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Optimal design and planning of biodiesel supply chain considering crop rotation model
Part 1. Mathematical model formulation of the problem

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This paper addresses the optimal design and location facility of biodiesel supply chains (BSC) under economic and environmental criteria. The economical aspect scale is assessed by the total annualized cost. The environmental objective is evaluated by the total GHG (Green House Gases) emissions for a whole life cycle. A mathematical model that can be used to design the supply chain (SC) and manage the logistics of a biodiesel is proposed. The model determines the number, size and location of biorefineries needed to produce biodiesel using the available biomass. Mixed-integer linear programming model is proposed that takes into account infrastructure compatibility, demand distribution, as male as the size and location of biorefineries needed to produce biodiesel using the available biomass and carbon tax. An important feature of the model proposed is the account requirement of crop rotation important from agronomic perspective. In second part of this study Bulgaria is examined as the testing ground of the model.

KEYWORDS: Biodiesel supply chains, Energy crops, Production cost, Carbon tax, Crop rotation, MILP

INTRODUCTION

Aimed at mitigating emissions, diversifying the energy supply and reducing dependence on imported fossil fuels, the European Union (EU) has set ambitious targets for a 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 2020 [8].

Among the available alternative energy sources that would help to respond to such challenges, biomass crops have many advantages over conventional energy and over some other renewable energy sources (e.g. wind, photovoltaic, etc.). In particular, this is due to reduced dependence on short-term weather changes, promotion of regional economic structures and provision of alternative sources of employment in rural areas.

Becouse biomass can replace fossil fuels in the transport sector increased production and use of bioenergy is promoted as a key to facher the targets. In order to explicitly stimulate a shift to renewables in transportation, thes European Commission has, in addition to the overall 20% renewable energy target, set a mandatory target of 10% renewable energy in transport by 2020 [8], with a transitional target of 5.75% for 2010 [4].

A number of policy instruments that directly or indirectly affect the production and use of biofuels are today in place in the EU. Targeted biofuel policies such as exemption from or reduction of transport fuel taxes, quotas and blend obligations effect directly the competitiveness and market shares of biofuels.

This paper presents development and use of a optimisation model suitable for extensive analysis of biofuel production scenarios aimed at determiniation and investigation of advantageous locations for biodiesel production. The main focus is on assessing how different parameters affect biodiesel production regarding costs, plant locations, production volumes and the possibility of reducing global fossil emissions. Key parameters to be studied are economic policy instruments affecting biodiesel production, such as targeted biofuel support and the cost for emitting, energy prices, feedstock costs and availability, and capital

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costs. The above mentioned 5.75% share of biofuels for meeting the 2010 target is used as a starting point, with the analysis focusing on boundary conditions that affect the possibility of meeting this goal.

The paper is focused on the creation of conditions for stable operation of BSC by providing a stable supply of feedstock. According to recent research in agricultural activities [21,17,12,18] crop rotation is the basis for sustainable yields. The model proposed includes conditions for crop rotation as realistic ones.

LITERATURE REVIEW

The papers most relevant to the problem addressed in this work are on the optimal design and operations of the process (SC). A general review of this area is presented by *Shah (2005)* [5] and *Papageorgiou (2009)* [9]. Some recent work specifically focused on BSCs is reviewed below.

Zamboni et al. (2009) [10] presented a MILP model for the strategic design of biofuel supply networks. The model takes into account the issues affecting a general BSC simultaneously, such as agricultural practice, biomass supplier allocation, production site locations and capacity assignment, logistics distribution, and transport system optimisation.

Eksioglu et al. (2009) [11] proposed a MILP model for the design and operations of a biomass to biorefinery SC. The model determines the optimal number, size, and 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.

Recently, Kim et al. (2011) [13] proposed a MILP model for the optimal design of biorefinery supply chains. The model aims to maximize the overall profit and takes into account different types of biomass, conversion technologies, and several feedstock and plant locations.

Another recent contribution in this area is the work by *Aksoy et al. (2011)* [14]**.** The authors investigated four biorefinery technologies for feedstock allocation, optimal facility location, economic feasibility, and their economic impacts in Alabama, through a MILP based facility location model that minimizes the total transportation cost and takes into account county-level information.

Akgul et al. (2011) [15] presented recently a MILP model based on the one proposed by *Zaboni et al. (2009)* [10] for the optimal design of a bioethanol SC with the objective of minimizing the total SC cost. Their model aims to optimize the locations and scales of the bioethanol production plants, biomass and bioethanol flows between regions, and the number of transport units required for the transfer of these products between regions as well as for local delivery. The model also determines the optimal bioethanol production and biomass cultivation rates.

You and Wang (2011) [16] recently addressed the life cycle optimisation of biomass-to-liquids SC under the economic and environmental criteria. Their work shows that distributed biomass processing followed by centralized upgrading of intermediates may lead to economically viable and environmentally sustainable biofuels supply chains.

Akgul, O., et al. (2012) [18] presents a multi-objective, static modeling framework for the optimisation of hybrid first/second generation biofuel supply chains. Using the proposed modelling framework, different aspects are analysed including the potential GHG savings, the impact of carbon tax on the economic and environmental performance of a BSC, the trade-off between the economic and environmental objectives and the maximum bioethanol throughput that can be achieved at different cap levels on the total SC cost. The trade-off between the conflicting objectives is analysed by solving the proposed multi-objective model using the ε-constraint method.

