Optimal design of an integrated 1st generation biodiesel / diesel supply chain based on solid waste management for energy efficiency improvement

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Abstract: *The transport sector is a major consumer of diesel fuel, which ranks it among the main greenhouse gas (GHG) emissions generators. They can be reduced by gradually introducing biofuels into transport fuels and their share is expected to increase over the years. However, full sustainability can only be achieved by simultaneously consideration of all stages of the product life cycle with a tendency to close it, by utilization of solid waste by-products to improve the energy efficiency of considered biofuel production.*

This study proposes an approach for optimal design of an Integrated Biodiesel/Diesel Supply Chain (IBDSC) based on 1st generation feedstock, taking into account the impact of the used feedstock for its energy efficiency improvement. It based on mathematical models of the environmental and economic impact of the considered IBDSC. The latter are included in an optimization problem for determination of optimal number, size and location of bio refineries and solid waste facilities; areas and quantities of raw materials needed for the production of biodiesel and mode of transport. Two optimization criteria are defined: environmental - minimum generated GHG emissions from IBDSC operation and economic - the total annual costs optimization criteria. The problem is solved if either at one of the two criteria, or at an integrated environmental and economic criterion. The approach involves an additional analysis of different feedstock as well as useful by-products. Based on this analysis, the sunflower has been selected as the most appropriate feedstock which can be used as a generator of a useful by-product - sunflower husks. The obtained optimal amount of sunflower husks generated in the production of tons of biodiesel is $0.431(t/t.)$*. They are used to produce the required amount of heat in biorefineries, where there are plants for burning flakes and is* $0.215(t/t.)$*. The remaining amount of sunflower husks is used for the production of pellets. When using an integrated environmental-economic optimization criterion, the following results are obtained - 33.4% of sunflower husks are used for the production of pellets, and 66.6% for the production of heat in biorefineries. This would have a positive impact on the formation of the final price of biodiesel.*

Keywords*: INTEGRATED BIODIESEL/DIESEL SUPPLY CHAIN, OPTIMAL DESIGN, SUNFLOWER FEEDSTOCK, SOLID WASTE UTILIZATION, ENERGY EFFICIENCY IMPROVEMENT, PRODUCTION OF PELLETS, GHG EMISSIONS MINIMIZATION, TOTAL ANNUAL COST MINIMIZATION*

1. Introduction

The transport sector is one of the largest consumers of fuels, mainly diesel, which ranks it among the main generators of greenhouse gas emissions. Improving the sustainability of this sector is at the heart of Directive 2009/28 / EC which imposes gradually introduction of biofuels, providing for an increase in their share over the years, as in 2020 it is 10%. Modern biodiesel production, however, is associated with large costs compared to fossil diesel, which hinders its widespread use. One of the ways to improve its economic indicators is to optimize all processes in the chain, from obtaining the raw materials for its production to distributing the products to the end user or applying the concept of so-called supply chains (SC). An additional effect for improving the sustainability has the inclusion in the SC for the production of biodiesel from raw materials of the 1st generation of the processes related to the utilization of the waste from the processing of the raw materials (biomass). The latter leads to improved energy efficiency of this type of production [1, 2] and is associated with optimal management of waste and by-products [3]. An example of such a process is the utilization of sunflower husk in the production of biodiesel sunflower. It can be used to generate steam and electricity for the production needs of refineries, as a substitute for fossil fuels and at the same time has a positive effect on the generated amounts of greenhouse gas emissions [4]. Therefore, the proper choice of raw material, from the point of view of the obtained by-product related to its production, is extremely important for increasing the sustainability of considered biodiesel SC.

This study proposes an approach for optimal design of an integrated 1st generation biodiesel/diesel supply chain from sunflower and rapeseed, using the sunflower husk in order to improve the energy efficiency of production. The approach includes consideration of the stages of the product life cycle, namely: growing the raw material, transporting it to the biorefineries, production of biodiesel and transport to the blending centers. The aim is to simultaneously minimize the amounts of greenhouse gas emissions during the operation of the production system and the total annual operating costs. The optimization is performed by including one of the criteria in the system of constraints and looking for the optimal values of the main criterion.

2. Mathematical Model

2.1. General Formulation of the Problem

The optimization model is formulated in terms of MILP and its solution is related to determining the optimal values of: (1) the number, sizes and locations of bio refinery and installations for the production of sunflower husk pellets; (2) the sites and amount of 1G feedstock; (3) the transportation plans of 1G feedstock, sunflower husk, fossil diesel, glycerine and biodiesel, (Fig. 1).

