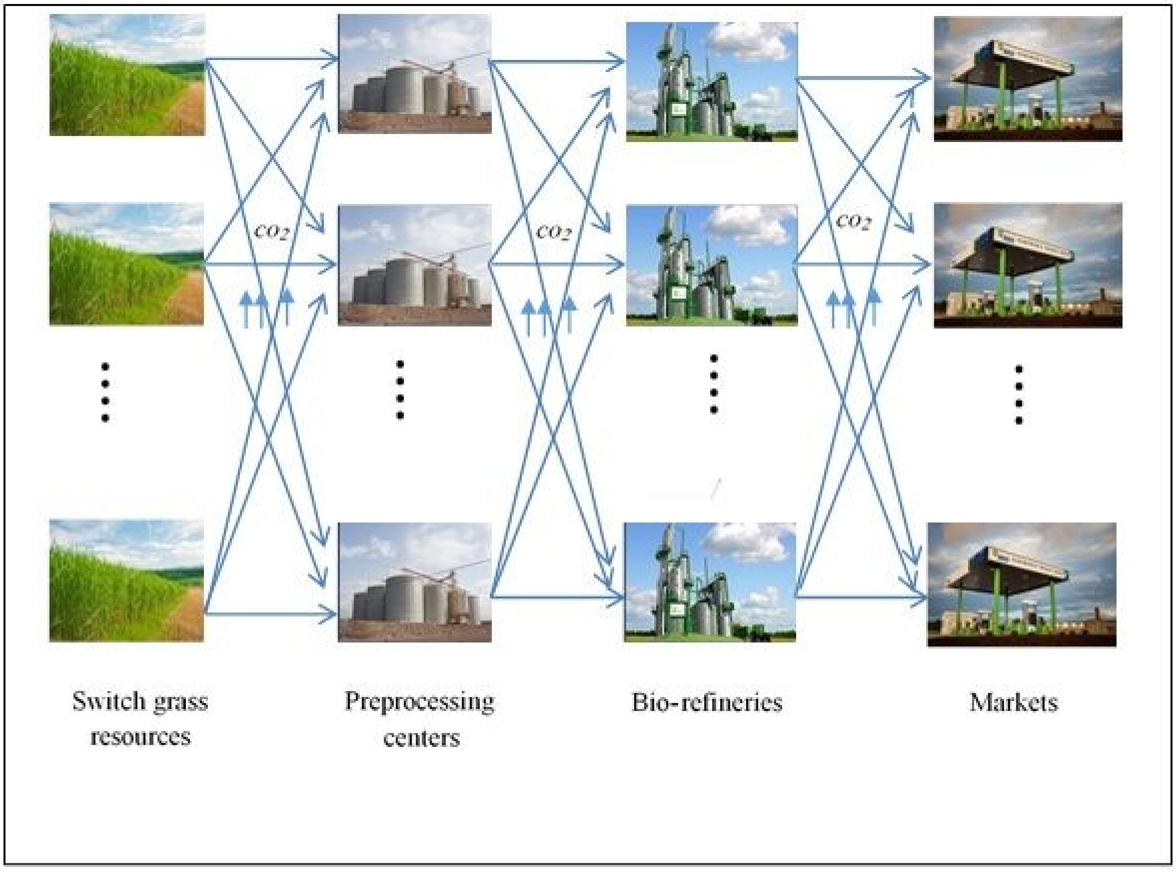

Figure 1

An illustration of the BSC structure

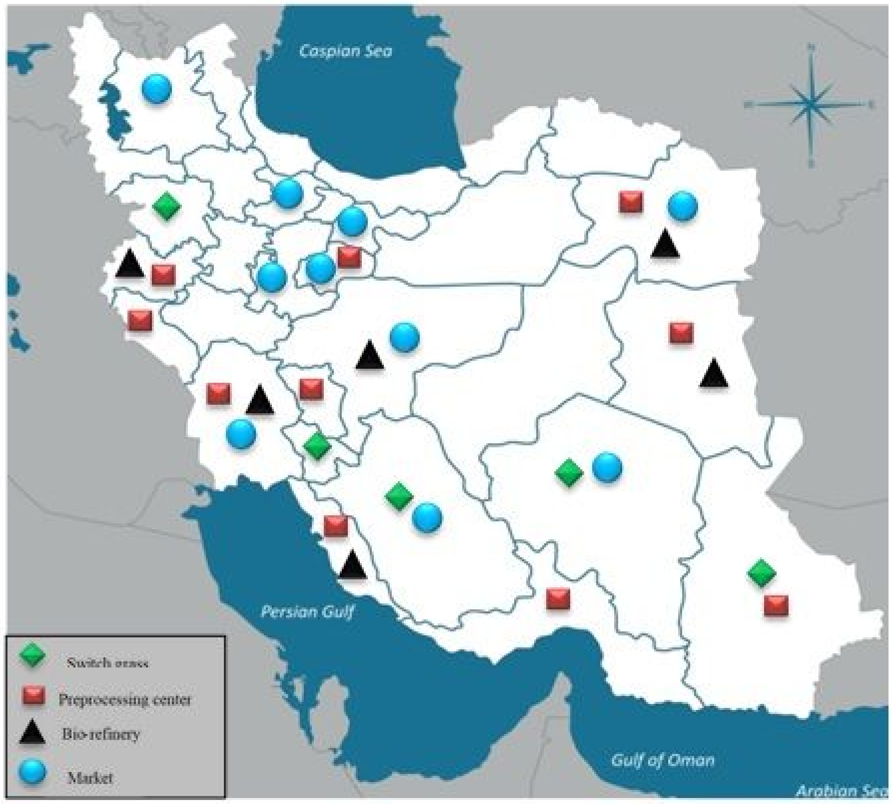

Figure 2

A geographic map of Iran and potential locations for facilities

