Development and implementation of an optimisation model for biofuels supply chain

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Abstract
Biofuels supply chain comprises a wide set of activities involving a rather complex set of parameters. Cultivation of the raw materials is closely related to the agricultural sector whereas the production of the final product presumes the operation of a conversion plant. The distribution network aims at delivering the final product close to the consumption. The extent of the involvement of each one of the previously mentioned sectors is the result of strategic and operational planning of the whole supply chain and, in the general case, determines the efficiency of the biofuels sector. Taking also into account the very rapidly changing opinions related to the environmental behaviour of the whole biofuels supply chain, it becomes very clear that the parameters in the sector are continuously changing. Therefore, the consideration of an integrated supply chain appropriately modelled is believed to be very critical and could result in the optimal solution per case, economically and/or environmentally speaking. In this paper the development of a mathematical model for the optimal design and operation of Biofuels Supply Chain is proposed as an integrated approach that can take into account both technical and economic parameters affecting the performance of the whole value chain. Model implementation would facilitate and support the decision taking in various planning and operational issues such as infrastructure investments, the quantities of raw materials to be cultivated, the quantities of biofuels to be produced in the domestic market or imported, identifying the best available solution for the optimal design and operation of the biofuels supply chain.

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1. Introduction — scope and objectives of the work

Driven by the necessity to reduce oil dependence, address the imperative needs for energy security and mitigate the greenhouse effect and climate change on a global level, various promising ideas and activities for fuel substitution in the transportation sector have seriously been investigated during the last years. In that framework the use of biofuels and other alternative fuels i.e. biogas, hydrogen, natural gas, is being encouraged and promoted through various actions. Bioethanol and biodiesel present a competitive advantage compared to the other alternative fuels, since they have a large field of applicability in the existing car fleet, as many of their attributes and characteristics are similar to the respective ones of conventional fuels, i.e. diesel and gasoline.

Although offering a prosperous solution, at least in the energy supply part, biofuels deployment has undergone a rather slow progress [1] both at EU and national level. The majority of Member States failed to reach the targets initially set by the Directive 2003/30/EC [2], due to their relatively high production costs, in some cases reinforced by the different support schemes per country applied. Similarly in Greece, the use of a quota mechanism, allowing the Government to decide the amount of biofuel (biodiesel) that has to be supplied each year, resulted in a very small penetration rate and didn’t set the fundamentals for the establishment of a free market for biofuels trade.

In any case, the technical and economic feasibility of biomass-derived fuels has been extensively examined [3–9] and many efforts have been made in order to identify and quantify all the interrelated parameters; however, no extended work has been done with regards to the evaluation of the entire biofuels’ supply chain.

Additionally, the public opposition that has risen relative to biofuels’ sustainability throughout their Life Cycle [10–15], reinforced...
by the food versus fuel debate [16,17] caused a major push back in biofuels policy and rendered a new challenge to face.

Biofuels’ successful penetration in a country’s energy fuel mix presupposes numerous strategic and operational level decisions, being currently reinforced by the new Renewable Energy Directive 2009/28/EC for an overall share of 10% energy from renewable sources in transportation by 2020 [1]. Biofuels environmental sustainability throughout their Life Cycle is a vague story, with the results of various Life Cycle Analyses (LCAs) appearing to be controversial [18,19]. Considering the above and taking into account the importance of the biofuels issues, this work aims to identify the structure of the entire biofuels supply chain and the various types of problems that emerge in strategic and operational level. The work also attempts to develop an integrated mathematical model for the appropriately defined optimisation of the biofuels supply chain. The value chain that has been defined in the context of the present work typically includes the feedstock production, the biofuel production, the blending (if applicable), the distribution and the consumption of biofuels. It is believed that the model can be very useful for the evaluation of the biofuels supply chain performance either at strategic or operational level.

2. Supply chain management considerations

Supply Chain Management (SCM) is the determination of the optimal material flow among vendors, facilities, warehouses and customers. It is an integrating environment which includes all the stages from the product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers and end-of-life management of the product after its useful life. A supply chain includes a network of retailers, distributors, transporters, storage facilities, and suppliers that participate in the production, delivery, and sale of a product to the consumer. The supply chain is typically made up of multiple companies who coordinate activities to set themselves apart from the competition.

In parallel, the SCM involves the optimal coordination of the various operations included in the production of raw materials and final products, the storage, the importing and/or exporting raw materials, intermediate and final products. It usually implies the optimisation of a performance criterion financial and/or operational, either in a short or in a long time horizon.

