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Optimal Design of a Sustainable Integrated Biodiesel/Diesel Supply Chain Using First and Second Generations Bioresources

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This study proposes an optimization model for strategic design of a sustainable Integrated Biodiesel/diesel Supply Chain (IBSC) using 1st & 2nd generations (1G & 2G) bioresources for biodiesel production such as sunflower and rapeseed; and waste cooking oil (WCO) and animal fats. The optimization model is formulated in terms of MILP providing all aspects of the sustainability – economic, environmental and social. The model takes into account key supply chain activities such as infrastructure compatibility, the demand distribution, the size and location of biorefineries for biodiesel production and the available biomass and carbon taxes. The economic and environmental performance of IBSC is assessed by the costs for IBSC design and Green House Gas (GHG) emissions of pollutants associated with its operation. As a social criterion, the number of expected new jobs associated with IBSC design and operation has been used. The approach is implemented on a Bulgarian scale with corresponding districts. The results obtained give the optimal biodiesel facilities locations, logistics design, inventory management, and information exchange. It is shown that for the case of the environmental criterion used, the average biodiesel price for the considered period (2016-2020) is 14 % higher and the total GHG emissions are 6.6 % lower than ones obtained when an economic criterion is used.

1. Introduction

The trend global energy consumption shows a steady increase until 2030, with liquid fuels accounting for the largest share of fuel demand for the transport sector. Biodiesel is one of the most commercially available biofuels, which has a lot of advantages. As a result of its production glycerine as by-product is obtained. The latter also finds a number of applications in medicine, cosmetics, etc. (Alsaleh et al., 2018). However, the higher costs of biodiesel production than fossil diesel are the main drawback for its commercialization. It has been found that the price of biodiesel mainly depends on the costs of feedstock which makes up 70 – 95 % of the total production costs. When the nutritional resources of oil, such as sunflower, rapeseed are used as a feedstock, biodiesel from 1G is produced. The production of 1G biodiesel is associated with some food supply problems but it is a proven and well-established technology with high productivity. On the other hand, biodiesel, which is produced from non-food feedstock such as wastes of vegetable oils and animal fats, biomass sources, are referred as 2G biodiesel. The production of 2G biodiesel is associated with high production costs due to applying expensive pre-treatment technologies. However, the latter is offset by the low feedstock costs and the fact that it leads to their full utilization which makes a valuable contribution to GHG emission reduction.

Nowadays, a large amount of WCO and animal fats are generated by restaurants, hotels, agro-food industries, etc. The disposal of WCO has become an environmental issue of high importance, as it can be hazardous for public health, and the potential of WCO to biodiesel production has great advantages for its utilization (Kirubakaran et al., 2018). WCO based biodiesel can reduce greenhouse gases (Filho et al., 2018) and toxic organic pollutants from diesel engines.

Besides the used feedstock, the quality and the price of the biodiesel produced depends on other factors such as transport logistics, production and storage technology used and the location of biorefineries. One way to

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increase its economic and environmental benefits is an optimization of all activities associated with the life cycle of the product. The latter results in a large supply chain combining several stages with different options at each stage (Azevedo et al. 2019).
In this study, an approach for optimal design of integrated biodiesel/diesel supply chain based on 1G & 2G bio resources for biodiesel production such as sunflower and rapeseed; and WCO and animal fats is proposed. The approach has been implemented on a Bulgarian scale with corresponding regions.

2. Problem statement

This study considers an integrated biodiesel/diesel supply chain represented in Figure 1.