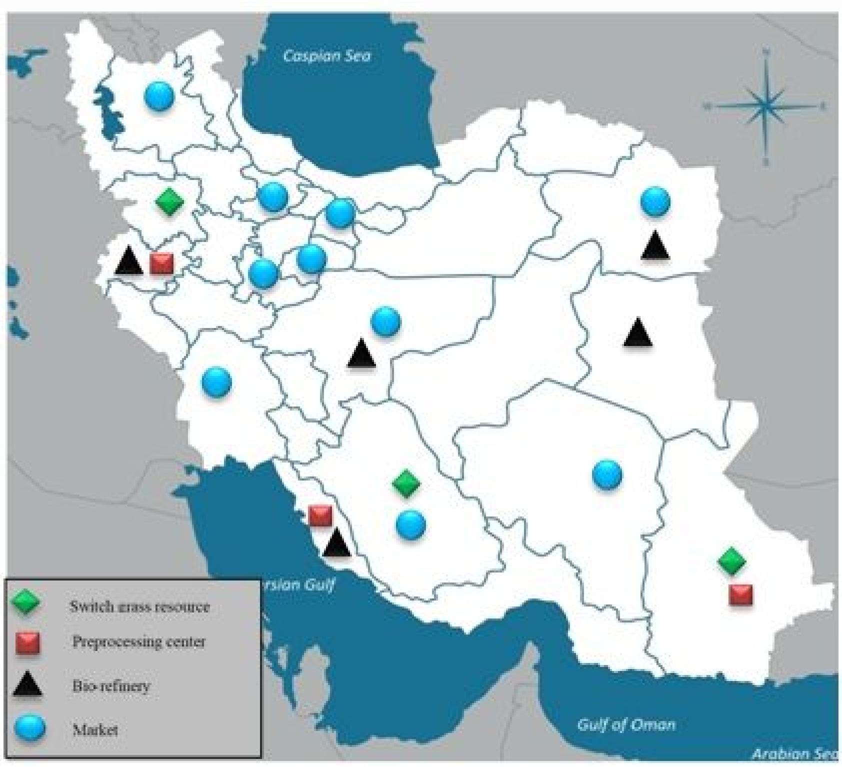

Figure 3

The optimal design of the basic mode

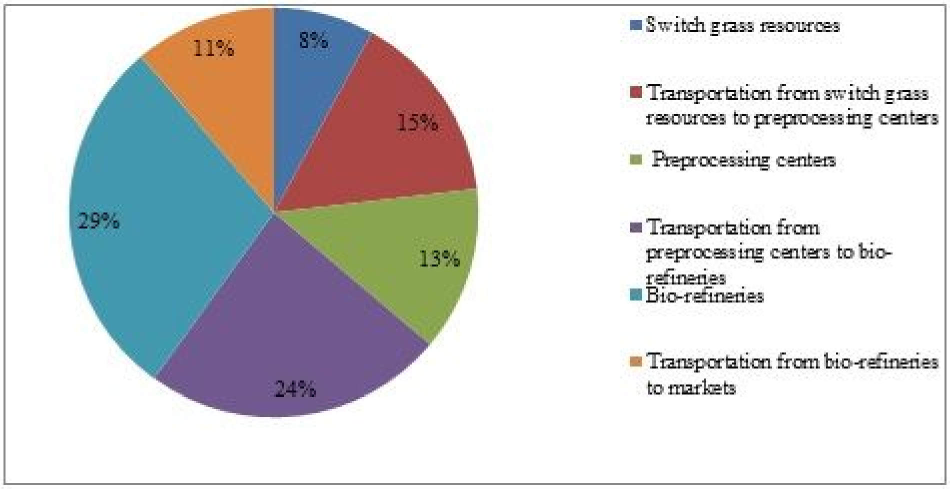

Figure 4

