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Optimal Design of a Sustainable Biodiesel/Diesel Supply Chain using Sunflower and Rapeseed as Feedstock under Different Scenarios of Blending Centers

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Global energy consumption shows a steady upward trend until 2030, with liquid fuels, in particular biodiesel, accounting for a large share of fuel demand for the transport sector. One way to increase its economic and environmental benefits is through optimization of all activities across the supply chain. However, the presence of uncertainties concerning the supply chains parameters may cause to the risk of releasing large amounts of GHG emissions and increasing the total costs and prices of biodiesel on the markets. One way to predict this is by analysing the results obtained by applying mathematical approaches to the design of sustainable supply chains for different scenarios. The study proposes a MILP (mixed integer linear programming) model for optimal design of a sustainable biodiesel/diesel supply chain using different feedstock. It aims to determine the optimal level of the following: arable land and costs for cultivation of feedstock, number, locations, and capacities of biorefineries, transportation network; amounts of feedstock and biodiesel transported between regions while satisfying an economic or an environmental criterion, with the other being set as a constraint. The approach has been implemented on a real case study from Bulgaria. Four optimization problems have been formulated using both criteria for two scenarios - Scenario 1, in which 27 blending centers have been considered and Scenario 2, in which only one blending center has been considered. The obtained results from solving the optimization problems using both criteria for Scenario 1 results in a reduction of the generated GHG emissions with 503 $(\mathrm{kg_{CO_2eq}}/\mathrm{d})$ and 3,136 $(\mathrm{kg_{CO_2eq}}/\mathrm{d})$ at both criteria and the total annual costs with 240,576 ($) at environmental criterion. The analysis of the obtained results shows that the decision made regarding the number of blending centers has an impact on the sustainable operating the biodiesel/diesel supply chain.

1. Introduction

Increasing energy costs, depletion of fossil fuels and the presence of harmful environmental and social impacts caused by their consumption has led to increased demand for cleaner and more sustainable energy resources (Dutta et al., 2014). Renewable fuel, such as biodiesel, has become an alternative to standard fossil fuels in recent decades, as it has many advantages over them, which include a higher flash point, improved lubrication and lower toxicity. Biodiesel can be produced from a variety of food (Ganev et al. 2021) non-food (Mohtashami et al., 2021) or waste sources (Habib et al., 2021).

The large expansion of biodiesel production and the imposed requirements for improving its sustainability require optimization of all activities in the supply chain from the choice of feedstock to customers (Doliente and Samsatli, 2020). This leads to the development of mixed integer linear programming (MILP) programming approaches for optimal design and operation of the sustainable biodiesel/diesel supply chain satisfying economic (Kang et al., 2020), economic and environmental (Habib et al., 2021) or economic, environmental, and social criteria (Ganev et al., 2020). However, varying of some of the supply chain parameters can cause uncertainties regarding the amounts of GHG emissions released and the total costs and prices of biodiesel on the markets. In order to predict the risks that may arise in relation to the latter and to identify the parameters that have the impact on the economic or environmental viability of the considered chains, it is necessary to conduct an analysis of the results obtained by applying the considered optimization approaches for different

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scenarios. According to this, different MILP approaches for optimal design of biofuel supply chain have been developed and applied for different scenarios. They most often study the influence of parameters such as products demands (An et al., 2011), type, quantity and price of used feedstock (Akgul et al., 2012), type of used transportation network (Avami, 2012) on the GHG emissions generated (Valencia and Cardona, 2014) and the profit of the biofuel supply chains (An et al., 2011). There are no approaches to analysis of the environmental and economic performance of the biodiesel supply chains related with decisions made concerning the number of used centers for blending biodiesel with petroleum diesel.

The present study proposes a multi-objective approach for optimal design of sustainable biodiesel/diesel supply chain using two types of feedstock - sunflower and rapeseed while meeting environmental and economic criteria. The environmental assessment is in terms of the GHG emissions generated when considering the entire life cycle of the product, and the economic assessment is in terms of the annual capital and operating costs related to the optimal design of the considered supply chain. The approach has been implemented for two scenarios of using blending centers - competitive and monopoly using either an economic or an environmental criterion, with the other being set as a constraint. Solved MILP problems lead to obtaining the optimal: the arable land and amounts of feedstock needed for biodiesel production; number, capacities, and locations of bio-refineries; optimal flows of raw materials and products between different sites and the transportation mode. The analysis of the results obtained in solving the optimization problem in both scenarios and in both criteria shows that the choice of decision concerning to the number of the blending centers used affects both environmental and economic results of the considered supply chain. The latter is directly related to the sustainable operation of the biodiesel/diesel supply chain.