SCM has been a widely applied approach for coordinating and controlling in an integrated manner all the stages that may seem independent in other considerations, recognising that any parameter affecting one specific point of the supply chain, in fact affects its entire behaviour and performance. It has been used extensively in solving classical production and operations management problems and organising the production and distribution of products in a global level. The main advantage of the early incorporation of the operational research tools into the classic SCM concept and visualisation is the optimisation approach, which may also integrate the spatial and temporal characteristics of the supply chain. The optimisation criterion, depending on the problem under consideration, may be the minimisation of the transportation cost or the total cost, the maximisation of the supply chain’s efficiency and various others optimisation criteria [20].

Over the years the implementation fields and, consequently, the amount of literature on SCM has growing rapidly. The research community has developed global supply chain design and optimisation models. The business environment that surrounds the problem is continuously changing. First, firms are increasingly outsourcing to both domestic and global locations. Second, many companies that had viewed their sourcing problems as an enterprise-level concern, now strive to integrate decision processes across tiers in the supply chain. A third issue is the broadened definition of supply chain performance, as mission, strategy and objectives can vary considerably based on the value of the product offered to the customer. Supplier selection decisions change the global supply chain design problem in fundamental ways, in part because they are based on more broadly defined criteria [21].

The SCM concepts become more interesting not only because of the continuously changing characteristics of the main SCM actors but also due to their wide applicability. Recently the supply chain approach has been extended much further than the classical product/production consideration. During the last years research works have been developed that apply very successfully the SCM basic principles and approaches to other material and non-material flows. For example, novel supply chains have been introduced concerning biofuels, biomass, natural gas, hydrogen, energy in general and water. Representation and modeling of these new supply chains and the development of the optimisation models can be very essential to the identification of the problems characteristics, the integration of the various initially independent parameters and processes and the solution of various different level problems [22–26].

A challenging aspect of a great importance in the successful and efficient consideration of these novel supply chains, the ones of biofuels and alternative fuels in general, is their optimal design and operation. Following that, many models and solutions have been employed as Decision Support Tools, assisting at choice making in the level of strategic and/or operational planning.

More precisely in the biomass sector, mathematical models have been developed and applied into bioenergy systems planning [5], in decision support modeling methodologies for product and process design decisions under economic evaluation [27,28], in raw material supply estimations [8], in bio-fuel multi-stage activity modeling aiming at determining efficient public policy in uncertain agricultural markets [7], in integrated economic and environmental Life Cycle optimisation of biofuel production [6].

Additionally in the field, more innovative, State-Task-Network (STN) approaches have also been used in order to minimize total system cost whilst ensuring satisfaction of the prescribed energy demand load [29], whilst also, modeling principles have been applied to Waste to Biomass SCs, so as to minimize the total cost of the system throughout the entire planning horizon, identifying the more cost effective strategy of supplying end product from biomass waste over a planning horizon, under projected annual demands and available feedstock supply [30–32].

Thus, traditionally, mathematical modeling applications have been focussed on process models and simulation tools to facilitate the assessment of supply chain performance, in terms of raw material availability, energy supply demand satisfaction, logistics and geospatial- siting parameters of the production plants. However, no integrated mathematical model assessment, incorporating both the optimisation of raw materials–feedstock and end product selection in biofuels field, has been made. Acknowledging that, in the present work a Mixed-Integer Linear Programming model has been developed to determine the optimal exploitation of the appropriately defined BSC aiming at facilitating decision making in a nexus of complex contradictory issues like feedstock to be cultivated and/or imported, local biofuel production and/or imports, creation of a strategic plan for the associated sector or an operational level activity.

3. Biofuels supply chain characteristics

The Biofuels Supply Chain (BSC) is very interesting and complex, involving factors from various different fields. Typically, a biofuel production (chain) involves domains such as agriculture (energy crops, raw materials production), biofuel production (modification
and adaptation of already existing plants or/and infrastructure development for new plants) and of course it involves the integrated distribution and trade network.

In the context of the integrated BSC, various problems emerge and call for solution. More specifically, in the strategic decision making, the identification of the best supply chain configuration includes:

- The selection of raw materials and the decision on domestic cultivation or import
- The location of the conversion facility, its capacity and production technology
- The partial or total satisfaction of the domestic demand from own production
- The design and setup of the storage and distribution network.