The total carbon emissions in the basic model

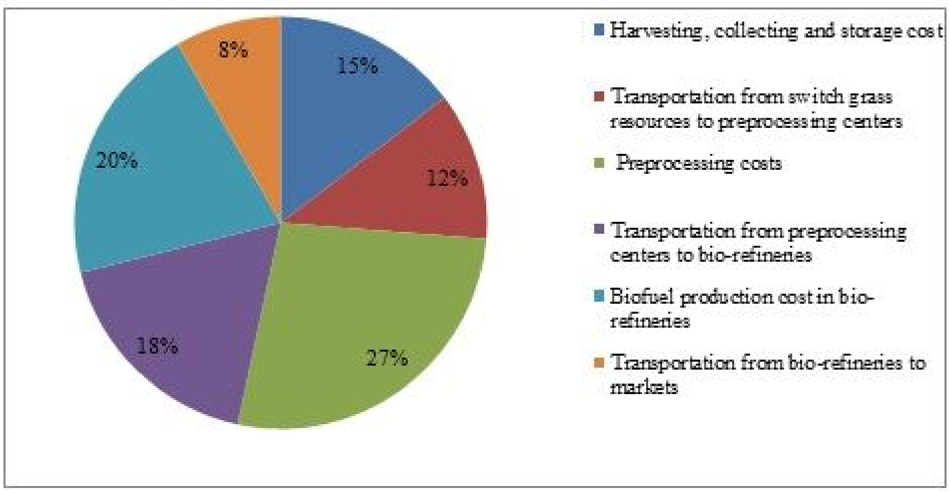

Figure 5

The components of the economic objective of the basic model

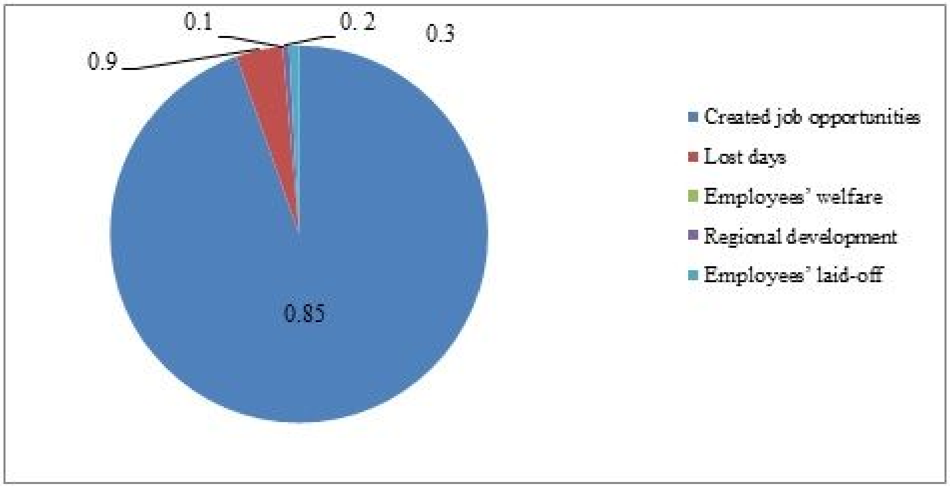