2. Problem statement

The study proposes a multi-objective approach for optimal design of sustainable biodiesel / diesel supply chain using two types of feedstock - sunflower and rapeseed, while satisfying either an economic or an environmental criterion, with the other being set as a constraint. The supply chain includes: a set of biomass cultivation areas, a set of locations for building biorefineries with different capacities; a set of blending areas; a set of products sales areas; a set of existing refineries for petroleum diesel. Four optimization problems have been formulated and solved using environmental and economic criteria for two scenarios - Scenario 1 where 27 blending centers have been considered and Scenario 2, in which only one blending center has been considered within a time horizon of ten years. The purpose is to be shown how the decision made concerning the blending centers used affects GHG emissions generated and the prices of biodiesel. When solving the formulated optimization problems in both scenarios and both criteria, they are obtained the optimal: areas and raw material cultivation costs; number, locations and costs of biorefineries to be built with different capacities; costs for production of biodiesel and petroleum diesel; market demands; type of vehicles used and transport costs; the quantities of raw materials of different types and biodiesel transported between the regions.

The following assumptions are considered in development of the supply chain model: 1. Two feedstocks (sunflower and rapeseed) are considered for biodiesel production. 2. The potential biomass cultivation areas, locations, capacities of all facilities and cost parameters are predetermined. 3. Facilities' capacity is limited. 4. Two type of vehicles for transportation of raw materials of different types and biodiesel are considered. 5. Their payload capacities are predetermined.

3. Formulation of the biodiesel/diesel supply chain optimization model

A MILP deterministic optimisation model including data sets, decision variables, mathematical models of the environmental and economic impacts of the supply chain, constraints and optimization criterion has been formulated. The optimization problem has been solved using an economic criterion, as the environmental one is defined as a constraint and vice versa. The planning period *H* of ten years has been determined. The latter is divided into several equal time intervals, t={0,1,2,…,T}, each of which has a duration Δt.

3.1 Modeling of biodiesel/diesel supply chain environmental impact

The environmental impact criterion includes assessments for GHG emissions generated at each stage of the life cycle of the products $(kgCO_{2eq})$ for each time interval $t \in T$. They are defined in terms of environmental costs, multiplying them by the price of carbon emissions on the market determined for each time interval $t \in T$:

$$TEI_t = ELBC_t + ELBP_t + ELTR_t + EBCAR_t, \qquad \forall t, t \in T \qquad (1)$$

where

$\mathrm{TEI_t}$ the total environmental impact of the biodiesel/diesel supply chain, $(\mathrm{kg_{CO_2eq}}/\mathrm{d})$;

$\mathrm{ELBC_t}$, $\mathrm{ELBP_t}$, $\mathrm{ELTR_t}$ the environmental impact of entire life cycle of the products including biomass cultivation, biodiesel production and transportation of biomass and products, $(\mathrm{kg_{CO_2eq}}/\mathrm{d})$;

$\mathrm{EBCAR_t}$ the environmental impact related with biodiesel (B100) combustion in vehicle engines, $(\mathrm{kg_{CO_2eq}}/\mathrm{d})$.

The environmental objective function aims to reduce the annual GHG emissions resulting from the activities of the SC for biodiesel (B100) and diesel to meet the energy needs of the regions.
The annual GHG emissions equivalent of the fuels used is determined as:

$$TEIF_t = TEI_t + EG_{CAR,t}, \qquad \forall t, t \in T \tag{2}$$

$\mathrm{TEIF_t}$ the total environmental impact of the fuels used (biodiesel (B100) and diesel) to ensure the energy balance of the regions, $(\mathrm{kg_{CO_2eq}}/\mathrm{d})$;

$\mathrm{TEI_t}$ the total environmental impact of biodiesel/diesel SC's operation, $(\mathrm{kg_{CO_2eq}}/\mathrm{d})$;

$\mathrm{EG_{CAR}}$ the GHG emissions resulting from the use of petroleum diesel in vehicles, $(\mathrm{kg_{CO_2eq}}/\mathrm{d})$.