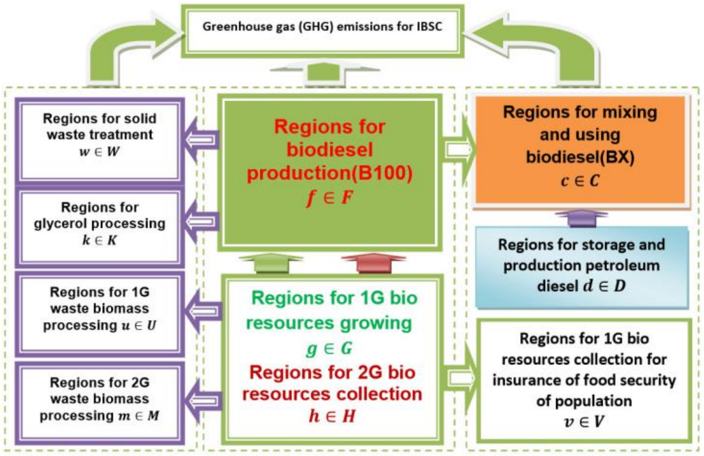


Figure 1: Superstructure of IBSC

It comprises suppliers of bioresources, integrated biorefineries and demand areas. The WCO and animal fats are collected by small trucks at specific locations in each region and then transported to integrated biorefineries for pre-treatment and biodiesel conversion. At the same time, 1G bioresources such as sunflower, rapeseed, etc. can be grown in each region and transported from there to the biorefineries. The biodiesel produced is finally delivered to the demand areas. A planning horizon for government regulations including manufacturing, design and carbon tax is considered. The presented IBSC superstructure includes a set of harvesting sites, set of demand areas, set of potential locations of collection facilities and set of biorefineries. Data for crops harvesting and biodiesel production are also given. For each demand zone, the biodiesel demand is given, and the environmental burden associated with biodiesel distribution in the local region is known. For each transportation link, the transportation capacity, available transportation modes, distance, and emissions of each transportation type are known.

2.1 General formulation of the problem

Three key problems should be addressed for the optimal design of the supply chain: (1) the number, sizes and locations of biorefinery and solid waste plants; (2) the sites and amount of 1G feedstock and 2G feedstock; (3) the transportation plans of 1G & 2G feedstock, solid waste, fossil diesel, glycerine and biodiesel.

3. Formulation of deterministic model

The problem for the optimal location of biodiesel (B100) production plants and the efficient use of the available land aims to identify what combination of options is the most efficient approach to supply the facilities. It is formulated as a MILP to minimize economic, environmental and social criteria.

3.1 Mathematical description

MILP optimization model includes the definition of constant parameters and decision variables; modelling of the environmental impact and the economic performance of IBSC. An objective function and constraints are included. To model the set of time intervals of the planning horizon $\tau = \{1,2,\dots,T\}$ is introduced. The ecological, economic constants and continuous and binary variables are taken from (Ivanov and Stoyanov, 2016).

3.2 Modeling of IBSC environmental impact

The environmental impact objective function is defined in terms of total GHG emissions ($\mathrm{kgCO_{2eq}}$) stemming from the supply chain activities as they are converted to carbon credits by multiplying them with the carbon price at the market. During formulation of the objective function the following life cycle stages of biodiesel production are taken into account: biomass cultivation, growth and acquisition; biomass transportation from source locations to facilities; transportation of biodiesel facilities to the demand areas; solid waste transportation from biodiesel facilities to utilization plants; local distribution of liquid transportation fuels in demand areas; emissions from biodiesel and fossil diesel usage.

The objective function represents the total environmental impact of IBSC operation resulting in the generation of GHG emissions for each time interval $\tau, \tau \in \mathrm{T}$. These emissions are equal to the sum of the impact that each of the stages of the life cycle has on the environment. The total GHG emissions are defined as follows:

$$\mathrm{TEI_t = ELS_t + ELB_t + ELD_t + ETT_t + ESW_t + ESTRAW_t + ECAR_t + EWCO_t}, \forall \mathrm{t} \tag{1}$$

where

$\mathrm{TEI_t}$	total environmental impact of IBSC operation, $[\mathrm{kgCO_{2eq}/d}]$;
$\{\mathrm{ELS_t, ELB_t, ELD_t, ETT_t}\}$	environmental impact of life cycle stages, $[\mathrm{kgCO_{2eq}/d}]$;
$\mathrm{ESW_t}$	GHG emissions generated during solid waste recovery, $[\mathrm{kgCO_{2eq}/d}]$;
$\mathrm{ESTRAW_t}$	GHG emissions generated during residual straw utilization in the regions, $[\mathrm{kgCO_{2eq}/d}]$;
$\mathrm{ECAR_t}$	GHG emissions generated during the use of biodiesel (B100) &fossil diesel in vehicles, $[\mathrm{kgCO_{2eq}/d}]$;
$\mathrm{EWCO_t}$	GHG emissions generated during WCO and waste animal fats utilization if it is not used for the biodiesel(B100) production, $[\mathrm{kgCO_{2eq}/d}]$.

