OPTIMAL LOCATION OF BIODIESEL REFINERIES: THE BULGARIAN SCALE

B. Ivanov¹, B. Dimitrova¹, D. Dobrudzhaliev²

¹Process Systems Engineering Laboratory, Institute of Chemical Engineering, Bulgarian Academy of Sciences, Acad. St. Angelov str. Blok. 103, Sofia 1113, Bulgaria
²“Prof. Dr Assen Zlatarov” University, Bourgas, Prof. Yyakimov Str. 1, 8000 Bourgas, Bulgaria

ABSTRACT

Biodiesel has been recognized as an important source of energy that will reduce dependency on petroleum, and have a positive impact on the economy, environment, and society. This paper addresses the optimal facility location of biodiesel supply chains (BSC) under environmental criteria. The environmental objective is measured by total GHG emissions for the whole life cycle. We also propose a mathematical model that can be used to design the supply chain and manage the logistics of biodiesel. The model determines the number, size and location of biorefineries needed to produce biodiesel using the available biomass. A mixed-integer linear programming model is proposed that takes into account infrastructure compatibility, demand distribution, size and location of biorefineries needed to produce biodiesel using the available biomass. The important feature of the model is to account the requirement for crop rotation which is relevant from an agronomic perspective. We use the Bulgaria as the testing ground of the model.

Keywords: biodiesel supply chains, energy crops, crop rotation, MILP model.

INTRODUCTION

With the aim of mitigating emissions, diversifying the energy supply and reducing dependence on imported fossil fuels, the European Union (EU) has set ambitious targets for transition to renewable energy. The integrated energy and climate change policy adopted in 2008 defines general targets of 20 % greenhouse gas reduction, 20 % reduced energy use through increased energy efficiency and a 20 % share of renewable energy by Directive 2009/28/EC [1].

Increased production and use of bioenergy is promoted as a key for reaching the targets, as biomass can replace fossil fuels in the transport sector. In order to explicitly stimulate a shift to renewables in transportation, the European Commission has, in addition to the overall 20 % renewable energy target, set a mandatory target of 10 % renewable energy in transport by 2020 [1], with a transitional target of 5.75 % for 2010 [2].

The most relevant to the problem addressed in this work publications are those on the optimal design and operations of processes (SC). A general review of this area is presented by Shah [3] and Papageorgiou [4].

Zamboni et al. [5] presented a MILP model for the strategic design of biofuel supply networks. The model takes into account the issues affecting a general biodiesel supply chains (BSC) simultaneously, such as agricultural practice, biomass supplier allocation, production site locations and capacity assignments, logistics distribution, transport system optimisation but does not address problems with the stability of yields.

Eksioglu et al. [2] proposed a MILP model for the design and operations of biomass to biorefinery supply chain (SC). The model determines the optimal number, size, location of biorefineries and feedstock collection, as well as the amount of biomass to be processed and shipped, and biomass inventory levels through a multi period formulation.
The last few years have seen an increase in criticism of biofuels, especially regarding first generation biofuels, that are commercially available today and that in general use agricultural feedstocks. The criticism is to a large extent related to issues regarding competition with food production and potential negative environmental impact from biofuel production, in particular associated with effects from land use rotation [6, 7].

Bioenergy is a sustainable solution for energy generation. To achieve its goals, one must create the conditions for sustainable yields of energy crops. According to research conducted in recent years [8, 9] this can be realized by rotation of crops. Further studies [10, 11] in this direction indicate that crop rotation has a beneficial impact on reducing greenhouse gases generated in the cultivation of energy crops.

Crop rotation has been long recognized as a system that can reduce soil erosion, improve soil structure, enhance permeability, increase the soil microbial activity, enhance soil water storage capacity, and increase soil organic matter [12, 13]. Moreover, crop rotation can reduce the use of external inputs through internal nutrient recycling, maintenance of the long-term productivity of the land, avoidance of accumulation of pests associated with monoculture, and consequently increase crop yields [13]. The aforementioned beneficial effects on soil physical, chemical and biological properties can further be improved by combining crop rotations with cover crops and reduced or no tillage practices.

From the literature available in this area it can be concluded that the existing models of BSC account for the basic characteristics but not for the rational use of the available land. They do not include also agronomic conditions for long-term cultivation of crops for biofuel production, such as the ones needed for different bio cultures.