Figure 6

The social objective components of the basic model

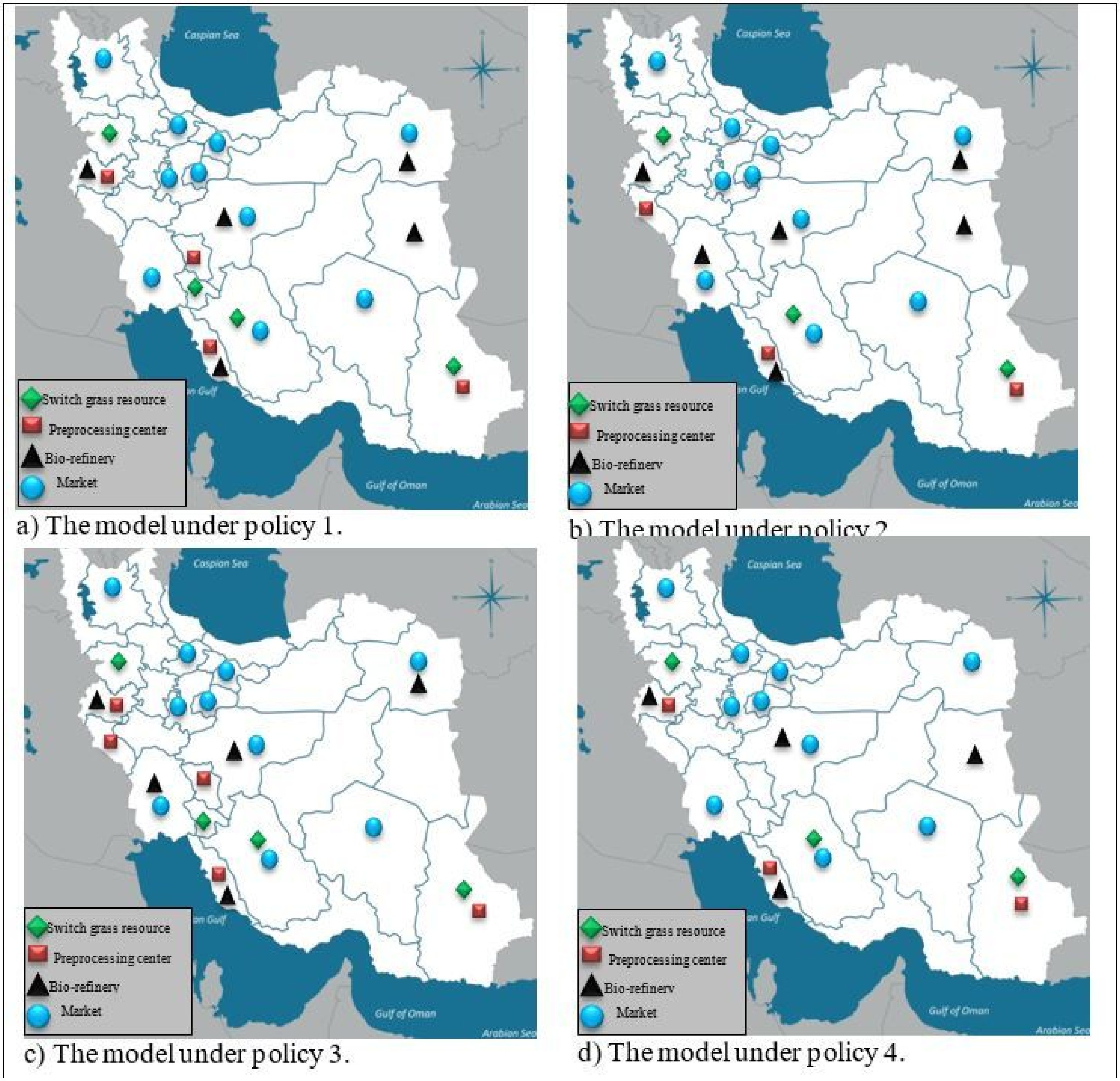

Figure 7

The optimal design of the BSC under different carbon policies