3.3 Modeling of IBSC economic performance

The economic objective function is defined in terms of the total annual costs for IBSC design. It includes the biomass feedstock acquisition costs, the local distribution costs of final product, the production costs and the transportation costs of biomass, and final products. The production costs take into consideration both the fixed annual operating costs, which is given as a percentage of the corresponding total capital investment, and the net variable costs, which is proportional to the processing quantity. The transportation costs include both distance-fixed costs and distance-variable costs. The economic criterion includes total investment cost of biodiesel production facilities and IBSC operation:

$$\mathrm{TDC_t = TIC_t + TIW_t + TPC_t + TPW_t + TTC_t - TL_t - TA_t + TWCO_t}, \forall \mathrm{t} \tag{2}$$

where

$\mathrm{TDC_t}$	IBSC total costs, $[\$/\mathrm{y}]$;
$\mathrm{TIC_T}$	Total investment costs for the production capacity of IBSC compared to the operating period and purchase of the plant, $[\$/\mathrm{y}]$;
$\mathrm{TIW_T}$	Total investment costs for IBSC solid waste treatment plants compared to the operating period and purchase of the plant, $[\$/\mathrm{y}]$;
$\mathrm{TPC_T}$	Biodiesel (B100) production costs, $[\$/\mathrm{y}]$;
$\mathrm{TPW_T}$	Production costs for solid waste utilization, $[\$/\mathrm{y}]$;
$\mathrm{TTC_T}$	Total IBSC transportation costs, $[\$/\mathrm{y}]$;
$\mathrm{TL_t}$	Costs associated with government incentives for biodiesel (B100) production and consumption, $[\$/\mathrm{y}]$;
$\mathrm{TA_t}$	Total costs associated with obtained by-products (glycerol, cusp), $[\$/\mathrm{y}]$;
$\mathrm{TWCO_t}$	This unused quantity of WCO is considered to be an environmental pollutant that should be minimized.

3.4 Modeling of IBSC social performance

The social objective function is defined as the expected total number of jobs created as a result of all elements of IBSC operation for each time interval $\tau, \tau \in \mathrm{T}$.

$$\mathrm{Job_t = NJ1_t + LT_tNJ2_t + LT_tNJ3_t}, \quad \forall \mathrm{t} \tag{3}$$

where

$\mathrm{NJ1_t}$	Number of jobs created during the installation of biodiesel refineries and solid waste plants;
$\mathrm{NJ2_t}$	Number of jobs created during the operation of biodiesel refineries and solid waste plants;
$\mathrm{NJ3_t}$	Number of jobs created by cultivation bioresources for biodiesel production;
$\mathrm{LT_t}$	Duration of time intervals, [y].

3.5 Constraints

The system constraints includes: 1). Plants capacity; IBSC flow acceptability; 2). Solid waste plants capacity; 3). Logical constrains; 4.) Transportation links; 5). Constraints for total environmental impact; 6). Constraints for mass balances between biodiesel plants & biomass regions; 7). Constraints for mass balances between biodiesel plants & customers; 8). Constraints for energy balances; 9). Constraints for total cost network.

3.6 Economic objective function

The economic cost includes all IBSC operating costs, from the purchase of raw materials to the transport of the final product, as well as the investment costs of bio refineries and waste utilization facilities which are subject to minimization. The costs of the IBSC are the cost of the raw material, the transportation of the raw material to the facilities, the cost of biomass, the cost of transportation to the bio refineries, the cost of conversion to biodiesel and the cost of transportation the biodiesel to the mixing regions. Economic objective function represented in terms of the total annual costs for IBSC design:

$$\mathrm{COST} = \sum_{t \in T} (\mathrm{LT}_t \mathrm{TDC}_t), \tag{4}$$

3.7 Environmental objective function

The environmental objective function represents the minimum total GHG emissions. It integrates the Eco indicator 99 method, taking into account the specific activities that are carried out in the IBSC operation. The cumulative environmental impact of the IBSC operation, is expressed by the equation:

$$\mathrm{ENV} = \sum_{t \in T} (\mathrm{LT}_t \mathrm{TEI}_t), \tag{5}$$

3.8 Social objective function

To evaluate the social impact of IBSC operation, coefficients are used. They represent indirect jobs in the social economy. Then social impact in terms of number of jobs is determined as follows:

$$\mathrm{JOB} = \sum_{t \in T} (\mathrm{LT}_t \mathrm{Job}_t)\ . \tag{6}$$

3.9 Integrated Economic and Environmental objective function

The integrated Economic and Environmental objective function is formulated as follows:

$$\mathrm{Int\_COST} = \mathrm{COST} + \mathrm{C}_{\mathrm{CO}_2} \sum_{t \in T} (\mathrm{LT}_t \alpha_t \mathrm{TEI}_t) \tag{7}$$

where

α_t IBSC operating period for one year, $[\mathrm{d/y}]$;

The total emissions are converted into carbon credits by multiplying with the carbon price $\mathrm{C}_{\mathrm{CO}_2}$ on the market, where it has a value $[0.149\$/\mathrm{kgCO}_{2\mathrm{eq}}]$, (Carlos et al., 2016).