Bioenergy represent a sustainable solution for energy generation. To achieve these goals, one must create the conditions for sustainable yields of energy crops. According to research conducted in recent years [17,18] this can be achieved by rotation of crops. Further studies [12,21] 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 [1,2]. 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 [2]. 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

An additional novelty of our work is that the proposed model takes into account most of the major characteristics of the BSC and is integrated with LCA. From the literature available in this area it can be concluded that the models of BSC biofuels used account for the basic characteristics but no works go into details to account for the rational use of the available land. The models do not include also agronomic conditions for long-term cultivation of crops for biofuel production such as the ones the needed for different bio cultures.

AIM

The main objective this sudy is to propose an optimisation model hat could predic determine location and size of biodiesel production plants, given the locations of feedstock and energy demand. The model comed minimise the costs of the complete BSC of the studied system, including biomass harvest, biomass transportation, and conversion to biodiesel, transportation and delivery of biodiesel. Economic performances can be evaluated in terms of Net Present Value (NPV). Environmental impact based on GHG emissions reduction, calculated through 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 emisions, such as tax or tradable emission permits. Sustainability of the work of BSC can be ensured through sustainable supply of bio-resources, that in turnis guaranteed by annual rotation areas for different bio cultures.

PROBLEM STATEMENT

The problem addressed in this work can be stated formally, as follows. A set of biofuel crops that can be converted to biodiesel. These includes agricultural e.g. sunflower, energy crops and a.s.o. A planning horizon of one year government regulations including manufacturing, construction and carbon tax is considered. 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 is descanted. Feed stocks can be shipped to the bio refineries directly.

Unit cost and emission data for biofuel crops production and harvesting are also given. For each potential collection facility, we the fixed and variable cost of facility construction are given. For each potential biorefinery given the cost of production for different levels and capacity.

For each demand zone, the biofuel demand is given, and the environmental burden associated with biofuel distribution in local region is known. For each transportation link, the transportation capacity (in both volume and weight), available transportation modes, unit transportation cost of each mode, transportation distance, and emissions of each transportation type are known.

General formulation of the problem

Finally, the overall problem can be summarized as:

Given are:

- potential locations of biofuel demand centers and their biofuel demand,
- demand for liquid fuels (diesel) for each of the demand centers for fuel,
- the minimum required ratio between classical proportions fuels and biofuels for blending,
- biomass feedstock types and their geographical availability,
- unit biomass cultivation cost for each feedstock type,
- unit production cost of biodiesel based on the technology and feedstock type,
- transport logistics characteristics (cost, modes),
- capital investment cost for the biodiesel production facilities,
- specific GHG emission factors of the biodiesel life cycle stages,
- carbon tax,
- government incentives for biodiesel production and use.

MATHEMATICAL FORMULATION OF THE PROBLEM

Given the scenario, the role of the optimization model is to identify what combination of options is most efficient to supply the facility. A very important efficiency measure is to minimize the facility supply cost taken as a present value.

The problem for optimal location of biodiesel (B100) production plants and efficient use of the available land is formulated as a mixed integer linear programming (MILP) model with the notations, given in **Tables 1-3**.

As noted in item 3, the assessment work of BSC production and distribution of biodiesel (B100) will be carried out based on two criteria, namely, economically and environmentally. The optimal solution would be a compromise between these two criteria.

Table 1. Input Sets used in the model

Sets	Description of Sets/Indices
I	Set of biomass types indexed by i;
L	Set of transport modes for biomass indexed by l;
B	Set of transport modes for biodiesel is a subset of L ($B \subset L$) indexed by b;
S	Set of life cycle stages of a BSC indexed by s;
P	Set of plant size intervals indexed by p;
G	Set of regions of the territorial division indexed by g
F	Set of candidate regions for biodiesel plants established, which is a subset of G indexed by f;
C	Set of biodiesel customer zones, which is a subset of G ($C \subset G$) indexed by c.