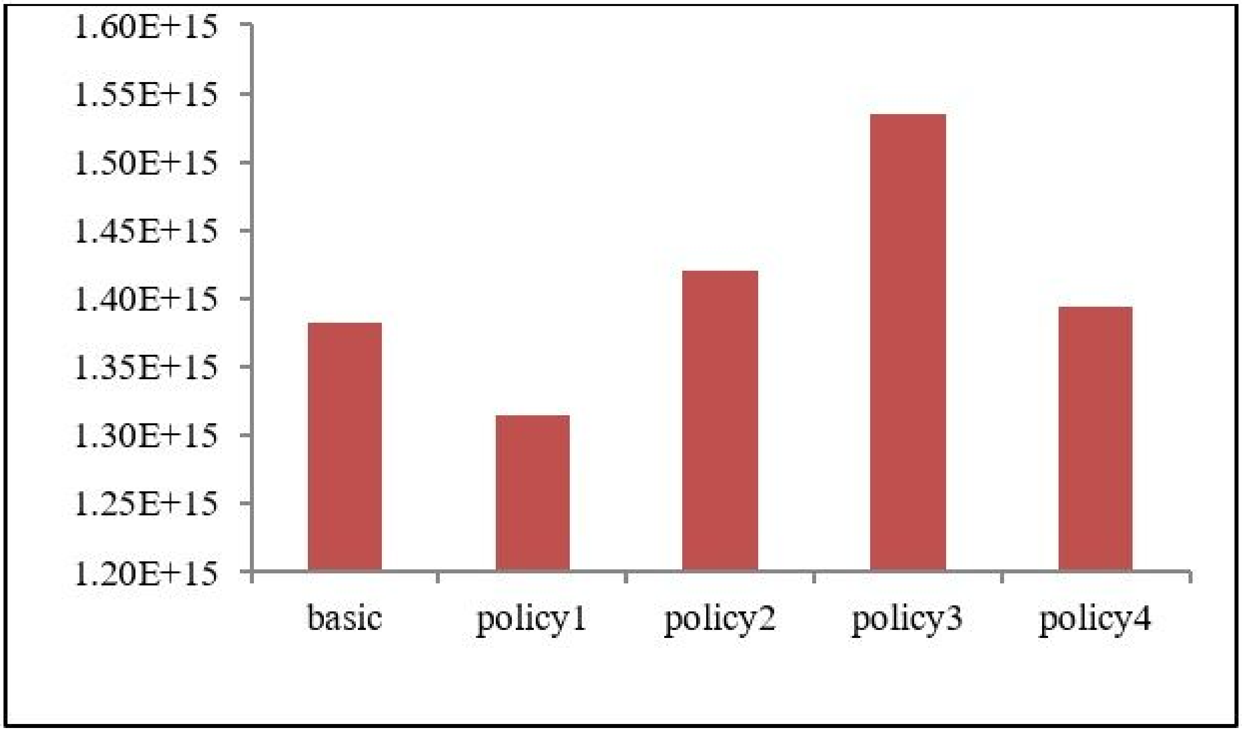

Figure 8

The economic objective function of different models

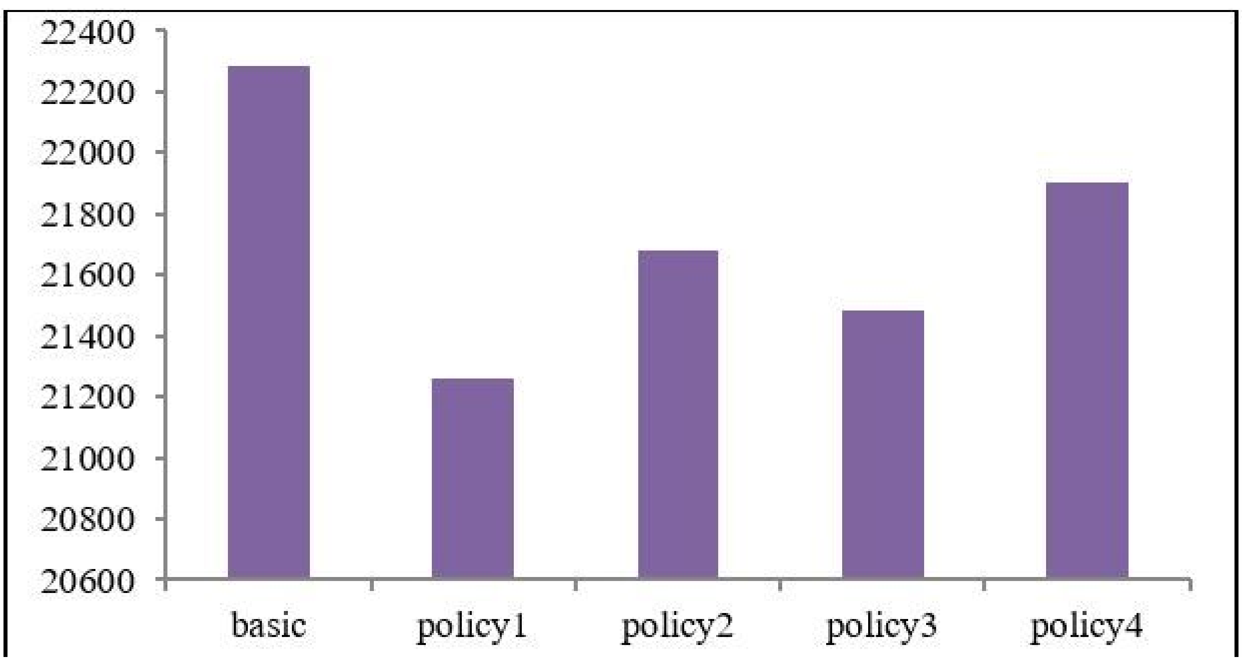

Figure 9

The social objective function of different models