In the operational level the decision making involves mainly planning problems, such as:

- The economic and performance measures that will evaluate the efficiency of the supply chain
- The material flows in each stage

The structure, the design and the operation of the BSC is the result of decision making that involves various considerations on economic, energy, environmental and in some cases social acceptability aspects. The added value from the biofuels sector for a country may be defined in terms of domestic raw materials and/or biofuel production, regional development, employment and other not strictly financial measures. Thus a country, depending on the availability of land and/or production facilities and knowhow, may decide to invest in any or all of these activities.

In more detail, the major activities-stages usually incorporated in BSC are the following (Fig. 1):

- Raw materials production (which is related to the land availability and suitability, soil’s efficiency associated to different types of plants).
- Biofuels production (which refers to the transformation of raw materials into biofuels through various conversion processes).
- Blending (in the case that biofuels are provided to the end consumers mixed with conventional fuels).
- Biofuels’ transportation; and finally
- Consumption in the distribution network.

As it is illustrated in Fig. 1, in any stage of the supply chain there is a flexibility of importing the required quantities in case that they are not produced locally. As it is implied by the figure, the development of the domestic biofuels market, in a geographical area of a country, does not put any constraint on the origin of the raw materials and/or end products.

Accordingly, it is possible in any stage of the supply chain that sub-products are exported due to over adequacy or economic profitability. The decision point, i.e. in which stage of the supply chain an investor is going to step in, is a strategic decision for the development of biofuels’ market and it is determined by multiple technical and financial parameters. The parameters that are determined in this decision point require firstly a techno-economic evaluation of the integrated biofuels production activity and a rational and structured appraisal method of different/alternative scenarios for the design and the operation of the supply chain.

However, Biofuels Supply Chain is changing very rapidly, not only in technical and operational terms but in the hard core of its existence and validity as well. A strong evidence of the rapidly changing character of the BSC is reflected in the LCAs results showing that the environmental problem caused from the use of the biofuels may be much more serious than the expected benefit of their exploitation. Nevertheless, nobody can refuse the great prospects from biomass/biofuels sectors. To that effect, second, third and fourth generation of biofuels have emerged to face the drawbacks of the previous generations and certainly the present work can offer a significant contribution to the optimal performance of the sector; approaching the problem as a whole and being able to take into account a wide spectrum of its aspects. In addition, concerning the biomass as such, the optimisation may offer a significant contribution to the decision making on its final uses.

One of the major debates that have taken place recently concerning the basic strategic decisions on the use of biofuels is related to their energy output and their environmental and social benefits during their whole Life Cycle [19,33]. This is a major issue being addressed in the long-lasting debate whether biofuels should or should not be included in the fuels energy balance of a country or a specific area. Certainly there are many conflicting opinions and the replacement of the first generation of biofuels with the second, third and fourth generation tries to answer these environmental concerns. However, this is not a problem to be considered within the context of a mathematical optimisation approach. Rather it is a crucial decision of national energy policy.

4. Optimisation model concepts and model development

The proposed mathematical optimisation model is formulated as a Mixed Integer Linear Programming (MILP) problem. The model reflects the major considerations and operational constraints of the system, while, at the same time is not extremely complex in order to be adaptable and solvable in any case considered and provide valuable results to the users. As it includes a series of different time scale problems, the model could be used by diverse/multiple stakeholders and therefore be adjusted accordingly. The main indices, parameters and variables of the model are defined in the end of this manuscript. Then the model constraints and the optimisation criterion are analysed.
4.1. Constraints

4.1.1. Biofuel demand constraints

As previously mentioned, in order to fulfill the local demand there is a flexibility to import either raw materials or the end product, setting primarily no constraints to the origin of them and secondly to the production capability of a country with limited inland resources. Additionally in any stage of the supply chain, the semi-final and/or final products may be exported if there is over adequacy or economic profitability.

Therefore, for a certain time horizon “t”:

\[(Y_j - Y_j^{exp} + Y_j^{imp}) \geq DB_j, \forall j\] (1)

For each biofuel(s) the total produced quantity is the algebraic sum of the raw material(s), locally cultivated or imported and/or exported multiplied by the specific yield of the feedstock for the biofuel processing.

\[Y_j = \sum b_{ij} \times (X_i - X_i^{exp} + X_i^{imp})\] (2)

4.1.2. Land constraints

The land used for raw materials cultivation must not exceed the available one for this specific purpose.

\[A_i \leq A_i^{max}, \forall i\] (3)

(note: This constraint is included since the model deals with the production of first generation biofuels. In case that second or third generation biofuels are produced, the equivalent constraint will be easily accommodated in the model)

Whilst the productivity of the land in raw materials, is totally related on the initially selected feedstock yield \(e(i)\).