The main objective of this study is to propose an optimisation model that can predict, determine the location and size of biodiesel production plants, given the locations of feedstock and energy demand. The environmental impact based on GHG emissions reduction, calculated through life cycle assessment (LCA), is important in order to ensure proper or wise criteria approach to sustainability and to allow distinguishing the differences between various feedstock as. Fossil emissions meet be also considered, by including costs for emissions, such as tax or tradable emission permits. Sustainability of the work of BSC can be ensured through sustainable supply of bio-resources, that in time guarantee annual rotation areas for different bio cultures.

1. Problem statement

The problem addressed in this work can be formally stated as follows. We are given a set of biofuel crops that can be converted to biodiesel. These include agricultural feedstock’s e.g. sunflower, energy crops, and etc. A planning horizon of one year for government regulations including manufacturing, construction and carbon tax is considered. We are also given a BSC network superstructure, including a set of harvesting sites and a set of demand zones, as well as the potential locations of a number of collection facilities and bio refineries.

Data for biofuel crops production and harvesting are also given. For each demand zone, the biofuel demand is given, and the environmental burden associated with biofuel 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.

1.1. General formulation of the problem

The overall problem can be summarized as:

Given are:

- potential locations of fuel demand centers and their biofuel demand,
- demand for petroleum diesel for each of the demand centers for fuel,
- the minimum required ratio between petroleum diesel and biodiesel for blending,
- biomass feedstock types and their geographical availability,
- specific GHG emission factors of the biodiesel life cycle stages,

The objectives are to maximize the environmental performances of the BSC by optimizing the following decision variables:

Supply chain network structure, locations and scales of biodiesel production facilities and biomass cultivation sites, flows of each biomass type and biodiesel between regions, modes of transport for delivery for biomass and biodiesel (B100), the GHG emissions for each stage in the life cycle, supply strategy for biomass to be delivered to production facilities, distribution processes for

514
biodiesel to be sent to demand zones.

2. MILP model formulation

The role of the optimization model is to identify what combination of options is the most efficient approach to supply the facility.

The problem for the optimal location of biodiesel (B100) production plants and the efficient use of the available land is formulated as a mixed integer linear programming (MILP) model with the following notation:

2.1. Basic relationships:

As noted in item 1 the assessment of BSC production and distribution of biodiesel(B100) will be made by environmental criteria.

2.1.1. Total environmental impact at work on BSC

The environmental impact of the BSC is measured in terms of total GHG emissions \((\text{kg CO}_2 - \text{eq})\) stemming from supply chain activities and the total emissions are converted to carbon credits by multiplying them with the carbon price (per \(\text{kg CO}_2 - \text{eq}\)) in the market.

The environmental objective is to minimize the total annual GHG emission resulting from the operations of the biodiesel supply chains. The formulation of this objective is based on the field-to-wheel life cycle analysis, which takes into account the following life cycle stages of biomass-based liquid transportation fuels:

- biomass cultivation, growth, and acquisition,
- biomass transportation from source locations to processing facilities,
- transportation of biodiesel (B100) facilities to the demand zones,
- local distribution of liquid transportation fuels in demand zones,
- emissions from biodiesel (B100) usage in vehicle operations.

The ecological assessment criterium is the total environmental impact at work on BSC, estimated through the resulting greenhouse gas emissions as proposed in Akgul, O., et al. [14]. These emissions are equal to the sum of the impact of each stage of the life cycle:

\[
TEI = EL_{BC} + EL_{BP} + EL_{TR} + EB_{CAR} \quad (1)
\]

where:
- \(TEI\) Total environmental impact on BSC \((\text{kg CO}_2 - \text{eq} / \text{day})\);
- \(EL_{BC}\), \(EL_{BP}\), \(EL_{TR}\) Environmental impact of the life cycle stage \((\text{kg CO}_2 - \text{eq} / \text{day})\);
- \(EB_{CAR}\) Emissions from biodiesel (B100) usage in vehicle operations \((\text{kg CO}_2 - \text{eq} / \text{day})\).

The evaluation of the environmental impact at every stage \(s \in S\) of the life cycle estimates:
- A. Growing biomass;
- B. Production of biodiesel (B100);
- C. Transportation resources (biomass and biodiesel (B100)).

The greenhouse gases to grow biomass \(EL_{BC}\) are:

\[
EL_{BC} = \sum_{i} \sum_{g \in G} \left( EF_{BC_{ig}} P_{BB_{ig}} \right) \quad (2)
\]

where, \(EL_{BC}\) denotes the total environmental impact \((\text{kg CO}_2 - \text{eq} / \text{day})\) of biomass cultivation, which in general represents the production rate of resource \(i\) in region \(g \in G\), in this equation it refers to the cultivation rate of biomass \(i \in I\) in that region.