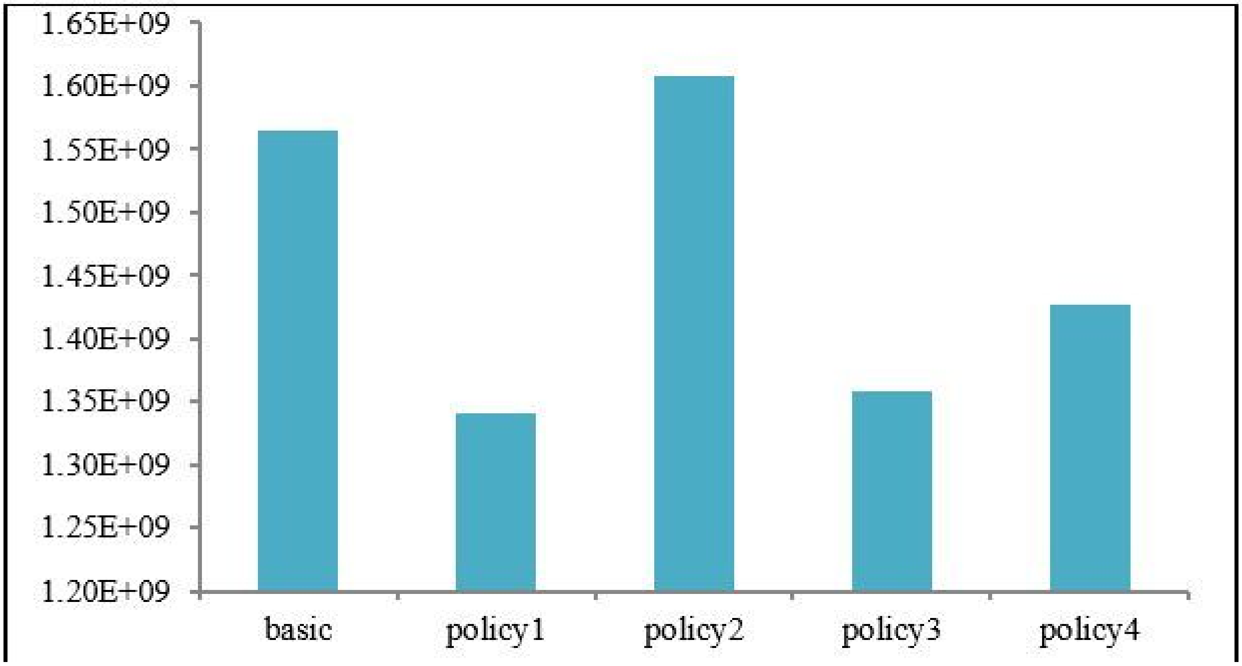

Figure 10

Total carbon emissions in different models

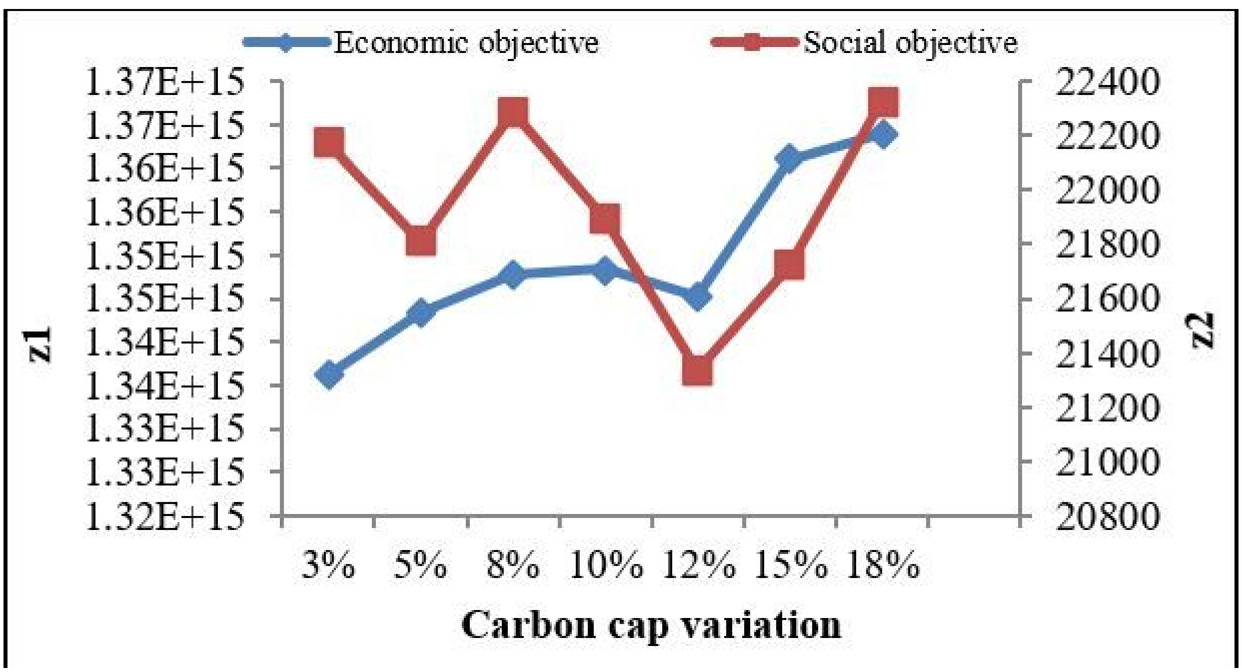

Figure 11