\[A_i \times e_i = X_i, \forall i\] (4)

4.1.3. Production capacity constraints

The total quantity of biofuel produced from each facility plant must not exceed the production capacity of the plant, here defined in an annual basis. In case the produced quantity of each plant is considered rather than the total, then the capacity constraint should be taken separately for each plant.

\[Y_j \leq CAP_j, \forall j\] (5)

4.1.4. Water use constraints

Another very important natural resource that is used in various points of the BSC is the water. In fact water is a very critical resource that may play decisive role in the selection of an area, a raw material or a production process in the BSC. When evaluating the various alternatives for the strategic decisions on the development of the biofuels sector, one of the parameters under consideration is the water.

In the mathematical model water use may be included either as a constrained resource (i.e. within certain limits) or in a wider context of the environmental cost of a solution.

In either case it may be accommodated in the mathematical model easily and rationally, with constraints of the type:

\[W_{ip} \times X_i \leq W_{ip}^{max}, \forall i\] (6)

\[W_{jp} \times Y_j \leq W_{jp}^{max}, \forall j\] (7)

4.1.5. Other constraints

Similar constraints for other resources may be included in the same way, e.g. the competitive use of land compared to its use for food, for the limited use of fertilizers and/or other resources. Furthermore, the analytical cost for each stage needs to be taken into account, e.g. in the raw materials cultivation the fertilisers costs should also be included.

It should also be noticed that some constraints such as the land use, the water consumption are included since the model deals with the production of first generation biofuels. In case that second or third generation biofuels are produced, the equivalent constraint will be easily accommodated in the model.

Finally, the serious parameter of the intermediate storage may easily be accommodated in the model. Intermediate storage may exist for the raw materials, the semi-finished or the final products. This consideration may alter significantly the behavior of the biofuels supply chain and make it more functional and flexible, i.e. provide the model with the capability to decide whether it is preferable to store some materials, if there is storage availability and/or the materials can be stored without deterioration, instead of importing the corresponding quantities. Definitely, the intermediate storage exploitation is time dependent and should be included in the model with two additional sets of constraints.

Namely,

For each time step \(t\), the stored quantity of any material will be equal with the corresponding quantity in the previous time step plus what enters the storage minus what exits at that time step.

\[\text{In addition, at each time step the stored quantity should not exceed the maximum storage capacity.}\]

Finally, the selection will be also based on the inventory cost, i.e. in the objective function a cost term should also be added equal to a total storage cost per unit of stored material multiplied by the corresponding stored quantity.

4.1.6. Non- negativity constraints

This renews the non- negativity of all utilized variables:

\[A_i \geq 0, \forall i\] (8)

\[X_i \geq 0, \forall i\] (9)

\[X_i^{exp} \geq 0, \forall i\] (10)

\[X_i^{imp} \geq 0, \forall i\] (11)

\[Y_j \geq 0, \forall j\] (12)

\[Y_j^{exp} \geq 0, \forall j\] (13)

\[Y_j^{imp} \geq 0, \forall j\] (14)

4.1.7. Optimization criterion

The aim of the proposed model is to maximize the total value or total performance of biofuel supply chain which equals to:

\[
\text{Max (Total Value) or Total System Performance = } \max (\Sigma \text{(inflows)} - \Sigma \text{(outflows)}) - \text{other costs (transportation, environmental etc)}
\]
Total Value = \left\{ \sum_j \left( p_j \times (Y_j - Y_j^{exp}) + p_j^{exp} \times Y_j^{exp} - c_j^{imp} \times Y_j^{imp} - C_j \times Y_j \right) - \sum_i \left( c_i \times X_i + c_i^{imp} \times X_i^{imp} - p_i^{exp} \times X_i^{exp} \right) \right\} (15)

Total incomes from biofuels (BINC):
The total income in the supply chain derives from the contracted price of biofuel in the local market multiplied by the assorted quantity and/or by the selling of the surplus in an external or secondary market.

\left\{ B_{INC} : \sum_j \left( p_j \times (Y_j - Y_j^{exp}) + p_j^{exp} \times Y_j^{exp} \right) \right\} (16)

Total incomes from feedstock (FINC):
Accordingly additional revenues may result from the export of the over adequate feedstock

\left\{ F_{INC} = \sum_i \left( p_i^{exp} \times X_i^{exp} \right) \right\} (17)

4.1.8. Costs estimation
On the costs side one may assign all the parameters related to biofuel and raw material cost concerning the charge of imported quantities (raw material and biofuel) as well as the production cost of those two. It should be emphasized that the production cost of biodiesel does not include the cost of raw materials that is considered separately, since the raw material selection is one of the issues that is resolved with the optimisation.