The total emissions from biodiesel (B100) production \(EL_{BP}\) are determined by the equation:

<table>
<thead>
<tr>
<th>Sets/Indices</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set of biomass types indexed by (i);</td>
<td>(I)</td>
</tr>
<tr>
<td>Set of transport modes for biomass indexed by (l);</td>
<td>(L)</td>
</tr>
<tr>
<td>Set of transport modes for biodiesel is a subset of (L (B \subseteq L)) indexed by (b);</td>
<td>(B)</td>
</tr>
<tr>
<td>Set of life cycle stages of a BSC indexed by (s);</td>
<td>(S)</td>
</tr>
<tr>
<td>Set of plant size intervals indexed by (p);</td>
<td>(P)</td>
</tr>
<tr>
<td>Set of regions of the territorial division indexed by (g);</td>
<td>(G)</td>
</tr>
<tr>
<td>Set of candidate regions for biodiesel plants established, which is a subset of (G) indexed by (f);</td>
<td>(F)</td>
</tr>
<tr>
<td>Set of biodiesel customer zones, which is a subset of (G (C \subseteq G)) indexed by (c).</td>
<td>(C)</td>
</tr>
</tbody>
</table>
Where $E_{BP}$ is total environmental impact of biodiesel (B100) production ($CO_2 - eq / day$).

The environmental impact of transportation $E_{TR}$ is calculated by:

$$E_{TR} = \sum_{i=1}^{n} \sum_{g \in G} \sum_{f \in F} \sum_{c \in C} \left( EFTRA_{gi} ADD_{gfl} QI_{gfl} \right)$$

$$+ \sum_{j=1}^{m} \sum_{l \in L} \sum_{b \in B} \sum_{c \in C} \left( EFTRB_{bj} ADF_{jcb} QB_{jcb} \right)$$

where $E_{TR}$ is environmental impact of transportation of resources ($kg CO_2 - eq / day$);
Emissions from biodiesel (B100) usage in vehicle operations $EB_{CAR}$:

$$EB_{CAR} = \sum_{f \in F} \sum_{c \in C} \sum_{b \in B} (ECB \cdot QB_{fb})$$  \hspace{1cm} (5)

where $EB_{CAR}$ is emissions from biodiesel usage in vehicle operations (kg CO$_2$ - eq/day).

2.1.2. Total environmental impact of the used fuels (biodiesel (B100) and diesel) to provide the energy balance of the region

The environmental goal is to reduce the annual equivalent of GHG emission, resulting from the operations of SC of biodiesel and petroleum diesel to meet the energy needs of the regions.

The annual equivalent of greenhouse gases by the used fuels is determined by the equation:

$$TEIF = TEI + EG_{CAR}$$  \hspace{1cm} (6)

where

$TEIF$ Total environmental impact of the used fuels (biodiesel (B100) and petroleum diesel) to provide the energy balance of the region (kg CO$_2$ - eq/day);

$TEI$ Total environmental impact at work on BSC (kg CO$_2$ - eq/day).

$EG_{CAR}$ Emissions from petroleum diesel usage in vehicle operations (kg CO$_2$ - eq/day);

Emissions from diesel $EG_{CAR}$ vehicles used, to supplement the energy balance:

$$EG_{CAR} = \sum_{c \in C} \left( ECG \cdot QEO_c \right)$$  \hspace{1cm} (7)

2.2. Restrictions

2.2.1. Plants capacity limited by upper and lower constrains

Plants capacity is limited by upper and lower bounds as indicated by Eqs. (8), where the minimal production level in each region is obtained by:

$$\sum_{p \in P} (PB_{p,MIN} \cdot Z_{pf}) \leq \alpha f \sum_{c \in C} \sum_{b \in B} QB_{fb} \leq \sum_{p \in P} (PB_{p,MAX} \cdot Z_{pf}), \quad \forall f \in F$$  \hspace{1cm} (8)

2.2.2. Balance of biodiesel (B100) to be produced from biomass available in the regions

$$\sum_{c \in C} QEB_c \leq \sum_{i \in I} \sum_{g \in G} (\gamma_i B_{mc} A_{ig})$$  \hspace{1cm} (9)