The effect of the carbon cap on objective functions

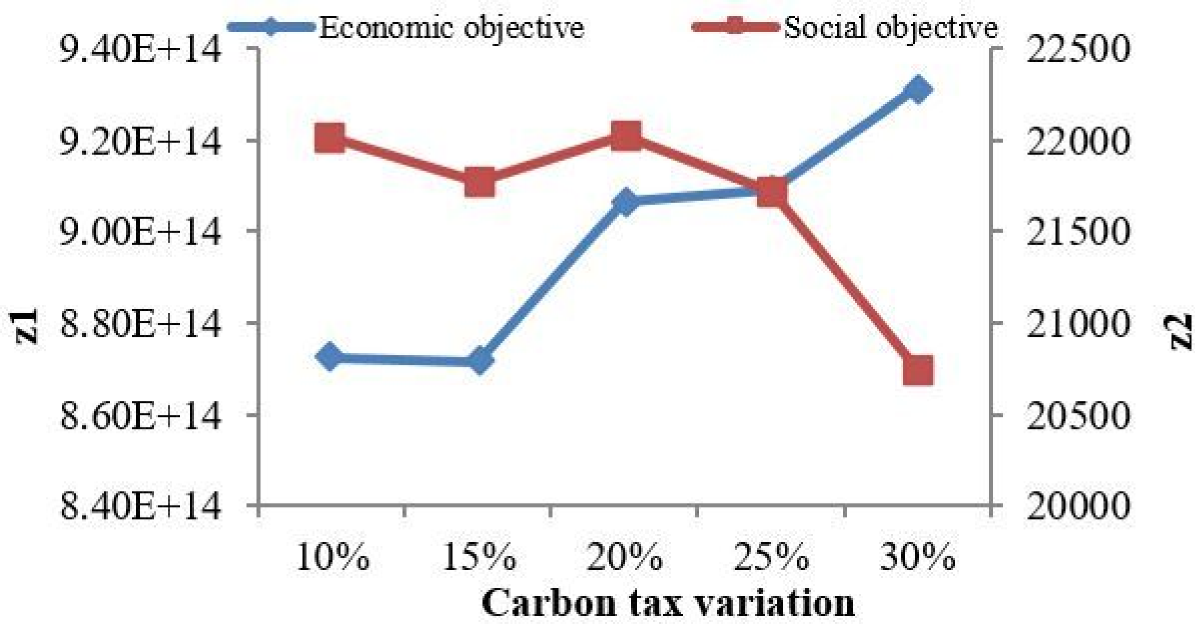

Figure 12

The effect of the carbon tax on objective functions

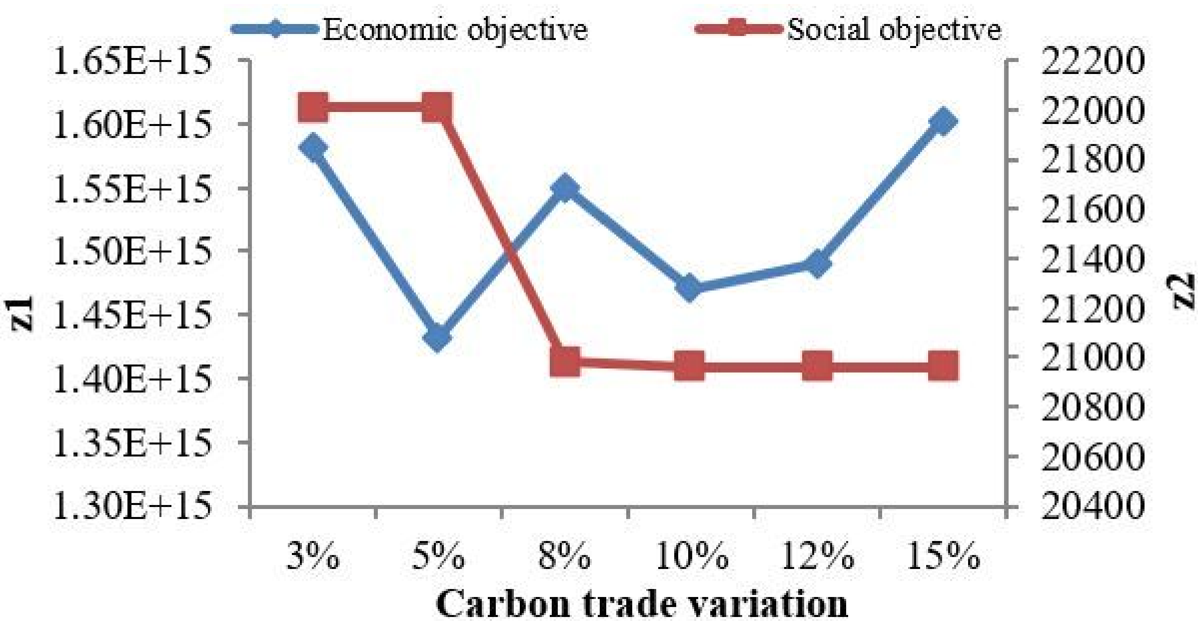