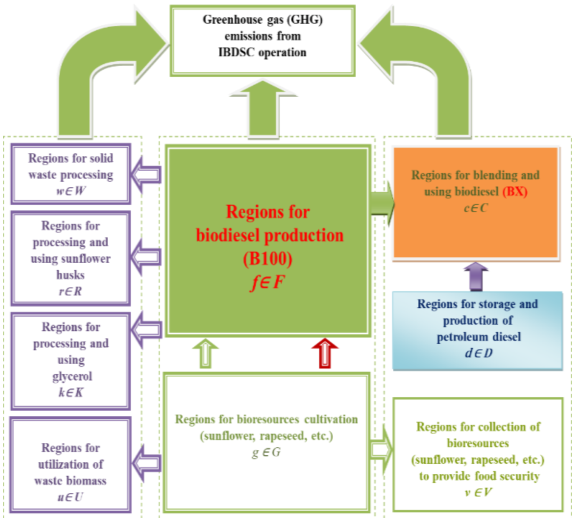


Fig. 1 *Superstructure integrated biodiesel supply chain (IBSC).*

2.2. Mathematical Description

MILP optimization model includes definition of constant parameters and decision variables; models of the environmental impact and the economic performance of IBSC. An objective function and constraints are also included. For the purpose of modelling the set of time intervals of the planning horizon $\tau =$

$\{1,2,\ldots,T\}$ is introduced. The environmental, economic constants and continuous and binary variables are taken from [5].

2.3. Modeling of IBSC Environmental Impact

The environmental impact objective function is defined in terms of total GHG emissions $[\mathrm{kg}_{\mathrm{CO_2eq}}]$ 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; sunflower husk 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 generation of GHG emissions for each time interval $\tau, \tau \in T$. These emissions are equal to the sum of the impact that each of the stages of life cycle has on the environment. The total GHG emissions are defined as follows:

$$(1)\ TEI_t = ELS_t + ELB_t + ELD_t + ETT_t + ESW_t + ESTRAW_t + ECAR_t + E_{RECYCLING\,t}, \forall t$$

where:

TEI_t Total environmental impact of IBSC operation, $[\mathrm{kg}_{\mathrm{CO_2eq}}/\mathrm{d}]$;

$\{ELS_t, ELB_t, ELD_t, ETT_t\}$ Environmental impact of life cycle stages, $[\mathrm{kg}_{\mathrm{CO_2eq}}/\mathrm{d}]$;

ESW_t GHG emissions generated during sunflower husk recovery, $[\mathrm{kg}_{\mathrm{CO_2eq}}/\mathrm{d}]$;

$ESTRAW_t$ GHG emissions generated during residual straw utilization in the regions, $[\mathrm{kg}_{\mathrm{CO_2eq}}/\mathrm{d}]$;

$ECAR_t$ GHG emissions generated during the use of biodiesel(B100) &fossil diesel in vehicles, $[\mathrm{kg}_{\mathrm{CO_2eq}}/\mathrm{d}]$;

$E\_RECYCLING_t$ GHG emissions from the disposal of unused sunflower husks.

2.4. 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:

$$(2)\ TDC_t = TIC_t + TIW_t + TPC_t + TTC_t - TL_t - TA_t - T\_ENERGY_t - T\_PELLETS_t + T\_RECYCLING_t,\ \forall t$$

where:

TDC_t IBSC total costs, $[\$/\mathrm{y}]$;

TIC_T Total investment costs for the production capacity of IBSC to the whole operating period and purchase of the plant, $[\$/\mathrm{y}]$;

TIW_T Total investment costs for IBSC facilities for the production of sunflower husk pellets to the whole operating period and purchase of the plant, $[\$/\mathrm{y}]$;

TPC_T Biodiesel(B100) production costs, $[\$/\mathrm{y}]$;

TTC_T Total IBSC transportation costs, $[\$/\mathrm{y}]$;

TL_t Costs associated with government incentives for biodiesel(B100) production and consumption, $[\$/\mathrm{y}]$;

TA_t Total costs associated with obtained by-products (glycerol, cusp), $[\$/\mathrm{y}]$;

T_ENERGY_t Price of sunflower husks for heat production in biorefineries $[\$/\mathrm{y}]$;

$T\_PELLETS_t$ Price of sunflower husks for pellet production $[\$/\mathrm{y}]$;

$T\_RECYCLING_t$ Price for utilization of unused sunflower husks $[\$/\mathrm{y}]$;

2.5. Constraints

It is introduced a system of constraints on: 1.) Plants capacity; IBSC flow acceptability; 2.) Sunflower husk pellets plants capacity; 3.) Logical constrains; 4.) Transportation links; 5.) Total environmental impact; 6.) Mass balances between biodiesel plants & biomass regions; 7.) Mass balances between biodiesel plants & customers; 8.) Energy balances; 9.) Total network cost.