\left\{ \sum_j \left( c_j^{imp} \times Y_j^{imp} + C_j \times Y_j \right) + \sum_i \left( c_i \times X_i + c_i^{imp} \times X_i^{imp} \right) \right\} (18)

The model provides the flexibility to include in detail transportation cost parameters and/or environmental costs in a more complicated version of the model.

5. Case study: biofuels in Greece

5.1. Biofuels present state situation in Greece: production and raw materials availability

Model implementation supports decision making and evaluation of the Greek BSC, under the present economic framework. The Greek biodiesel sector, following the evolution of the European one, did not present a significant penetration rate during the past four years (2006–2010), primarily because of the high production costs of biofuels and secondly because of the adopted detaxation quoting scheme. Greece has enforced Directive 2003/30/EC by harmonizing it with the National Law in 2005, Law 3423/2005 (valid up to today), which enables either the production or import and/or trading of biofuels. The quota scheme that was followed supported full detaxation of pre-arranged biodiesel quantities being allocated to a number of selected beneficiaries.

In terms of production, in 2008, the Greek instate capacity accounted for about 13 biodiesel plants of nominal in total – capacity of 702,500tn/annum [33], whereas there are additional 4 firms which select to import their raw material (biodiesel) from associated EU producers, in order to place it, under favorable terms, in the Greek Market (see Table 1).

The main process that is at the moment employed in biodiesel domestic production is trans-esterification of a lipid feedstock, which can be produced from any vegetable oil, such as rapeseed, soybeans, cottonseed, peanuts, corn, olives sesame and sunflower seeds.

Examining the agricultural feedstock in Greece, most of biodiesel raw materials (70%) are imported by Greek producers (mainly rapeseed and soybean oils). The remaining 30% is in-house produced, consisting of cotton-seed, sunflower and used cooking oils. In 2008 the majority of the oilseeds produced locally have been cotton seeds (900,000 kg). This quantity of raw material along with the rest energy crops that have been cultivated in the area of 116,725,000 m² resulted in 36,900,000lt of biodiesel (i.e. a 30% of the total — fully detaxed, allocated in 2008 Greek market quantity) (see Tables 2,3).

As far as the present state situation is concerned, it seems that further land is occupied for the cultivation of rapeseed and sunflower in Thrace and in Macedonia (Northern Greece) whilst the total soy oil quantity remains still imported.

5.2. Case study specifications

As aforementioned, biofuels production in Greece refers only to biodiesel and more specifically biodiesel produced by the first generation production methods and techniques (Table 4). In order to evaluate the Greek biofuels sector and its possible contribution to the fossil energy - dependent transportation sector, two economic scenarios have been considered:

- a high cost scenario, whereas no inclusion of land support schemes or any subsidization of feedstock cultivation or de-taxation of biofuels is taken into account, and

Table 1
Production capacities of Greek Biodiesel producers and importers [33].