Figure 13

The effect of the carbon trade on objective functions

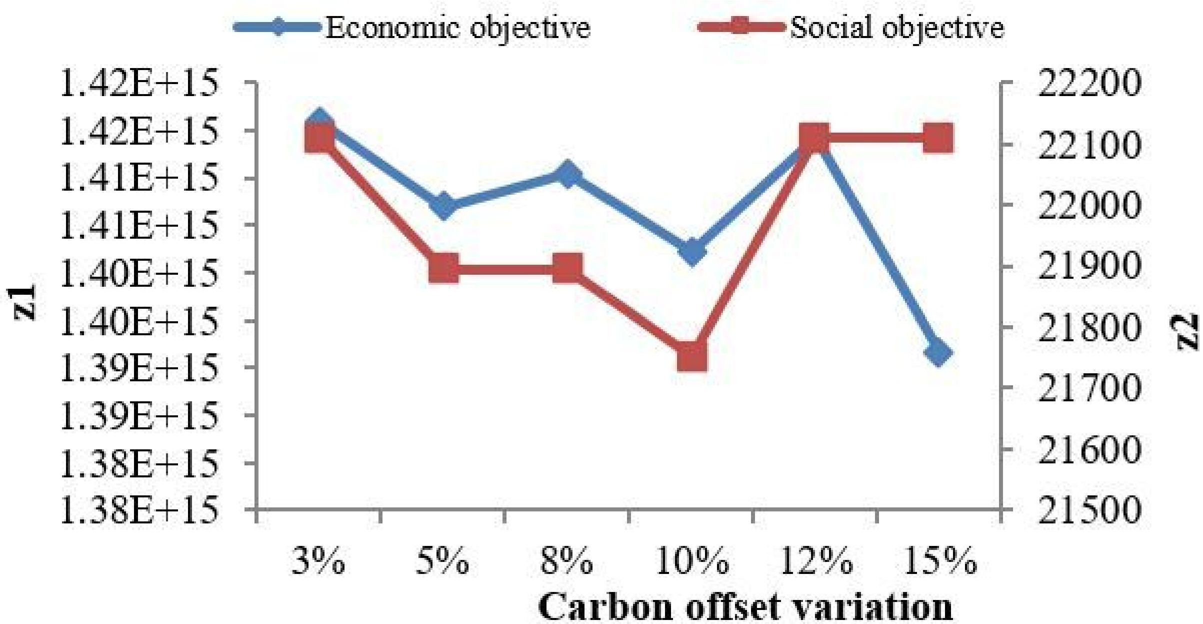

Figure 14

The effect of the carbon offset on objective functions