Table 2 Input variables for the problem

Symbol	Description
$EFBC_{ig}$	Emission factor for cultivation of biomass type i in region g, $kg\,CO_2-eq/ton\,biomass$
$EFBP_i$	Emission factor for biodiesel(B100) production from biomass type $i \in I$, $kg\,CO_2-eq/ton\,biofuel$
$EFTRA_{il}$	Emission factor for transport of biomass per unit of type $i \in I$ with transport type l, $kg\,CO_2-eq/ton\,km$
$EFTRB_b$	Emission factor for transport of biodiesel(B100) with transport type $b \in B$, $kg\,CO_2-eq/ton\,km$
$EFTM_l$	Transportation emission factor of for mode $l \in L$, $kg\,CO_2-eq/ton\,km$
$GHGB$	GHG emission from BSC, $kg\,CO_2-eq/ton$
ADD_{gfl}	Actual delivery distance between regions producing biomass and regions producing biodiesel(B100) via model l, km
ADF_{fcb}	Actual delivery distance between regions producing biodiesel(B100) and demand regions $c \in C$ via model $b \in B$, km
γ_i	Biomass to biodiesel(B100) conversion factor for biomass type $i \in I$ to biodiesel(B100) $(ton\,biodiesel)/(ton\,biomass)$, Dimensionless
C_{CO_2}	Carbon tax per unit of carbon emitted from the operation of the BSC, $\$/kg\,CO_2-eq$
YO_c	Years demands of petroleum diesel in the customer zones, $ton/year$
ENO	Energy equivalent unit of petroleum diesel, GJ/ton
ENB	Energy equivalent unit of biodiesel(B100), GJ/ton
PO	Price of petroleum diesel, $\$/ton$
PB	Price of biodiesel(B100) produced from biomass, $\$/ton$
$Cost_p$	Capital cost of plant size $p \in P$ for biodiesel(B100) production, $\$$
$PB_p^{MIN/MAX}$	Minimum/Maximum annual capacity of the plant of size $p \in P$ for biodiesel(B100) production, $ton/year$
ZB_c^{MAX}	The annual demand for biodiesel(B100) in the customer zones, $ton/year$
QI_{ig}^{MAX}	Maximum flow rate of biomass $i \in I$ from region $g \in G$, ton/d
QB_f^{MAX}	Maximum flow rate of biodiesel(B100) from region $f \in F$, ton/d
$PBI_{ig}^{MIN/MAX}$	Minimum/Maximum biomass of type $i \in I$ which can be produced in the region $g \in G$ per year, $ton/year$
α_g	Operating period for the region $g \in G$ in a year, $d/year$

αf_f	Operating period for biodiesel(B100) production plants in region $f \in F$ in a year, $d\ /\ year$
αc_c	Operating period for the region $c \in C$ in a year, $d\ /\ year$
INS_f	The government incentive includes construction incentive and volumetric, $\$/ton$
ECB	Emissions emitted during the combustion of CO_2 unit biodiesel(B100), $kg\,CO_2 - eq/ton\,biofuel$
ECG	Emissions emitted during the combustion of CO_2 unit petroleum diesel, $kg\,CO_2 - eq/ton\,biofuel$
CCF	Capital charge factor, $year^{-1}$
UCC_{ig}	Unit biomass cultivation cost of biomass type i in region g, $\$/ton$
UPC_{ipf}	Unit biodiesel production cost from biomass type i at a biorefinery of scale p installed in region $f \in F$, $\$/ton$
UTC_{igfl}	Unit transport cost of biomass $i \in I$ via mode $l \in L$ between region $g \in G$ and biorefinery $f \in F$, $\$/ton$
UTB_{fcb}	Unit transport cost of biodiesel(B100) via mode $b \in B$ between biorefinery $f \in F$ and demand regions $c \in C$, $\$/ton$
A_g^S	Set-aside area available in region $g \in G$, ha
A_g^{Food}	Set-aside area available in region for food $g \in G$, ha
$TEIF^{MAX}$	Maximum permissible values for the total environmental impact of biodiesel(B100) network of SC and fossil fuel in the regions, $kg\,CO_2 - eq/d$
TDC^{MAX}	Maximum total cost of a biodiesel(B100) SC network, $\$$
β_{ig}	The yield per hectare of type $i \in I$ biomass in the region $g \in G$, ton/ha
QB_i^{Food}	The total amount of bio-resources of type $i \in I$, which must be provided for all regions $g \in G$ for food security, ton
QT_{il}^{MIN}	Optimal capacity of transport $l \in L$ used for transportation of biomass $i \in I$, ton
QTB_b^{MIN}	Optimal capacity of transport $b \in B$ used for transportation of biodiesel(B100), ton
K_c^{mix}	Proportion of biodiesel(B100) and petroleum-diesel subject of mixing for each of the customer zones. The ratio of biodiesel(B100) and petroleum diesel is more energy equivalent between the two fuels. $K_c^{mix} = \dfrac{ENB\sum_{c\in C} QEB_c}{ENO\sum_{c\in C} YO_c}$, Dimensionless
M_f^{const}	Factor to the change of the base price, depending on the region $f \in F$ where the plant is installed $M_f^{const} \geq 1$, Dimensionless

Table 3. Decision variables for the problem

Positive Continuous Variables	
PBB_{ig}	Production rate of biomass $i \in I$ in region $g \in G$, ton/d
QI_{igfl}	Flow rate of biomass $i \in I$ via mode $l \in L$ from region $g \in G$ to $f \in F$, ton/d
QB_{ipfcb}	Flow rate of biodiesel produced from biomass $i \in I$ via mode $b \in B$ from region $f \in F$ to $c \in C$ at a plant of scale p located in region $f \in F$, ton/d
QEO_c	Quantity of petroleum diesel to be supplied to meet the energy needs of the region $c \in C$, $ton/\ year$

QEB_c	Quantity of biodiesel(B100) produced from biomass to be supplied to meet the energy needs of the region $c \in C$, $ton/year$
A_{ig}	Land occupied by first generation crop i in region g, ha
A_{ig}^F	Land by crops $i \in I$ needed for food security of the population in the region $g \in G$, ha
Binary variables	
X_{igfl}	0-1 binary 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
Y_{fcb}	0-1 binary 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
Z_{pf}	0-1 binary variable, equal to 1 if a plant size $p \in P$ is installed in $f \in F$ and 0 otherwise

Basic relationships

Total environmental impact at work on BSC. The environmental impact of the BSC is measured in terms of total GHG emissions ($kgCO_2-eq$) stemming from SC activities and the total emissions are converted to carbon credits by multiplying them with the carbon price (per $kgCO_2-eq$) in the market.