4. Formulation of the optimization problem

The optimization problem is formulated and solved either with economic criterion - the total annualized cost for IBSC design or using environmental ones such as: the total GHG emissions associated with its operation and the integrated economic and environmental criterion. The rest criteria are defined as constraints. The aim is to be defined the optimal biodiesel facilities locations in regions and their parameters. Formulated optimisation problems were solved using GAMS® optimization software-CPLEX solver.

5. Case study

Two types of bio resources such as sunflower and rapeseed and waste cooking oil (WCO) and animal fats have been used for 1G and 2G biodiesel production.

5.1 Input data

For the purpose of evaluation of the effectiveness of the proposed optimization approach, the 27 districts of Bulgaria were considered as searching areas. 5-year planning horizon (2016-2020) with an annual time step is considered. To estimate the quantity of the biodiesel required for these regions, data for the quantities of fossil diesel are taken from the National Statistical Institute of Bulgaria. For the considered time period (2016-2020) they are: 2016→2,050,000 t, 2017→2,219,000 t, 2018→2,401,000 t, 2019→2,583,000 t, 2020→2,775,500 t. It is anticipated that by 2020, 10 % of the districts' biodiesel needs must be met. In 4 districts in Bulgaria solid waste utilization facilities can be installed and in 4 other districts the glycerine produced can be sold at the plants located there. The search areas are provided with the required fossil diesel from 3 refineries or combined warehouses. In this study, when determining the optimal number of biorefineries, it should be borne in mind that they are four types with different maximum capacity. The necessary investment costs for their building are as follows: Size-1→8,500 t/y →3.8 $M\$$, Size-1→19,000 t/y →4.8 $M\$$, Size-1→48,000 t/y →7.3 $M\$$, Size-1→74,000 t/y →8.9 $M\$$. It is assumed that the consumption of vegetable oil in a given region to be proportional to its population and the amount of WCO generated is 30 % of it. The rest data related with the population, cultivated and free cultivated areas used for crops production are taken from (Ivanov et al., 2018).

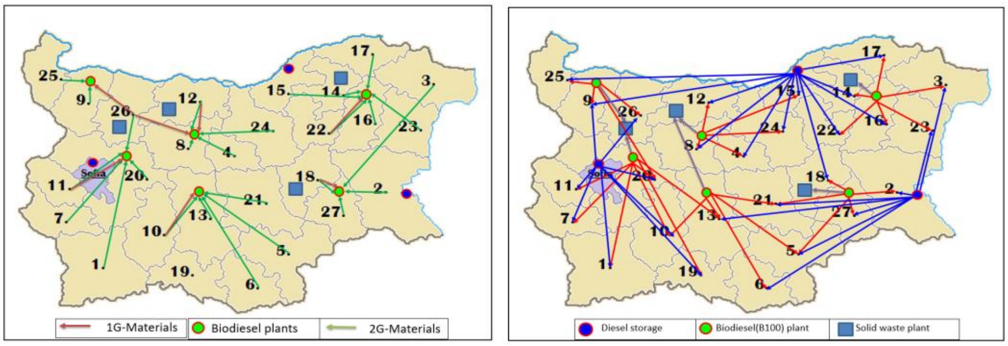
5.2 Results and discussion

The MILP models have been solved using 2.5 GHz Intel Core-i7 Processor with 6 GB Memory. The obtained results are listed in Table 1, Figure 2 and Figure 3.

Table 1: Results in case of minimization of Integrated Economic and Environmental objective function