Table 3. Decision variables for the problem.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
<th>Domain</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$PBB_{ig}$</td>
<td>Production rate of biomass $i$ in region $g$;</td>
<td>ton / day</td>
<td>R+</td>
<td>Continuous</td>
</tr>
<tr>
<td>$QI_{igl}$</td>
<td>Flow rate of biomass $i$ via mode $l$ from region $g$ to $f$;</td>
<td>ton / day</td>
<td>R+</td>
<td>Continuous</td>
</tr>
<tr>
<td>$QB_{fb}$</td>
<td>Flow rate of biodiesel via mode $b$ from region $f$ to $c$;</td>
<td>ton / day</td>
<td>R+</td>
<td>Continuous</td>
</tr>
<tr>
<td>$QEO_c$</td>
<td>Quantity of petroleum diesel to be supplied to meet the energy needs of the region $c$;</td>
<td>ton / year</td>
<td>R+</td>
<td>Continuous</td>
</tr>
<tr>
<td>$QEB_c$</td>
<td>Quantity of biodiesel (B100) to be supplied to meet the energy needs of the region $c$;</td>
<td>ton / year</td>
<td>R+</td>
<td>Continuous</td>
</tr>
<tr>
<td>$A_{ig}$</td>
<td>Land occupied by crop $i \in I$ in region $g$;</td>
<td>ha</td>
<td>R+</td>
<td>Continuous</td>
</tr>
<tr>
<td>$A_{ig}^F$</td>
<td>Land occupied by crops $i \in I$ needed for food security.</td>
<td>ha</td>
<td>R+</td>
<td>Continuous</td>
</tr>
<tr>
<td>$X_{igl}$</td>
<td>0-1 variable, equal to 1 if a biomass type $i \in I$ is transported from region $g \in G$ to $f \in F$ using transport $l \in L$ and 0 otherwise</td>
<td>(0 or 1)</td>
<td>Binary</td>
<td></td>
</tr>
<tr>
<td>$Y_{fb}$</td>
<td>0-1 variable, equal to 1 if a biodiesel is transported from region $f \in F$ to $c \in C$ using transport $b \in B$ and 0 otherwise</td>
<td>(0 or 1)</td>
<td>Binary</td>
<td></td>
</tr>
<tr>
<td>$Z_{pf}$</td>
<td>0-1 variable, equal to 1 if a plant size $p \in P$ is installed in $f \in F$ and 0 otherwise</td>
<td>(0 or 1)</td>
<td>Binary</td>
<td></td>
</tr>
</tbody>
</table>
2.2.3. Logical constraints

A. Restriction guarantees that a given region \( g \in G \) installed power plant with \( p \in P \) for biodiesel (B100) production

Constraint (10) states that can be chosen only one size for each facility.

\[
\sum_{p \in P} Z_{pf} \leq 1, \quad \forall f \in F
\]  

B. Limitation ensure the availability of at least one connection to a region of bioresources and region for biofuel

\[
\sum_{g \in G} \sum_{l \in L} X_{igl} \geq \sum_{c \in C} \sum_{b \in B} Y_{fbg} \sum_{p \in P} Z_{pf}, \quad \forall i \in I, \forall f \in F
\]  

C. Limit which guarantees that each region will provide only one plant with a biomass type \( i \)

\[
\sum_{f \in F} \sum_{l \in L} X_{igf} \leq 1, \quad \forall i \in I, \forall g \in G
\]  

D. Limitation of assurance that at least one region \( g \in G \) producing biomass is connected to a plant located in a region \( f \in F \)

\[
\sum_{b \in B} Y_{fb} \leq 1, \quad \forall f \in F, \forall c \in C
\]  

2.2.4. Transport links

Restrictions on transportation of biomass are

\[
PBI_{mg}^{MIN} \sum_{l \in L} X_{igl} \leq \sum_{l \in L} QI_{igl}, \quad \forall i \in I, \forall g \in G, \forall f \in F
\]  

2.2.5. Restriction for total environmental impact of all regions

\[
TEIF \leq TEIF^{MAX}
\]  

where \( TEIF^{MAX} \) are the maximum permissible values for the total environmental impact of the biodiesel (B100) network of supply chain and fossil fuel in the regions (\( kg \ CO_{2} \)-eq/day).

2.2.6. Mass balances between biodiesel (B100) plants and biomass regions

The connections between biodiesel (B100) plants and biomass regions are given by:

\[
\sum_{i \in I} \sum_{g \in G} \sum_{l \in L} \sum_{rel} \sum_{b \in B} (Y_{fbg} \cdot QI_{igl}) \leq \sum_{p \in P} (PBI_{mg}^{MAX} \cdot Z_{pf}), \quad \forall f \in F
\]  

2.2.7. Mass balances between biodiesel (B100) plants and biofuel customer zones

\[
\sum_{b \in B} \sum_{f \in F} \sum_{c \in C} (\alpha f_c QF_{kb} \cdot Z_{fc}) \leq ZB_{c}^{MAX}, \quad \forall c \in C
\]  

2.2.8. Limitation guaranteeing crop rotation

The crop rotation allows to ensure control of pests, improve soil fertility, maintenance of the long-term productivity of the land, and consequently increase the yields and profitability of the rotation [15, 16]. The combination of crop rotation and fallowing is a common practice that is gaining momentum again due to environmental benefits and promoted reduction in the dependence on external inputs.