The three main greenhouse gases emitted from the SC are methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2). The values of these parameters for life cycle inventory are obtained. Life Cycle Inventory after grouping the GHGs (i.e., CO_2, CH_4 and N_2O) into a single indicator in terms of carbon dioxide equivalent emissions ($CO_2-eq/year$) by using their respective global warming potentials (GWPs) based on the recommendation of Intergovernmental Panel on Climate Change (IPCC, 2007) [6] for the 100 year time horizon is, as follows: 1 for CO_2, 25 for CH_4, and 298 for N_2O.

The environmental objective is to minimize the total annual GHG emission (te) resulting from the operations of the biodiesel supply chains. The formulation of this objective is based on the field-to wheel life cycle analysis that 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,
- emissions from biodiesel production,
- transportation of biodiesel(B100) facilities to the demand zones,
- emissions from biodiesel(B100) usage in vehicle operations.

Ecological assessment criteria will represent the total environmental impact at work on BSC through the resulting greenhouse gas emissions. These emissions are equal to the sum of the impact that each of the stages of the life cycle has on the environment and are expressed by the dependence:

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

where

TEI Total environmental impact at work on BSC ($kg\,CO_2-eq\,d^{-1}$);

$\left.\begin{array}{l} EL_{BC} \\ EL_{BP} \\ EL_{TR} \end{array}\right\}$ Environmental impact of life cycle stages ($kg\,CO_2-eq\,d^{-1}$);

EB_{CAR} Emissions from biodiesel usage in vehicle operations ($kg\,CO_2-eq\,d^{-1}$);

The environmental impact is evaluated at every stage $s \in S$ of the life cycle as:

A. Growing biomass (including drying, storage);
B. Production of biodiesel(B100);
C. Transportation resources (biomass and biodiesel(B100)).

Greenhouse gases to grow biomass is:

$$EL_{BC} = \sum_{i\in I}\sum_{g\in G}\left(EFBC_{ig}\,\frac{\beta_{ig}A_{ig}}{\alpha_g}\right) \quad (2)$$

where, EL_{BC} denotes the total environmental impact of biomass cultivation, which in general represents the production rate of resource $i \in I$ in region $g \in G$, refers in this equation to the cultivation rate of biomass $i \in I$ in that region.

Total emissions from biodiesel(B100) production is determined by the equation:

$$EL_{BP} = \sum_{g \in G} \sum_{i \in I} \sum_{f \in F} \sum_{l \in L} \left(EFBP_i \gamma_i QI_{igfl} \right) \tag{3}$$

where EL_{BP} is total environmental impact of biodiesel(B100) production through given technology ($kg\, CO_2 - eq\, d^{-1}$).

The environmental impact of transportation is calculated by:

$$EL_{TR} = \sum_{i \in I} \sum_{g \in G} \sum_{f \in F} \sum_{l \in L} \left(EFTRA_{il} ADD_{gfl} QI_{igfl} \right) + \sum_{i \in I} \sum_{p \in P} \sum_{f \in F} \sum_{c \in C} \sum_{b \in B} \left(EFTRB_b ADF_{fcb} QB_{ipfcb} \right) \tag{4}$$

where EL_{TR} is environmental impact of transportation of resources ($kg\, CO_2 - eq\, d^{-1}$);

Emissions from biodiesel (B100) usage in vehicle operations:

$$EB_{CAR} = \sum_{i \in I} \sum_{p \in P} \sum_{f \in F} \sum_{c \in C} \sum_{b \in B} \left(ECB\; QB_{ipfcb} \right) \tag{5}$$

where EB_{CAR} is emissions from biodiesel(B100) usage in vehicle operations ($kg\, CO_2 - eq\, d^{-1}$).

Total environmental impact of the used fuels (biodiesel(B100) and diesel) to provide the energy balance of the region. Environmental goal is to reduce the annual equivalent of greenhouse gases, resulting from the operations of SC of biodiesel(B100) and diesel to meet the energy needs of the regions.