3.2 Modeling of biodiesel/diesel SC economic performance

The economic assessments are the costs related to the plant, which include the total investment costs for biodiesel production capacity (B100) and the operation of the SC.

$$TDC_t = TIC_t + TPC_t + TTC_t + TTAXB_t - TL_t, \qquad \forall t, t \in T \tag{3}$$

where

$\mathrm{TDC_t}$ the total costs of biodiesel/diesel SC, $(\$/\mathrm{y})$;

$\mathrm{TIC_t}$ the total investment costs for biodiesel/diesel SC production capacity according to the period of operation and the purchase of biorefineries, $(\$/\mathrm{y})$;

$\mathrm{TPC_t}$ the production costs in biodiesel production (B100), $(\$/\mathrm{y})$;

$\mathrm{TTC_t}$ the total transportation costs, $(\$/\mathrm{y})$;

$\mathrm{TTAXB_t}$ the GHG emissions tax charged according to the total CO_2, generated during the operation of the SC $(\$/\mathrm{y})$;

$\mathrm{TL_t}$ the government incentives for biodiesel production and consumption (B100), $(\$/\mathrm{y})$.

3.3 Constraints

The optimization problem includes constraints related with: plant capacity, balance of biodiesel (B100) to be produced from biomass available in the regions; admissibility of flows during operation of the supply chain; providing the supply of crops to regions to provide food security, logical constraints; transportation; design of biodiesel/diesel SC; whole environmental impact of all regions; arable land; crop rotation; energy balances; total costs of the supply chain, (Ganev et al., 2021).

3.4 Environmental objective function

The environmental impact optimization criterion includes environmental assessments for all activities over the biodiesel/diesel SC expressed in terms of the amount of CO_2 equivalent generated throughout the whole life cycle of the products. For its definition, Eco-Indicator 99 method is used (The Eco-Indicator 99, 2016). The environmental criterion is an object of minimization and is determined as follows:

$$ENV = \sum_{t \in T} (LT_t TEI_t) \tag{4}$$

where
LT_t is the duration of time interval $t, (y)$.

3.5 Economic objective function

The economic optimization criterion includes the annual costs related to cultivation and collection of biomass, its transportation to the collection facilities, storage and conversion, storage of biodiesel and its transportation to the blending facilities. It also includes the investment costs for building of biorefineries. The economic criterion is an object of minimization and is determined as follows:

$$COST = \sum_{t \in T} (LT_t TDC_t) \tag{5}$$

4. Case study

The proposed approach has been implemented on a real case study, in which the territory of the Republic of Bulgaria with its 27 administrative regions is considered as potential areas for feedstock cultivation and biodiesel production. Four optimization problems have been formulated and solved at Optimization criterion (a) - minimum amount of GHG emissions and Optimization criterion (b) – minimum average annual costs for two scenarios (Scenario 1 and Scenario 2). In Scenario 1, 27 regions for blending biodiesel and petroleum diesel have been considered, while in the Scenario 2 – only 1 region has been considered as potential center for blending the two types of fuel.

5. Results and discussion

There have been formulated optimization problems using an economic optimization criterion, the environmental one being defined as a constraint and vice versa for the two scenarios. The optimization problems have been solved using GAMS® optimization software-CPLEX solver.
Figure 1 and Figure 2 show the optimal structure of the SC for biodiesel production on the territory of the Republic of Bulgaria obtained by applying the presented approach in Scenario 1 and Scenario 2 for both criteria. In Table 1 the values of the parameters of the obtained optimal solutions are listed.

5.1 Optimal structure of the SC for biodiesel production for Scenario 1 for both criteria

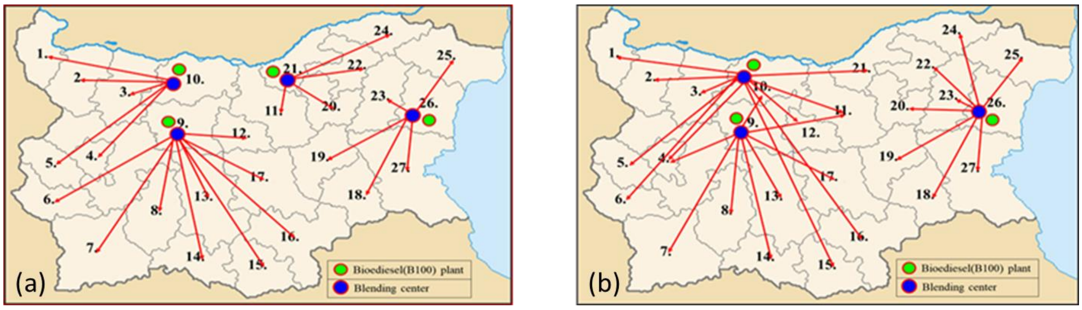

Figure 1: Optimal structure of the SC for biodiesel production on the territory of the Republic of Bulgaria in Scenario 1 for: (a) Minimum amount GHG emissions and (b) Minimum average annual costs