Crop rotation implemented in a region \( g \in G \) means that the growing area of energy crops are rotated so that the next time the same area is used by other crops grown under are optimal scheme of crop rotation. This can be achieved if for land \( A_g \) and \( A^F_g \) inequalities are implemented:

\[
(A_g + A^F_g) \leq (A^F_g - A^F_g^{food}), \quad \forall i \in I, \forall g \in G
\]  

2.2.9. Energy restriction

A. Limitation ensuring that the overall energy balance in the region is provided

\[
ENO \sum_{c \in C} QEO_c + ENB \sum_{c \in C} QEB_c \geq ENO \sum_{c \in C} YO_c
\]  

B. Limitation ensuring that each region will be provided in the desired proportions with fuels

\[
ENB QEB_c \geq K_{min} ENO YO_c, \quad \forall c \in C
\]  

2.3. Optimization problem formulation

The problem for the optimal design of a biodiesel supply chain is formulated as a mixed integer linear programming (MILP) model for the objective function of Minimizing GHG emissions.

As discussed in section 2.1.1., the environmental objective is to minimize the total annual \( CO_2 \)-equivalent greenhouse gas emissions resulting from the operations of the biodiesel supply chain and diesel, used to provide the energy balance of the regions. The formulation of this objective is based on total the GHG emissions in the supply chain and other fuels are estimated, throw LCA approach, where emissions are added for every life stage.

The task of determining the optimal location of facilities in the regions and their parameters is formulated as follows:

\[
\begin{aligned}
&\text{MINIMIZE } \{TEIF\} \rightarrow \text{(Eq.6)} \\
&\text{subject to } \{\text{Eq.8\)-(Eq.20)}\}
\end{aligned}
\]
The problem (26) is an ordinary Mixed Integer Linear Program (MILP) and can thus be solved using standard MILP techniques. The present model was developed in the commercial software GAMS [17] using the solver CPLEX. The model chooses the least costly pathways from one set of biomass supply points to a specific plant and further to a set of biodiesel (B100) demand points. The final result of the optimization problem would then be a set of plants together with their corresponding biomass and biodiesel (B100) demand points.

3. CASE STUDY: POTENTIAL BIODIESEL (B100) PRODUCTION IN BULGARIA

The model described in point 2 has been applied to a case study of biodiesel (B100) production in Bulgaria. Two major types of biomass resources, sunflower and rapeseed for production of first generation biodiesel (B100) are used.

One demand scenario have been investigated based on the Bulgaria domestic target for 2010 (5.75% by energy content) [18] to promote the use of biofuels.

3.1. Model input data

3.1.1. Territorial division of Bulgaria and data on energy consumption of petroleum diesel for transport

According to the Geodesy, Cartography and Cadastre Agency of the Ministry of Regional Development and Public Works, the territorial balance of the Republic of Bulgaria as of 31.12.2000, Bulgaria’s total area is 111001.9 square kilometers. Of these agricultural land is 63764.8 square kilometers. From this land the arable land and utilized agricultural area for 2011 is 3,162,526 hectares [15]. Areas that are employed for to feedstocks for 2011 are: 734,314 ha for sunflower and 209,347 ha, for industrial oleaginous crops, including rapeseed.

3.1.1.1. Territorial division of Bulgaria

Bulgaria has 27 regions. In this case study, each region is considered to be a feedstock production region, a potential location of an biorefinery facility and a demand zone. In other words, the biofuel supply chain network consists of 27 areas for feedstock production, 27 potential biorefinery locations and 27 demand zones. In the case study, we assumed a 10-year service life of biorefineries, and the fixed cost parameter for building refineries is amortized into annual cost to be consistent with other cost components.

For the purposes of this study, data on population, cultivated area, as well as the free cultivated area, which in principle can be used for the production of energy crops for biodiesel (B100) production are taken from [15]. For 2011 we know consumption of petroleum diesel fuel for transportation for the country which is 1,711,000 tons. For the purposes of this study we assume that the consumption of petroleum diesel fuel for each region is approximately proportional to its size.