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

$$TEIF = TEI + EG_{CAR} \tag{6}$$

where

$TEIF$	Total environmental impact of the used fuels (biodiesel (B100) and petroleum diesel) to provide the energy balance of the region ($kg\, CO_2 - eq\, d^{-1}$);
TEI	Environmental impact at work on BSC ($kg\, CO_2 - eq\, d^{-1}$);
EG_{CAR}	Emissions from petroleum diesel usage in vehicle operations ($kg\, CO_2 - eq\, d^{-1}$);

Emissions from petroleum diesel usage in vehicle to supplement the energy balance:

$$EG_{CAR} = \sum_{c \in C} \left(\frac{ECG\; QEO_c}{\alpha c_c} \right) \tag{7}$$

Total cost of a BSC network. The annual operational cost includes the biomass feedstock acquisition cost, the local distribution cost of final fuel product, the production costs of final products, and the transportation costs of biomass, and final products. In the production cost, we consider both the fixed annual operating cost, which is given as a percentage of the corresponding total capital investment, and the net variable cost, which is proportional to the processing amount. In the transportation cost, both distance-fixed cost and distance-variable cost are considered. The economic criterion will be the cost of living expenses to include total investment cost of biodiesel(B100) production facilities and operation of the BSC for the operating period. This price is expressed through the dependence:

$$TDC = TIC + TPC + TTC + TTAXB - TL \tag{8}$$

where

TDC	Total cost of a BSC network for year ($\$\, year^{-1}$);
TIC	Investment costs of production capacity of biodiesel(B100) relative to the operational period of redemption and up time of the plant per year ($\$\, year^{-1}$);
TPC	Production cost ($\$\, year^{-1}$);
TTC	Transportation cost ($\$\, year^{-1}$);
$TTAXB$	A carbon tax levied according to the total amount of CO_2 generated in the work of the whole BSC for year ($\$\, year^{-1}$);

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production and use ($\$\, year^{-1}$).

a/ Total investment costs model:

The components TIC of (8) shall be determined under the following relationships:

$$TIC = CCF \sum_{f \in F} \sum_{p \in P} \left(Cost^F_{pf} Z_{pf} \right) \tag{9}$$

The refinery capital cost consists of fixed and variable capital cost. The fixed capital cost varies by the refinery locations. The variable capital cost of biomass-to-biodiesel(B100) plants, is mainly influenced by the plant size, since the technology is considered mature.

Variable capital cost are scaled using the general relationship [20].

$$\frac{Cost_p}{Cost_{base}} = \left(\frac{Size_p}{Size_{base}}\right)^R,$$

where $Cost_p$ is variable capital cost and $Size_p$ represents the investment cost and plant capacity respectively for the new plant, $Cost_{base}$ indicates the known investment cost for a certain plant capacity $Size_{base}$, and R is the scaling factor usually between 0.6 and 0.8.

Capital cost of biorefinery for each region is determined by the equation:

$$Cost_{pf}^{F} = M_f^{\cos t} Cost_p, \forall p, f,$$

where $M_f^{\cos t}$ is a correction factor in the price of bio-refineries in the region $f \in F$ according to its installed $M_f^{\cos t} \geq 1$.

b/ Total production cost model

$$TPC = \sum_{i \in I}\sum_{g \in G}\left(UCC_{ig} A_{ig} \beta_{ig}\right) + \sum_{i \in I}\sum_{p \in P}\sum_{f \in F}\left(\alpha f_f UPC_{pf} \sum_{c \in C}\sum_{b \in B} QB_{ipfcb}\right), \quad (10)$$

c/ Total transportation cost model

$$TTC = \sum_{g \in G}\sum_{l \in L}\sum_{i \in I}\sum_{f \in F}\left(\alpha_g UTC_{igfl} QI_{igfl}\right) + TI \quad (11)$$

where,

$$\left.\begin{aligned} UTC_{igfl} &= IA_{il} + \left(IB_{il} ADD_{gfl}\right) \\ UTB_{fcb} &= OA_b + \left(OB_b ADF_{fcb}\right) \\ TI &= \sum_{i \in I}\sum_{p \in P}\sum_{f \in F}\sum_{b \in B}\sum_{c \in C}\left(\alpha f_f UTB_{fcb} QB_{ipfcb}\right) \end{aligned}\right\},$$

IA_{il} and IB_{il} are fixed and variable cost for transportation biomass type $i \in I$ and (OA_b, OB_b) are fixed and variable cost for transportation biodiesel (B100).

The biomass transportation cost UTC_{igfl} is described by *Börjesson and Gustavsson, 1996* [3]. They are composed of a fixed cost (IA_{il}, OA_b) and a variable cost (IB_{il}, OB_b). Fixed costs include loading and unloading costs. They do not depend on the distance of transport. Variable costs include fuel cost, driver cost, maintenance cost etc. They are dependent on the distance of transport.

d/ Government incentives for biodiesel (B100) production cost model

Government incentives for biodiesel(B100) production and use is determined by the equation:

$$TL = \sum_{f \in F}\left(INS_f \sum_{g \in G}\left(\sum_{i \in I}\left(\gamma_i A_{ig} \beta_{ig}\right)\right)\right) \quad (12)$$

e/ A carbon tax levied cost model

A carbon tax levied is determined by the equation:

$$TTAXB = \begin{pmatrix} YEL_{BC} + YEL_{BP} + \\ YEL_{TR} + FEB_{CAR} \end{pmatrix} C_{CO_2} \quad (13)$$

where, YEL_{BC} is the total GHG emissions for biomass cultivation, YEL_{TR} is the environmental impact of transportation of resources within the network and YEL_{BP} is the environmental impact of biodiesel (B100) production a year working in the BSC and determined by the following equations:

$$YEL_{BC} = \sum_{i \in I}\sum_{g \in G}\left(EFBC_{ig} A_{ig} \beta_{ig}\right),$$