According to what is presented in Figure 1(a) optimal configuration of the biodiesel supply chain for the criterion (a) - Minimum amount of greenhouse gas emissions, four biorefineries should be built with the plant capacities of 32,500 t/y, 34,838 t/y, 12,000 t/y and 26,000 t/y. They should be located in regions 9,10,21 and 26. The latter corresponding to the cities Lovech, Pleven, Ruse and Varna. The presented in Figure 1(b) optimal structure of the biodiesel supply chain is related with three biorefineries which should be built with plant capacities of 32,500 t/y, 44,866 t/y and 27,972 t/y in regions 9, 10, and 26 corresponding to the cities Lovech, Pleven, and Varna. In both solutions, the biorefineries that should be built are connected to the blending centers for petroleum diesel and biodiesel, which are located in the same regions.

5.2 Optimal structure of the SC for biodiesel production for Scenario 2 for both criteria

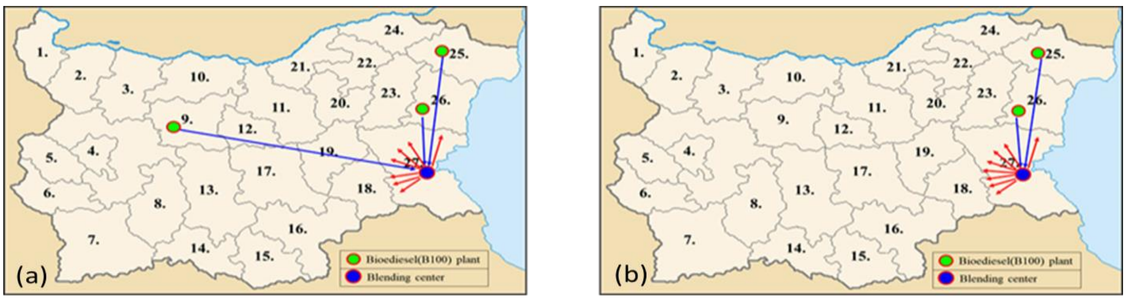

Figure 2: Optimal structure of the SC for biodiesel production on the territory of the Republic of Bulgaria in Scenario 2 for: (a) Minimum amount GHG emissions and b) Minimum average annual costs

According to the presented in Figure 2(a) optimal configuration of the biodiesel supply chain for the criterion (a) - Minimum amount of greenhouse gas emissions, three biorefineries should be built with the plant capacities of 30,000 t/y, 38,000 t/y and 37,339 t/y. The should be located in regions 9, 25 and 26. The latter corresponding to the cities Lovech, Dobrich and Varna. The presented in Figure 2(b) optimal structure of the biodiesel supply chain is related with two biorefineries which should be built with plant capacities of 41,080 t/y and 64,259 t/y in regions 25 and 26 corresponding to the cities and Varna.

It can be seen from both figures that solving the optimization problem in both scenarios and criterion (b) results in less regions for building biorefineries. This is related to lower investment costs, production costs, price of biodiesel produced, etc. This can be seen from Table 1.

Table 1: The results obtained in solving the formulated optimization problems for both scenarios and at optimization criterion: (a) Minimum amount of greenhouse gas emissions and optimization criterion (b) Minimum average annual costs