3.1.1.2. Data on energy consumption of petroleum diesel for transport by regions

In [12] are presented data for the distribution of cultivated area for each region, population size and fixed consumption of petroleum diesel fuel for transport.

3.1.2. Feedstock supply chain components for biodiesel (B100) production in Bulgaria

Biodiesel (B100) is produced from vegetable oils, which are derived from the seeds or the pulp of a range of oil-bearing crops. These oil crops for the Bulgarian climate are rapeseed and sunflower. Oil from sunflower was the first type used for biodiesel (B100) production.

3.1.3. Emission factor for cultivation of rapeseed and sunflower

Greenhouse gas emissions in the agronomy phase for cultivation of sunflower and rapeseed lifecycle phases include soil preparation, seeding, tillage, fertilization, and finally harvest [10].

For different regions in Bulgaria, the aggregate GHG emissions for the entire life cycle of growing energy crops vary greatly depending on terrain, weather conditions, the technology of growing crops and imported fertilizer to increase yields.

The emission factors for cultivation of one ton of sunflower and rapeseed for Bulgaria are: sunflower is in the range \( \frac{600-1700}{1700} \) kg CO\(_2\) eq, depending on the region and for rapeseed is in the range \( \frac{400-1350}{1350} \) kg CO\(_2\) eq. This study uses for all regions average emission factors for one ton sunflower 1100 and for rapeseed 850, respectively.

3.1.4. Yield of rapeseed and sunflower

Yields from rapeseed strongly depend on the region in which they are grown, as well as the technology of cultivation [10]. For the purposes of this study averages used are: sunflower is \( \beta_{sa} = 2.2 \) ton/ha and rapeseed is 2.6 ton/ha, equal for all 27 regions.

3.1.5. Feedstock that is required to ensure food security in Bulgaria

For ensuring food security in terms of sunflower and rapeseed in Bulgaria the used data were taken from [15]. The data for 2011 are 376,824 tons for rapeseed...
and 1,321,765 ton for sunflower, respectively

### 3.1.6. Potential sites for locations of biorefineries in Bulgaria

All 27 regions were selected as the candidate biorefinery locations, dispersed across the Bulgarian territory.

### 3.1.7. The technology of biodiesel (B100) production used in this study

This study is based on the use of technology for producing biodiesel (B100) by esterification of vegetable oils. It is assumed that pure vegetable oil is obtained from rapeseed oil trans or sunflower by mechanical pressing or solvent extraction. This technology for extracting oil from oilseeds has remained the same for the last 10 - 15 years and is not likely to change significantly.

### 3.1.8. Biomass to biodiesel (B100) conversion factor

Conversion efficiency of rapeseed and sunflower into biodiesel (B100) ranges from 389 \( l/ton \) to 454 \( l/ton \) [14]. We use a conversion efficiency of 421 \( l/ton \) (371 kg/ton) for sunflower and 344 \( l/ton \) (303 kg/ton) for rapeseed, which is the average of the lowest and highest conversion efficiency found in literature.

### 3.1.9. Data for biodiesel (B100) and petroleum diesel

The data necessary for the purposes of this study were taken from the literature [11, 16, 17].

### 3.1.10. Biodiesel (B100) and petroleum diesel proportion, subject of mixing

The national indicative targets for consumption of biofuels in Bulgaria are considered those set out in Directive 2003/30/EC and adopted by the European Council (8-9 March 2007). In the above documents the indicative target of 5.75% for 2010 is set.

### 3.1.11. Data for actual delivery distance between regions in Bulgaria

The distances in kilometers between settlements in Bulgaria for the purposes of this study were taken from the National Transport Agency for each type of transport (Tractor, Truck, Rail).

### 3.2. Computational results and analysis

The mathematical model proposed in section 2 of this work was used to solve the case study on the conditions of Bulgaria. The waín results are presented here under.

#### 3.2.1. Biomass supply

The optimal biomass flows are given in Table 4.

#### 3.2.2. Distribution of greenhouse gases stages of the life cycle of biodiesel (B100)

Table 5 shows the distribution of greenhouse gas life cycle stages of biodiesel (B100).