$$YEL_{BP} = \sum_{g \in G}\sum_{i \in I}\sum_{f \in F}\sum_{l \in L}\left(\alpha_g \gamma_i EFBP_i QI_{igfl}\right),$$

$$YEL_{TR} = \sum_{i \in I}\sum_{g \in G}\sum_{f \in F}\sum_{l \in L}\left(\alpha_g EFTRA_{il} ADD_{gfl} QI_{igfl}\right) + \sum_{i \in I}\sum_{p \in P}\sum_{f \in F}\sum_{c \in C}\sum_{b \in B}\left(\alpha f_f EFTRB_b ADF_{fcb} QB_{ipfcb}\right)$$

$$FEB_{CAR} = \sum_{c \in C}\left(ECBQEB_c\right),$$

$$QEB_c = \sum_{i \in I}\sum_{p \in P}\sum_{f \in F}\sum_{b \in B}\left(\alpha f_f QB_{ipfcb}\right).$$

Total cost of fuel used by the regions. The annual cost of providing the energy balance in the region includes the cost of diesel and the production and transportation cost in the stores for blending biodiesel (B100). In manufacturing costs, we consider both fixed annual operating costs, which is given as a percentage by the total amount of investment capital and net variable cost that is proportional to the amount of processing. In transport costs, distance fixed price and distance variable costs are considered. The economic criterion will be the total cost of year's base, including investment costs for biodiesel (B100) production and use of the BSC for the lifetime and cost of the used classic fuel supplement on the energy balance of the region. This price is given by the equation:

$$TBG = TDC + TG \quad (14)$$

where

TBG Total cost of fuel used (conventional and biofuels(B100)) to ensure region's energy balance ($\$ \ year^{-1}$);

TDC Total cost of a BSC network for year ($\$ \ year^{-1}$);

TG Total cost of petroleum diesel used from the regions ($\$ \ year^{-1}$);

The component TG of (14) shall be determined under the following relationships:

$$TG = PO\sum_{c\in C} QEO_c \tag{15}$$

5.6. Restrictions

Plants capacity limited by upper and lower bounds constrains. Plants capacity is limited by upper and lower bounds, as indicated by Eqs. (16), where the minimal production level in each region is obtained affecting the capacity installed.

$$PB_p^{MIN} Z_{pf} \le \alpha f_f \sum_{i\in I}\sum_{c\in C}\sum_{b\in B} QB_{ipfcb} \le PB_p^{MAX} Z_{pf}, \quad \forall p, f \tag{16}$$

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

$$\left.\begin{aligned} \sum_{c\in C} QEB_c &\le \sum_{i\in I}\sum_{g\in G}\left(\gamma_i PBI_{ig}^{MAX}\right) \\ \sum_{c\in C} QEB_c &\le \sum_{i\in I}\sum_{g\in G}\left(\gamma_i \beta_{ig} A_g^S\right) \end{aligned}\right\}, \tag{17}$$

$$\sum_{i\in I}\sum_{g\in G}\sum_{l\in L}\left(\gamma_i \alpha_g QI_{igfl}\right) = \sum_{i\in I}\sum_{p\in P}\sum_{b\in B}\sum_{c\in C}\left(\alpha f_f QB_{ipfcb}\right), \quad \forall f, \tag{18}$$

Logical constraints.

A/ Restriction guarantees that a given region g installed power plant with p for biodiesel(B100) production

Constraint (19) determined that only one size of the plant can be installed in a given region:

$$\sum_{p\in P} Z_{pf} \le 1, \quad \forall f \tag{19}$$

B/ Limitation of assurance is provided that the biomass plant installed in a region $g \in G$ of at least one different region $g \in G$

$$\sum_{g\in G}\sum_{l\in L} X_{igfl} \ge \sum_{p\in P} Z_{pf}, \quad \forall i, f \tag{20}$$

C/ Limit guarantee that each region g will provide only one plant of biomass type $i \in I$

$$\sum_{f\in F}\sum_{l\in L} X_{igfl} \le 1, \quad \forall i, g \tag{21}$$

D/ Limitation of assurance is provided that at least one region $g \in G$ produces biomass that is connected in a plant located in a region $f \in F$

$$\sum_{c\in C}\sum_{b\in B} Y_{fcb} \ge \sum_{p\in P} Z_{pf}, \quad \forall f \tag{22}$$

$$\sum_{b\in B} Y_{fcb} \le 1, \quad \forall f, c \tag{23}$$

$$\sum_{c\in C}\sum_{b\in B} Y_{fcb} \ge \sum_{g\in G}\sum_{l\in L} X_{igfl}, \quad \forall i, f \tag{24}$$

Transport links.