<table>
<thead>
<tr>
<th>Company brand name</th>
<th>Biodiesel origin</th>
<th>Annual capacity of the year 2008 (tn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ELVI HELLINIC</td>
<td>Greek Facility</td>
<td>Production 79,200</td>
</tr>
<tr>
<td>2 BIPETROLEUM S.A.</td>
<td>Greek Facility</td>
<td>Production 99,000</td>
</tr>
<tr>
<td>3 VERT OIL S.A.</td>
<td>Greek Facility</td>
<td>Production 10,450</td>
</tr>
<tr>
<td>4 AGROINVEST S.A.</td>
<td>Greek Facility</td>
<td>Production 230,000</td>
</tr>
<tr>
<td>5 STAFF COLOUR – ENERGY</td>
<td>Greek Facility</td>
<td>Production 11,000</td>
</tr>
<tr>
<td>6 NORTHERN GREECE</td>
<td>Greek Facility</td>
<td>Production 6600</td>
</tr>
<tr>
<td>GINNING - SPINNING MILLS S.A.</td>
<td>Greek Facility</td>
<td>Production 79,200</td>
</tr>
<tr>
<td>7 BIODIESEL S.L.R.</td>
<td>Greek Facility</td>
<td>Production 21,000</td>
</tr>
<tr>
<td>8 ELIN BIOFUELS S.A.</td>
<td>Greek Facility</td>
<td>Production 73,300</td>
</tr>
<tr>
<td>9 BIOENERGIA</td>
<td>Greek Facility</td>
<td>Production 9000</td>
</tr>
<tr>
<td>10 MIL OIL HELLAS A.E.</td>
<td>Greek Facility</td>
<td>Production 9900</td>
</tr>
<tr>
<td>11 PYTOENERGIA S.A.</td>
<td>Greek Facility</td>
<td>Production 21,000</td>
</tr>
<tr>
<td>12 GF ENERGY A.E.</td>
<td>Greek Facility</td>
<td>Production 99,000</td>
</tr>
<tr>
<td>13 MANOS S.A.</td>
<td>Greek Facility</td>
<td>Production 33,000</td>
</tr>
<tr>
<td>14 MOTOR OIL (Hellas), CORINTH</td>
<td>Imported from EU</td>
<td>Countries</td>
</tr>
<tr>
<td>15 BIODIESEL S.A.</td>
<td>Imported from EU</td>
<td>Countries</td>
</tr>
<tr>
<td>16 DP LUBRIFICANTI SRL</td>
<td>Imported from EU</td>
<td>Countries</td>
</tr>
<tr>
<td>17 CAFFARO CHIMICA SRL</td>
<td>Imported from EU</td>
<td>Countries</td>
</tr>
<tr>
<td>18 Total Production Capacity (Greek Biodiesel Facilities)</td>
<td>Total Production Capacity</td>
<td>702,450</td>
</tr>
</tbody>
</table>
Table 2
Efficiencies of the agricultural raw materials for the conversion into liquid biofuels \cite{9}.

<table>
<thead>
<tr>
<th>Biofuel</th>
<th>Raw material</th>
<th>Yield in raw material (kg/1000m²)</th>
<th>Efficiency of the process (Biofuel yield) (lt/1000m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biodiesel</td>
<td>Rapeseed</td>
<td>150–300</td>
<td>58–116</td>
</tr>
<tr>
<td></td>
<td>Sunflower</td>
<td>120–160</td>
<td>20–27</td>
</tr>
<tr>
<td></td>
<td>Cynara</td>
<td>100–150</td>
<td>28–41</td>
</tr>
<tr>
<td></td>
<td>Soya</td>
<td>160–240</td>
<td>32–48</td>
</tr>
</tbody>
</table>

- a low cost scenario where at the parameters estimation in the feedstock supply side and at the biodiesel production, economic subsidies are incorporated.

Thus, for biodiesel production five raw materials have been selected: two energy crops, rapeseed and cynara and three traditional ones, sunflower, cotton and soya. In view of ethical considerations, for the cultivation mainly of the traditional crops also serving for food purposes, it should be noticed that the area of the land exploited in the present optimisation problem is considered limited and less than 10% of the total available for each selected crop, in order to avoid any conflicts of fuel vs food in the land use.

In the same framework, water utilisation for the specific feedstock cultivations is assumed to be following the predetermined consumption practices and restrictions. Therefore, it is assumed that water and other resources (fertilizers, equipment, capital) availability is adequate to cover the needs of this specific case study. Furthermore, it is assumed that there is no intermediate storage available since that would in fact obscure the priorities of the optimisation problem.

Proceeding to the cost related parameters concerning the raw materials, one should note that the prices prescribed, also incorporate the transportation cost, from the "field of production" to the "door" of the biodiesel plants (Table 5). Likewise, in the value of the imported feedstock, the cost related parameters also include the transportation cost from the country of origin to the production facility in Greece.

Furthermore, the reason for the uniform price assignment in all the feedstock and in the case of imports and local production (both for the high and low cost scenario examination) is that the present work needs to enlighten the technical feasibility of biofuels production, which is generally applicable with respected to their economic viability, but not just the latter, which is very space dependent. Therefore the same cost consideration facilitates the optimisation model to choose over the more efficient raw material in terms of land and biofuel production yield and not just over the cheap one assigning at the same time an environmental character to model decision making as well. Nevertheless, in a non-established Greek biofuel market, whereas no exports of raw materials take place (price of exported feedstock = 0), the choice of consistent assorted price parameters is a rather safe option for the most representative optimisation results.

Considering the above, a rather promising scenario for local annual biodiesel production of 120,000 lt is examined, regarded to meet totally the 10% of biodiesel rate which was allocated in 2008 in the Greek market, at a modest, selling price of 1.2 €/lt. Moreover, it is considered that imported seed quantities should not exceed a 15% of the domestically produced ones, with view of reinforcement of the local agricultural sector. The only exception to that is soya, which is regarded as totally imported, as at the moment there is not instate seed production. Finally, biodiesel exports and imports are totally free to meet the needs of the optimisation problem, with the assorted prices been selected with provisions of fair trade enactment.