#### 3.2.3. Distribution of land

#### 3.2.4. Biodiesel (B100) production plant locations

#### 3.2.5. Summary of computational results

The proposed model was solved in GAMS 22.8 using CPLEX 11.1 solver on an Intel Core 2 Duo P8600 2.4 GHz with 4 GB RAM on a 32-bit platform. The mixed integer linear model is composed of 13510 constraints and 12123 variables (of which 6102 are binary variables, which rep-

---

### Table 4. Flow rate of biomass from growing region to biodiesel (B100) plants.

<table>
<thead>
<tr>
<th>No</th>
<th>Name of regions</th>
<th>Type of transport</th>
<th>Type of energy crops</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>TRACTOR</td>
<td>RAIL</td>
<td>ton / day</td>
</tr>
<tr>
<td>1.</td>
<td>Region-10 to Region-9</td>
<td>1.00</td>
<td>Sunflower</td>
<td>405.76</td>
</tr>
<tr>
<td>2.</td>
<td>Region-10 to Region-10</td>
<td>1.00</td>
<td>Rapeseed</td>
<td>517.42</td>
</tr>
<tr>
<td>3.</td>
<td>Region-21 to Region-21</td>
<td>1.00</td>
<td>Sunflower</td>
<td>77.98</td>
</tr>
<tr>
<td>4.</td>
<td>Region-25 to Region-26</td>
<td>1.00</td>
<td>Rapeseed</td>
<td>384.55</td>
</tr>
</tbody>
</table>

### Table 5. Distribution of greenhouse gases stages of the life cycle.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Criteria: Minimum GHG emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>kg CO₂ – eq / day %</td>
<td></td>
</tr>
<tr>
<td>1. GHG emission to grow</td>
<td>598253.76</td>
</tr>
<tr>
<td>2. GHG emission for biofuel production</td>
<td>809051.27</td>
</tr>
<tr>
<td>3. GHG emission of transportation</td>
<td>2914.98</td>
</tr>
<tr>
<td>4. GHG emission from biofuel usage</td>
<td>490033.59</td>
</tr>
<tr>
<td>Total GHG emission for BSC</td>
<td>1900253.61</td>
</tr>
</tbody>
</table>
Table 6. Distribution of arable land.

<table>
<thead>
<tr>
<th></th>
<th>Criterion: Minimum GHG emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>ha</td>
</tr>
<tr>
<td>1. BIOFUELS Land</td>
<td>99264</td>
</tr>
<tr>
<td>2. RESERVATION Land</td>
<td>1613611</td>
</tr>
<tr>
<td>3. FOOD Land</td>
<td>668093</td>
</tr>
<tr>
<td>4. FREE Land</td>
<td>846267</td>
</tr>
</tbody>
</table>

Table 7. Location of biorefinery, Min/Max capacity and annual production.

<table>
<thead>
<tr>
<th>No</th>
<th>Biodiesel(B100) production plant locations</th>
<th>MIN Capacity of Plants</th>
<th>MAX Capacity of Plants</th>
<th>Annual Biodiesel produced</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Units</td>
<td>ton / year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Region-9 ⇒ Lovech</td>
<td>30000</td>
<td>68000</td>
<td>30829</td>
</tr>
<tr>
<td>2</td>
<td>Region-10 ⇒ Pleven</td>
<td>30000</td>
<td>68000</td>
<td>39286</td>
</tr>
<tr>
<td>3</td>
<td>Region-21 ⇒ Rouse</td>
<td>1000</td>
<td>8500</td>
<td>6000</td>
</tr>
<tr>
<td>4</td>
<td>Region-26 ⇒ Varna</td>
<td>25000</td>
<td>50000</td>
<td>29222</td>
</tr>
</tbody>
</table>

We propose a mathematical model that can be used to design and manage the supply chain. We use Bulgaria as a case study to show how this model can be used to identify potential location for biorefineries, and give insights about the factors that impact the delivery cost of biodiesel (B100).

The data used to validate the model and perform the computational analyses presented above is collected from a number of sources, such as research articles and statistical yearbooks for Bulgaria. Due to the availability of data, we consider only two major sources of biomass feedstock- sunflower and rapeseed which are relevant for the practical application of this model.

We focus on the eco comparable behavior of the stakeholders in the biofuel supply chain, and incorporate them into the supply chain design model.

We firstly developed a model that includes the problem of crop rotation. We believe this is important for the practical application of this model.

Fig. 1. Optimal BG biodiesel(B100) supply chain configuration.
Based on the inputs and outputs of the optimal synthesis with the criterion for Minimum GHG emissions (see Table 8), we establish that about 31% of the emissions come from growing biomass, approximately 42% are for biofuel production and 25% from biofuel usage. GHG emission of transportation is only 0.15%. Improvements in the technology of converting biomass feedstock to biodiesel have a high impact on the unit cost of biodiesel (B100). This is due to the fact that less biomass will be required to produce the same amount of biodiesel. As a result, less biomass will be harvested and transported. This in turn will decrease the GHG emissions for producing a ton of biodiesel (B100).