A/ The quantity transported between different regions is limited by upper and lower bounds, as indicate by Eq. (25)

$$\frac{PBI_{ig}^{MIN}}{\alpha_g} \le \sum_{f\in F\neq g}\sum_{l\in L} QI_{igfl} \le \frac{\left(A_g^S - A_g^{Food}\right)\beta_{ig}}{2\alpha_g}, \quad \forall i, g \tag{25}$$

B/ Restrictions on transportation of biomass are

$$\sum_{l\in L} QI_{igfl} \le 0.5\left(A_g^S - A_g^{Food}\right)\beta_{ig} \sum_{l\in L} X_{igfl}, \quad \forall i, g, f \tag{26}$$

C/ Limitation that ensures the admissibility of flow rate for biomass and biofuel

Productivity of biomass in the region restriction

$$QI_{ig}^{MAX} X_{igfl} \ge QI_{igfl} \ge QT_{il}^{MIN} X_{igfl}, \quad \forall i, g, f, l \tag{27}$$

Flow rate of biomass restricting

$$QB_f^{MAX} Y_{fcb} \ge \sum_{i\in I}\sum_{p\in P} QB_{ipfcl} \ge QTB_b^{MIN} Y_{fcb}, \quad \forall f, c, b \tag{28}$$

Supply chain design constraints. These constraints are material balances among the different nodes in the SC. The following are constraints between different SC nodes:

A/ Productivity of biomass in the region restriction

$$PBB_{ig} \le \frac{\left(A_g^S - A_g^{Food}\right)\beta_{ig}}{2}, \quad \forall i, g \tag{29}$$

Restriction for total environmental impact of all regions.

$$TEIF \leq TEIF^{MAX} \tag{30}$$

where $TEIF^{MAX}$ is maximum permissible values for the total environmental impact of biodiesel(B100) network of SC and fossil fuel in the regions ($kg\,CO_2 - eq\,d^{-1}$)

Mass balances between biodiesel(B100) plants and biomass regions. The connections between biodiesel (B100) plants and biomass regions are determined by the equation:

$$\sum_{l\in L}\sum_{g\in G}\sum_{i\in I}\left(\gamma_i QI_{igfl}\right) \leq \sum_{p\in P}\left(PB_p^{MAX} Z_{pf}\right), \forall f \tag{31}$$

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

$$\sum_{i\in I}\sum_{p\in P}\sum_{b\in B}\sum_{f\in F}\left(\alpha f_f QB_{ipfcb}\right) \leq ZB_c^{MAX}, \forall c \tag{32}$$

Land constraints.

A/ The constraints explained in this section mainly aim to avoid the negative impacts on food production to avoid competition with other sectors for biomass use and to maintain the sustainable use of land. The following constraint is introduced to the model to avoid the competition between "biomass for food" and "biomass for fuel":

$$\sum_{g\in G}\left(\beta_{ig} A_{ig}\right) \geq \sum_{g\in G}\left(\alpha_g PBB_{ig}\right), \forall i \tag{33}$$

The land used for raw materials cultivation and for food security must not exceed the available land for each region:

$$\sum_{i\in I}\left(A_{ig} + A_{ig}^F\right) \leq \left(A_g^S - A_g^{Food}\right), \forall g, \tag{34}$$

B/ 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. Other criteria to take in consideration when planning crop rotation with energy crops are the environmental and economic conditions in a given region. Moreover, 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 can be applied if the quantity of energy crops in a given year can be produced in the next one but in other areas of the region. This can be achieved if land A_{ig} and A_{ig}^F such that inequalities are implemented.

$$\left(A_{ig} + A_{ig}^F\right)2.0 \leq \left(A_g^S - A_g^{Food}\right), \forall i, g \tag{35}$$

Energy restriction.

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

Limitation of enforceability of the energy balance:

$$EGD + EB \geq EO. \tag{36}$$

Energy equivalent diesel, which is necessary to meet the energy needs of the all customer zones where no use biodiesel(B100) is determined by the equation:

$$EO = ENO\sum_{c\in C} YO_c, \tag{36a}$$

where EO is annual requirement of energy (petroleum diesel) of all regions ($GJ\ year^{-1}$).

The energy equivalent of petroleum diesel that must be added, in order to balance the energy required for all customer zones is determined by the equation:

$$EGD = ENO\sum_{c\in C} QEO_c, \tag{36b}$$

where EGD is annual energy added to petroleum diesel fuel to balance the required energy for all regions ($GJ\ year^{-1}$).

The Energy equivalent of biodiesel (B100) received per year of work BSC is determined according to the dependence:

$$EB = ENB\sum_{c\in C} QEB_c, \tag{36c}$$

where EB is annual energy received from the extracted biofuel (biodiesel(B100)) of BSC for all customer zone ($GJ\ year^{-1}$).

B/ Limitation ensuring that the overall energy balance in each customer zones is provided

Limitation of enforceability of the energy balance for each region:

$$ENO\,QEO_c + ENB\,QEB_c \geq ENO\,YO_c, \forall c \tag{37}$$

C/ Limitation ensuring that each region will be provided in the desired proportions fuels

$$ENB\sum_{i\in I}\sum_{p\in P}\sum_{f\in F}\sum_{b\in B}\left(\alpha f_f QB_{ipfcb}\right) \geq K_c^{mix} ENO\,QEO_c, \forall c \tag{38}$$

Total cost of a BSC network restriction

$$TDC^{MAX} \geq TDC \tag{39}$$

where TDC^{MAX} is maximum total cost of a BSC network ($\$$).