Synopsisizing, for a time horizon of one year (\(t = 1\)), and considering the production of biodiesel only (\(j = 1\)) the specifications and the results of the model implementation are shown in Tables 4, 5, and 6.

6. Results and analysis

The optimisation model has been implemented in two different optimisation software programs; namely, in the EXCEL/Solver optimiser that is available in MS Office EXCEL and in the GAMS optimiser. The General Algebraic Modeling System (GAMS) is a high-level algebraic modeling system for large scale optimisation, being able to solve linear and non-linear, integer and mixed integer linear and non-linear problems.

For the high cost scenario, the model denotes that under the restriction that has been set for local production, the demand for both raw materials and biofuels is satisfied partially by the instate capacity and the rest by the imports, resulting in a negative total value of the BSC of (−100,275 €), taking into account the rough assumptions of cost that have been made (see Table 7).

### Table 2
Efficiencies of the agricultural raw materials for the conversion into liquid biofuels \cite{9}.

<table>
<thead>
<tr>
<th>Biofuel</th>
<th>Raw material</th>
<th>Yield in raw material (kg/1000m²)</th>
<th>Efficiency of the process (Biofuel yield) (lt/1000m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biodiesel</td>
<td>Rapeseed</td>
<td>150–300</td>
<td>58–116</td>
</tr>
<tr>
<td></td>
<td>Sunflower</td>
<td>120–160</td>
<td>20–27</td>
</tr>
<tr>
<td></td>
<td>Cynara</td>
<td>100–150</td>
<td>28–41</td>
</tr>
<tr>
<td></td>
<td>Soya</td>
<td>160–240</td>
<td>32–48</td>
</tr>
</tbody>
</table>

### Table 3
Biodiesel production from instate land cultivated feedstock for 2008 \cite{33}.

<table>
<thead>
<tr>
<th>Energy crops (1000m²)</th>
<th>116,725</th>
<th>36,900</th>
<th>30%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton seeds (kg)</td>
<td>900,000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 4
Specific considerations for the Greek case study.

<table>
<thead>
<tr>
<th>Raw materials</th>
<th>Traditional crops (sunflower, cotton, soya)</th>
<th>Energy crops (rapeseed, cynara)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedstock transportation mode</td>
<td>Biodiesel production technology</td>
<td>Biodiesel production facilities</td>
</tr>
<tr>
<td>Cost estimations for feedstock</td>
<td>Transportation in silos</td>
<td>Transamidification/Esterification</td>
</tr>
<tr>
<td></td>
<td>Mobilized only existing ones</td>
<td>Transportation and production cost is considered in the term</td>
</tr>
</tbody>
</table>

### Table 5
Selected parameters for model optimisation — raw materials origin.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rapeseed</th>
<th>Sunflower</th>
<th>Cotton</th>
<th>Cynara</th>
<th>Soya</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land related parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(A_{\text{max}}) (ha)</td>
<td>200.00</td>
<td>300.00</td>
<td>200.00</td>
<td>200.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Conversion factors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(e_i) (kg/ha)</td>
<td>350.00</td>
<td>300.00</td>
<td>160.00</td>
<td>150.00</td>
<td>240.00</td>
</tr>
<tr>
<td>(b_j) (lt/kg)</td>
<td>0.50</td>
<td>0.40</td>
<td>0.17</td>
<td>0.30</td>
<td>0.20</td>
</tr>
<tr>
<td>Cost parameters for selected raw materials—High and low cost scenario</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(CR_j) (€/kg)</td>
<td>0.50/0.20</td>
<td>0.50/0.20</td>
<td>0.50/0.20</td>
<td>0.50/0.20</td>
<td>0.50/0.20</td>
</tr>
<tr>
<td>(CR_{\text{exp}}) (€/kg)</td>
<td>0.40/0.18</td>
<td>0.40/0.18</td>
<td>0.40/0.18</td>
<td>0.40/0.18</td>
<td>0.40/0.18</td>
</tr>
<tr>
<td>(P_{\text{exp}}) (€/kg)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