Future study could consider involvement as feedstocks other energy sources such as waste oils from food and/or livestock.

**REFERENCES**


---

**Table 8. Summary of computational results.**

<table>
<thead>
<tr>
<th>Units</th>
<th>Criterion: Min. GHG emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. Total GHG emission</td>
<td>kg CO$_2$ – eq / day</td>
</tr>
<tr>
<td>25347651.82</td>
<td></td>
</tr>
<tr>
<td>Min. GHG emissions BSC</td>
<td>kg CO$_2$ – eq / day</td>
</tr>
<tr>
<td>1900253.61</td>
<td></td>
</tr>
<tr>
<td>GHG emission for diesel</td>
<td>kg CO$_2$ – eq / year</td>
</tr>
<tr>
<td>23447398.21</td>
<td></td>
</tr>
<tr>
<td>GHG emission to grow biomass</td>
<td>kg CO$_2$ – eq / day</td>
</tr>
<tr>
<td>598253.76</td>
<td></td>
</tr>
<tr>
<td>GHG emission for production:</td>
<td>kg CO$_2$ – eq / day</td>
</tr>
<tr>
<td>809051.27</td>
<td></td>
</tr>
<tr>
<td>GHG emission from transport:</td>
<td>kg CO$_2$ – eq / day</td>
</tr>
<tr>
<td>2914.98</td>
<td></td>
</tr>
<tr>
<td>GHG emission from biofuel:</td>
<td>kg CO$_2$ – eq / day</td>
</tr>
<tr>
<td>490033.59</td>
<td></td>
</tr>
<tr>
<td>Total Land all regions:</td>
<td>ha</td>
</tr>
<tr>
<td>3227237.00</td>
<td></td>
</tr>
<tr>
<td>Total BIOFUELS Land:</td>
<td>ha</td>
</tr>
<tr>
<td>99264.74</td>
<td></td>
</tr>
<tr>
<td>Total RESERVATION Land:</td>
<td>ha</td>
</tr>
<tr>
<td>1613611.00</td>
<td></td>
</tr>
<tr>
<td>Total FOOD Land:</td>
<td>ha</td>
</tr>
<tr>
<td>668093.45</td>
<td></td>
</tr>
<tr>
<td>Total FREE Land:</td>
<td>ha</td>
</tr>
<tr>
<td>846267.81</td>
<td></td>
</tr>
<tr>
<td>Sunflower Land for biodiesel(B100):</td>
<td>ha</td>
</tr>
<tr>
<td>285.71</td>
<td></td>
</tr>
<tr>
<td>Rapeseed Land for biodiesel(B100):</td>
<td>ha</td>
</tr>
<tr>
<td>98979.03</td>
<td></td>
</tr>
<tr>
<td>Sunflower Land for foods:</td>
<td>ha</td>
</tr>
<tr>
<td>514930.25</td>
<td></td>
</tr>
<tr>
<td>Rapeseed Land for foods:</td>
<td>ha</td>
</tr>
<tr>
<td>153163.20</td>
<td></td>
</tr>
<tr>
<td>FOOD&amp;BIOFUEL(Sunflower):</td>
<td>ha</td>
</tr>
<tr>
<td>515215.96</td>
<td></td>
</tr>
<tr>
<td>FOOD&amp;BIOFUEL(Rapeseed):</td>
<td>ha</td>
</tr>
<tr>
<td>252142.23</td>
<td></td>
</tr>
<tr>
<td>Diesel to meet the energy:</td>
<td>ton / year</td>
</tr>
<tr>
<td>1710987.00</td>
<td></td>
</tr>
<tr>
<td>Biodiesel(B100) in regions:</td>
<td>ton / year</td>
</tr>
<tr>
<td>105338.26</td>
<td></td>
</tr>
<tr>
<td>Diesel in regions:</td>
<td>ton / year</td>
</tr>
<tr>
<td>1617954.61</td>
<td></td>
</tr>
<tr>
<td>GHG emission by biodiesel(B100):</td>
<td>kg CO$_2$ – eq / ton biodiesel</td>
</tr>
<tr>
<td>4509.80</td>
<td></td>
</tr>
<tr>
<td>GHG emission by diesel:</td>
<td>kg CO$_2$ – eq / ton diesel</td>
</tr>
<tr>
<td>3623.00</td>
<td></td>
</tr>
</tbody>
</table>


10. Alfredo Iriarte, Joan Rieradevall, Xavier Gabarrell, Life cycle assessment of sunflower and rape-seed as energy crops under Chilean conditions, Journal of Cleaner Production, 2010, 18, 336-345