Optimization results	Scenario 1		Scenario 2	
	Optimization criterion (a)	Optimization criterion (b)	Optimization criterion (a)	Optimization criterion (b)
Value of optimization criterion (a), (kg_{CO_2eq}/d)	25,347,651.82	25,475,649.38	25,348,154.43	25,478,785.45
Value of optimization criterion (b), ($/y)	111,210,369.50	80,801,347.49	111,450,945.39	80,437,937.25
SC investment costs, ($/y)	6,681,600.00	4,365,600.00	6,320,400.00	3,949,200.00
Biomass and SC production costs, ($/y)	91,998,122.40	67,752,154.04	92,020,308.02	67,717,572.60
Production costs for SC, ($/y)	13,167,282.72	13,167,282.72	13,167,382.77	13,167,382.77
Cost for biomass, ($/y)	78,830,839.68	54,584,871.32	78,852,925.26	54,550,189.83
Transportation costs of SC, ($/y)	9,713,152.54	5,066,114.10	10,290,783.74	5,135,267.14
Carbon tax, ($/y)	11,876,585.08	12,676,569.85	11,878,612.97	12,695,056.85
Government incentives, ($/y)	-9,059,090.51	-9,059,090.51	-9,059,159.34	9,059,159.34
Total minimum GHG emissions related with biodiesel production, (kg_{CO_2eq}/d)	1,900,253.61	2,028,251.18	1,900,578.08	2,031,209.10
Total minimum GHG emissions related with diesel production, (kg_{CO_2eq}/d)	23,447,398.21	23,447,398.21	23,447,576.36	23,447,576.36
GHG related with growing biomass for biodiesel production, (kg_{CO_2eq}/d)	598,253.76	681,193.39	598,184.81	681,318.62
GHG related with biodiesel production, (kg_{CO_2eq}/d)	809,051.27	824,122.93	809,044.07	824,151.01
GHG related with transportation, (kg_{CO_2eq}/d)	2,914.98	32,901.26	3,311.88	35,702.15
GHG related with the biodiesel combustion in vehicle engines, (kg_{CO_2eq}/d)	490,033.59	490,033.59	490,037.32	490,037.32
Total arable land, (ha)	1,613,611.00	1,613,611.00	1,613,611	1,613,611.00
Arable land for growing biomass needed for biodiesel production, (ha)	99,264.74	81,175.40	99,281	81,149.84
Arable land for growing biomass to meet food needs, (ha)	668,093.45	657,463.95	657,464	657,463.95
Free arable land, (ha)	846,267.81	874,986.65	856,881	875,012.21
Biodiesel demand for the regions, (t/y)	105,338.26	105,338.26	105,339.06	105,339.06
Petrol diesel demand for the regions, (t/y)	1,617,954.61	1,617,954.61	1,711,000.00	1,711,000.00
Price of biodiesel (B100), ($/t)	1,055.745	767.065	1,055.745	767.065

From the results shown in Table 1, it can be seen that solving the problem in optimization criterion (b) for both scenarios leads to lower values for all economic parameters of the obtained solutions. These are the investments costs for biorefineries building, the costs associated with the production of biodiesel, the price of biodiesel produced on the markets, etc. The latter in Scenario 2 are lower than those in Scenario 1. Regarding to the environmental impact, these solutions have higher values for specific environmental parameters such as GHG related to growing biomass for biodiesel production, GHG related to transportation than those obtained at optimization criterion (a). However, the total environmental assessment expressed in terms of total GHG emissions associated with biodiesel production for the solutions obtained at optimization criterion (b) does not differ significantly from that obtained in solving the optimization problem at criterion (a). With regard to the values for the arable land for the cultivation of both types of crops for the production of biodiesel, the solutions in criterion (b) have lower values, ie they lead to more free arable land.

6. Conclusions

The study proposes a MILP (mixed integer linear programming) model for the optimal design of a sustainable biodiesel/diesel supply chain using different crops as feedstock. The proposed approach has been implemented on a real case study, in which the territory of the Republic of Bulgaria with its 27 administrative regions is considered as potential areas for cultivation of sunflower and rapeseed feedstocks for biodiesel production. There have been considered Scenario 1 with 27 blending centers and Scenario 2 with 1 blending center. For each one of the scenarios there have been formulated and solved optimization problems at different optimization criteria – economic and environmental ones. The obtained results from solving the optimization problems using both criteria for Scenario 1 results in a reduction of the generated GHG emissions with 503 $(\mathrm{kg_{CO_2eq}}/\mathrm{d})$ – (environmental optimization criterion) and 3,136 $(\mathrm{kg_{CO_2eq}}/\mathrm{d})$ (economic optimization criterion) and the total annual costs with 240,576 ($) (environmental optimization criterion). When solving the optimization problems for both scenarios at optimization criterion (b), for Scenario 1, the total annual costs are 363,410 ($) larger than for Scenario 2.

The analysis of the results obtained reveals that the choice of decision concerning the number of blending centers used affects both environmental and economic results of the considered supply chain, the latter being observed to have significant reduction in production and investment costs and prices of biodiesel on the markets. The latter is directly related to the sustainable operation of the biodiesel/diesel supply chain. Future research will include a development of a stochastic approach of optimal design of sustainable biodiesel/diesel supply chain which can handle uncertainties regarding the products demands and prices of used feedstock.

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