2.6. 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 sunflower husk pellets facilities which are subject to minimization. The IBSC operating costs include: the raw materials prices, the transportation costs of raw materials to the bio refineries, the cost of conversion to biodiesel and the transportation costs of biodiesel to the blending regions. Economic objective function is represented in terms of the total annual costs for IBSC design:

$$(3)\quad COST = \sum_{t \in T} (LT_t TDC_t),$$

2.7. 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:

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

2.8. Integrated Economic and Environmental Objective Function

The integrated economic and environmental objective function is formulated as follows:

$$(5)\quad Int\_COST = COST + C_{CO_2} \sum_{t \in T} (LT_t \alpha_t TEI_t)$$

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

The total emissions are converted into carbon credits by multiplying with the carbon price C_{CO_2} on the market, where it has a value $[0.149\,\$/\mathrm{kg}_{\mathrm{CO_2eq}}/\mathrm{d}]$.

3. Formulation of the Optimization Problem

The optimization problem is formulated and solved using either economic criterion - the total annualized cost for IBSC design or using the environmental ones such as: the total GHG emissions associated with its operation and the integrated economic and environmental criterion. The remainder criteria are defined as constraints. The aim is to be defined the optimal biodiesel facilities locations in the regions and their parameters. Formulated optimisation problems were solved using GAMS® optimization software-CPLEX solver [6].

4. Case Study

The model efficiency is approved on a case study from Bulgaria. Two main types of biomass resources are used - sunflower and rapeseed for the production of first generation biodiesel (B100).

4.1. 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. In 4 districts in Bulgaria pellets production facilities can be installed (Region_12, Region_14, Region_18, Region_26), 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 (Region_2, Region_15, Region_20) or combined warehouses. In this study, when determining the optimal number of bio refineries, 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-2→19,000 t/y →4.8 M$,

Size-3→48,000 t/y →7.3 M$, Size-4→74,000 t/y →8.9 M$.

The pellets production facilities have a maximum capacity of 85,000 t/y and their installation price is 0.380 M$. The main raw material that is a sunflower husks generator is sunflower. In the present work, the amount of sunflower husks that are generated in the production of tons of biodiesel is 0.431 t/t. They are used to produce the required amount of heat in biorefineries where there are plants for burning sunflower husks and is 0.215 t/t. The remainder amount of sunflower husks is used for the production of pellets. The study assumes that the price of sunflower husks for heat production is 80.00 $/t, and for pellet production is 70.00 $/t. The rest data related with the population, cultivated and free cultivated areas used for crops production are taken from [7].

4.2. Results and Discussion

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

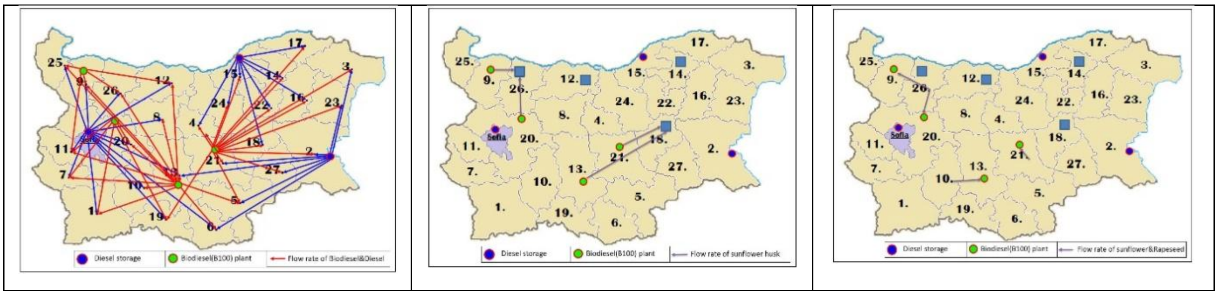
Table 1: *Localization, optimal size and load for biodiesel production from sunflower and rapeseed.*