Optimisation problem formulation

The problem for the optimal design of a BSC is formulated as a mixed integer linear programming

(MILP) model for different target functions as follows:

Minimizing GHG emissions. As discussed in section 4.5.2 environmental objective is to minimize the total annual CO_2-equivalent greenhouse gas emissions resulting from the operations of the BSC and petroleum diesel used to provide the energy balance of the regions. The formulation of this objective is based on total GHG emissions in the SC and other fuels are estimated based on life cycle assessment (LCA) approach, where emissions are added every life stage.

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

$$\left\{\begin{array}{l} Find : X\left[\text{Decision variables}\right]^T \\ MINIMIZE\ \{TEIF(X)\} \to (Eq.6) \\ s.t.: \{Eq.16 - Eq.39\} \end{array}\right\} \qquad (40)$$

Minimizing annualized total cost. The economic objective is to minimize the annualized total cost, including the total annualized capital cost, the annual operation cost, the annual governmental incentive, and the cost for emitting CO_2. The task of determining the optimal location of facilities in the regions and their parameters is formulated as (41)

The problem 5.7.1 and 5.7.2 is an ordinary Mixed Integer Linear Program (MILP) and can thus be solved using standard MILP techniques. The model was developed in the commercial software GAMS [7] using the solver CPLEX. The model will choose the less 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 optimisation problem would then be a set of plants together with their corresponding biomass and biodiesel(B100) demand points.

$$\left\{\begin{array}{l} Find : X\left[\text{Decision variables}\right]^T \\ MINIMIZE\ \{TDC(X)\} \to (Eq.8) \\ s.t.: \{Eq.16 - Eq.39\} \end{array}\right\} \qquad (41)$$

CONCLUSIONS

This study considers the optimal location of biodiesel (B100) production plants and the operation of the BSC. MILP approach for the design and planning of BSC under economic and environmental criteria is developed. The significance of the problem has been expressed by the extensive investigation of the biofuels sector that has been taking place during the recent years for particular fatal replacement of the highly polluting conventional fuels. An optimisation model was developed that enables decision making for the infrastructure of biofuel conversion processing including processing locations, volumes, supply networks, and logistics of transportation from regions of biomass to bio-refineries and from bio-refineries to markets. The development of a flexible optimisation model may solve a wide spectrum of biofuel problems since this area is very rapidly changing (not only in economic but also in other dimensions, such as strategic decisions concerning the development and progress in the field, i.e. land dedicated to biofuels). All these can very easily be accommodated in the optimisation model, resulting in significant benefits from the optimisation approach. One of the valuable features of the approach is the capability to identify and solve a wide range of different scale and level problems, such as facility location, raw materials selection, conversion facilities location and design and operational characteristics. Furthermore, the model itself could be easily extended to accommodate strategic planning issues, such as investing or not on new production facilities, their siting, and the introduction of environmental and other externalities in the calculation of the total cost. The model that has been developed includes technical constraints as well as constraints originating from the limits in various problem parameters. The optimisation criteria of the model will in any case express the goals of the stakeholder and may include maximum economic efficiency, best environmental behavior, minimum land occupation, minimum total cost, etc. Another characteristic of the proposed approach is that the model is rather simple and can easily be solved with the available solvers, without needing to develop new codes or optimisation methods. This characteristic is important in the potential future exploitation of the approach and the development of a Decision Support System. However, the main critical point in the implementation of this approach is the difficulty to identify reliable quantitative information of the various problem parameters. Therefore, significant progress in other fields or research in order to provide reliable quantitative information and data (such as the agricultural materials properties, the conversion process efficiency, various costs, land availability etc.) are critical factors in the performance and the contribution of the present work.

A final conclusion is that in order to reach the EU targets particularly in Bulgaria a more improved interdisciplinary and improved cross-sectoral in the energy system will be needed. Correspondingly the model developed and used within this study, may constitute a key component for this kind of studies. Consequently, it is which makes it highly relevant for policy makers.

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ОПТИМАЛНО ПРОЕКТИРАНЕ И ПЛАНИРАНЕ НА РЕСУРСНО ОСИГУРИТЕЛНАТА ВЕРИГА ЗА ПРОИЗВОДСТВО И ДОСТАВКИ НА БИОДИЗЕЛ С ОТЧИТАНЕ НА СЕИТБООБРАЩЕНИЕТО. ЧАСТ 1. ФОРМУЛИРОВКА НА МАТЕМАТИЧНИЯ МОДЕЛ

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(Резюме)

Тази статия е насочена към решаване на проблема за оптимално проектиране на ресурсно осигурителни вериги за производство и разпространение на биодизел. Използувани са два критерия за оценка на оптималността на веригата (икономически и екологичен). Икономическият критерий оценява общите годишни разходите, докато екологичният критерий оценява общите емисии на парникови газове в атмосверата за целия жизнен цикъл на продукта. Предложен е математически модел, който може да се използва за проектиране на веригата за доставки (SC) и управление на логистиката на биодизел. Моделът определя броя, размера и местоположението на биорафинериите необходими за производството на биодизел като се използва наличната биомаса. Моделът се формулира в термините на смесеното линеино програмиране. Важна особеност на този модел е че отчита влиянието на ротацията на биокултурите.