Years >Biodiesel(B100) fossil diesel ratio	2016>6 %	2017>7 %	2018>8 %	2019>9 %	2020>10 %
Objective function value (7) - >1,054.008 - $(M\$)$					
Objective function value (5) ->13,323,159,067-$(kgCO_{2eq}/d)$					
Objective function value (6) - >1,880 - $(Jobs/y)$					
Total IBSC operating cost $(M\$/y)$	143.01	162.51	240.83	249.52	258.11
Total biodiesel production costs $(M\$/y)$	37.88	54.60	73.41	95.66	104.27
Total GHG emissions$(t\ CO_{2eq}/d)10^6$	2,101.13	2,224.59	2,969.22	2,944.32	3,083.88
Total number of jobs $(Jobs/y)$	440	260	370	420	390
Total quantities of biodiesel and fossil diesel produced per year (t/y)					
1G Biodiesel (sunflower & rapeseed)(t/y)	27,738	50,732	77,479	107,865	106,940
2G Biodiesel (WCO & animal fat)(t/y)	90,786	99,184	108,201	117,217	162,218
Total biodiesel(B100) (t/y)	118,525	149,916	185,680	225,082	269,159
Total fossil diesel (t/y)	1,945,321	2,086,596	2,237,010	2,384,211	2,537,784
Price for biodiesel (B100) production $(\$/t)$	319	364	395	425	387
Distribution of available land (ha)					
Sunflower & rapeseed land (ha)	19,411	35,505	54,227	75,496	74,845
Sunflower & rapeseed land for food (ha)	1,464,199	1,493,331	2,002,839	1,897,456	1,897,456
Free land(ha)	1,997,379	1,952,153	1,423,924	1,508,037	1,508,688

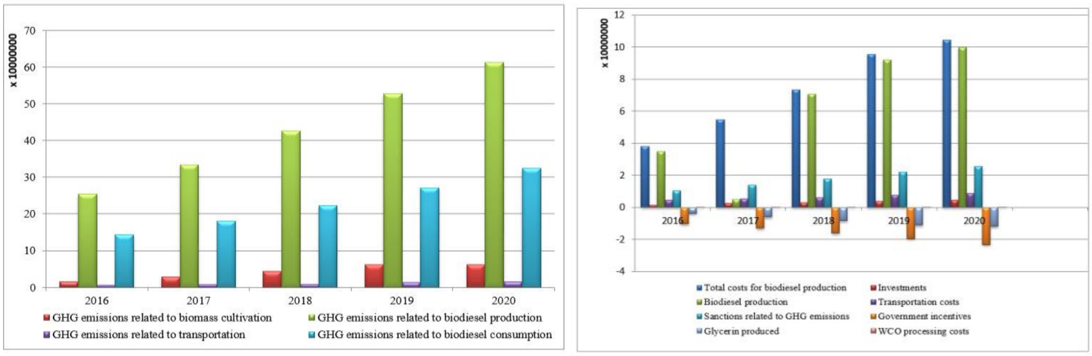
Most studies in the literature dealing with the strategic design of sustainable SCs for biodiesel production have focused mainly on the main indicators of this type of production, without considering their overall environmental and economic impact. They do not take into account the fact that biodiesel (B100) is used in certain proportions with petroleum diesel.



(a) (b)

Figure 2: Optimal IBSC obtained (case 3.9) regarding bio refineries, solid waste plants and diesel warehouses locations with corresponding transportation links between them and (a) the harvesting sites for 1G and 2G feedstocks and (b) the demand areas of fuel

The proposed study shows the overall environmental and economic impact of this type of production when considering biodiesel blends, as well as the impact of all ancillary processes (Figure 3b).



(a) *(b)*

Figure 3: Environmental and economic impact of obtained optimal IBSC regarding (a) the GHG emissions associated with its activities and (b) the design costs

The results presented in Figure 3a show that the main source of pollution in this type of production is the used biodiesel production technology, to a lesser extent, another type of process.

6. Conclusions

The available agricultural land in Bulgaria enables the production of sufficient amount of biological raw material to produce the required amount of biodiesel (B100) in order to reach the required quota of 10 % for liquid biofuels by 2020. The optimum area required for growing sunflower and rapeseed is concentrated in a small number of regions of the country. To obtain the optimal mixture of 1G bioresources, using the SC design approach “Minimum total annual costs”, it is necessary in 2020 that 14 % of the agricultural land be used for sunflower cultivation and 2 % for rapeseed. In the case of the "Minimum Total Greenhouse Gas Emissions" criterion using, 12 % of farmland is required for rapeseed cultivation and 3 % for sunflower. In both criteria, 2G bioresources are used as the main raw material. For the case of the Integrated objective function (case 3.9) for IBSC, the average biodiesel (B100) price for the considered period (2016-2020) is 378 $/t, while for the case 3.7 of the minimum total GHG emissions, it is 428 $/t, which is 14 % higher. On the other hand, for the case 3.7 of the environmental criterion used, the total GHG emissions are 6.6 % lower than ones obtained when an integrated economic and environmental criterion is used.

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