	Installed biorefineries in the regions				Installations for the production of pellets	
Facility location	**Region-9**	**Region-13**	**Region-20**	**Region-21**	**Region-18**	**Region-26**
Biorefinery size	Size_4	Size_4	Size_4	Size_4	Size_W1	Size_W1
Production of biodiesel from sunflower [t/y]	67,960	73,727	53,244	73,924		
Rapeseed biodiesel production [t/y]	75	75	75	75	[t/y]	
Biodiesel produced by biorefineries [t/y]	68,035	73,803	53,320	74,000		
Sunflower for biodiesel production [t/y]	183,180	198,726	143,515	199,256		
Rapeseed for biodiesel production [t/y]	250	250	250	250		
Sunflower husks for pellets in plants [t/y]					**31,879**	**26,166**
Sunflower husks for heat in biorefineries [t/y]	29,290	31,776	22,948	31,861		
Sunflower husks for cake in biorefineries [t/y]	14,672	15,918	11,493	15,960		
Sunflower husks generated by biorefineries [t/y]	**43,963**	**47,694**	**34,442**	**47,822**		

Table 2: *Results obtained for sunflower and rapeseed biodiesel production*

Years >Biodiesel(B100) fossil diesel ratio	2016>6%	2017>7 %	2018>8 %	2019>9 %	2020>10 %
Objective function value (7) - >1302.642- [M$]					
Objective function value (5) ->14.186 [t_{CO_2eq}]10^6					
Cost for the whole period [M$/y]	**73.434**	**96.266**	**135.441**	**153.440**	**166.025**
Investment for biorrafineries [M$/y]	1.786	2.679	2.679	3.572	3.572
Investment for pellet installations [M$/y]	0.076	0.076	0.076	0.076	0.076
Total biodiesel production costs [M$/y]	76.243	99.354	138.015	158.088	174.097
Costs of pellet production [M$/y]	0.022	0.028	0.035	0.042	0.051
Transport costs [M$/y]	5.645	6.910	8.875	9.960	11.735
Total sanction for CO_2-Ekv for the period [M$/y]	13.813	17.583	22.466	26.747	31.243
Government incentives for biodiesel [M$/y]	-10.193	-12.892	-15.968	-19.357	-23.147
Revenue from the sale of glycerin [M$/y]	-10.032	-12.780	-16.315	-19.465	-22.782
Revenues from the use of flakes for heat production in biorefineries [M$/y]	-2,038,636	-2,578,568	-3,193,708	-3,871,426	-4,629,534
Revenues from the use of pellet flakes [M$/y]	-1.788	-2.008	-1.117	-2.234	-4.063
Total GHG emissions (t_{CO_2eq}/y)	547,683	698,040	892,804	1,063,371	1,242,622
Total quantities of biodiesel and fossil diesel produced per year [t/y]					

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]	**619**	**642**	**729**	**681**	**616**
Distribution of available land [ha]					
Sunflower land for biodiesel [ha]	82,874	96,519	74,751	119,382	188,228
Rapeseed land for biodiesel [ha]	97	7,784	50,964	35,239	195
Sunflower land for food [ha]	1,063,531	1,157,169	1,388,851	1,464,935	1,464,935
Rapeseed land for food [ha]	400,668	336,161	613,987	432,521	1,464,935
Free arable land [ha]	**1,997,379**	**1,952,153**	**1,423,924**	**1,508,037**	**1,508,688**



Flow rate of Biodiesel(B100)$Diesel | *Flow rate of sunflower husk* | *Flow rate of sunflower*

Fig 2. *Optimal IBSC configuration for 2020 for Integrated Economic & Environmental objective function*

5. Conclusion

The optimal arable area needed for growing sunflower and rapeseed, is concentrated in a small number of regions of the country (Region 10, Region 21 and Region 26). In order to obtain the optimal mix of 1G bio resources, using the target function "Minimum total annual costs", in 2020 it is necessary to use 2.39% of the agricultural land for sunflower cultivation and 0.00028% for rapeseed. For the case of the integrated target function (case 6) for IBSC, the average price of biodiesel (B100) for the considered period (2016-2020) is $ 657 / t, while for case 5 of the minimum total GHG emissions, it is $ 698 / t, therefore 16% higher. On the other hand, for case 5 of the environmental criterion used, the total GHG emissions are 9.6% lower than those obtained using the integrated economic and environmental criterion. With regard to the sunflower husks used when using the integrated target function (case 6), about 33.4% of sunflower husks are used for the production of pellets and 66.6% are used for the production of heat in biorefineries.

Acknowledgements

This study was realized with the financial support of National Science Fund, Ministry of Education and Science of the Republic of Bulgaria, Contract No. КП-06-Н37/5/06.12.19.

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