### Table 6
Selected parameters for biodiesel production.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>High Cost Scenario</th>
<th>Low Cost Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_i) (€/lt)</td>
<td>0.75</td>
<td>0.50</td>
</tr>
<tr>
<td>(C_{\text{imp}}) (€/lt)</td>
<td>0.55</td>
<td>0.45</td>
</tr>
<tr>
<td>(P_{\text{ex}}) (€/lt)</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>(P_i) (€/lt)</td>
<td>1.20</td>
<td>1.20</td>
</tr>
<tr>
<td>(D_{\text{exp}}) (lt)</td>
<td>120,000.00</td>
<td>120,000.00</td>
</tr>
<tr>
<td>(C_{\text{AP}}) (lt)</td>
<td>750,000.00</td>
<td>750,000.00</td>
</tr>
</tbody>
</table>
More specifically for the high cost scenario, the production cost also incorporates the Specific Investment Cost of a small unit up to 5000 tn/year (0.45–0.60 €/lt [34]), which in the case of the large plants (i.e. indicative nominal capacity of 132,000 tn/year), may be reduced up to 0.2 €/lt [4]. For this scenario, there are imports in raw materials and biodiesel.

However for more moderate estimations of production costs (the low cost scenario), the resulting total value of the BSC tends to be beneficial at 12,295 €, satisfying the pre-set demand of 120,000 lt per annum, whilst all the required biodiesel quantity is produced by the domestic plants, with no biofuel imports taking place (see Table 8).

In all cases soya is imported since this raw material is not cultivated domestically. Furthermore, cotton has not been selected since its efficiency is rather low compared to others and its cost is higher that the corresponding ones of the other raw materials. In practice, the difference between the results of the high and the low cost scenario lie in the quantities of imported soya and imported biofuels. In the low cost case there is no biodiesel import. Since the production cost is rather low, obviously the model prefers to import more quantity of soya and produce the required quantity of biodiesel domestically. In the high cost scenario, the model prefers to import much less quantity of soya and produce less quantity of biodiesel locally; instead, the required quantity of biodiesel is imported in order to cover local demand.

Certainly the results under consideration are dependent upon the various assumptions that have been made and the specific values of the problem parameters. What should be emphasized in this point is that the model has the ability to take into consideration a variety of problems, strategic and operational. For example, the land that should be allocated for the cultivation of a certain raw material – a strategic decision determined by regional policy – is a variable provided by the results of the problem.

As far as the operational problem is concerned, the model implementation provides a wide variety of results. In both cases the model has selected the most efficient raw materials for the satisfaction of the local demand. Also the model has estimated the amount of the raw materials and the final products to be imported and exported, as well as the amount of raw materials that are domestically cultivated and the amount of final products domestically produced.

7. Conclusions

The present work deals with the design and the operation of the BSC. The significance of the problem has been expressed by the extensive investigation of the biofuels sector that has been taking place during the last years for the – at least partial - replacement of the highly polluting conventional fuels.

The present effort has been focused in the development and implementation of a mathematical model for the optimisation of the integrated biofuels supply chain. The development of a flexible optimization 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, domestic production or imports, domestic consumption or exports and many other issues). 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, trading policy, conversion facilities location and design and operational characteristics such as selling prices, funding and support schemes, quantities to be imported and/or exported etc. 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 behaviour, 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 routines. This characteristic is important in the potential future exploitation of the approach and the development of a Decision Support System. The model has been implemented in an exemplar case study in Greece, demonstrating the best available solution for the optimal planning and operation of the biofuels supply chain. 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 and yields, various costs, land availability etc.) are critical factors in the performance and the contribution of the present work.

References


Indices

i: Raw materials
j: Biofuels
\( t \): Time

Continuous variables

\( A_i \): Area being cultivated for raw material (in ha)
\( X_{i,j}\): Quantity of raw material i that is exported (in kg, included in \( X_{j} \))
\( V_{i} \): Quantity of raw material i being imported for domestic production of biofuels (in kg)
\( Y_{i,j} \): Quantity of biofuel j being domestically produced (in lt), from raw material \( i \)
\( Z_{i,j} \): Quantity of biofuel j being exported (in lt)—included in \( X_{j} \)
\( W_{i,j} \): Quantity of biofuel j being imported to in order to satisfy demand (in lt)

Parameters

\( A_{\text{max}} \): Maximum land available for cultivation of raw material i (in ha)
\( b_{ij} \): Yield of land in raw material i (in kg of seed/ha)
\( a_{ij} \): Yield of raw material i for the production of biofuel \( j \) (in kg of biofuel/kg of raw material)
\( \text{CAP} \): Capacity for the production of biofuel j (in lt/annum)
\( \text{DM}\text{M} \): Demand for raw material i for the biofuels to be produced (kg/annum)
\( \text{DB} \): Demand for biofuel(s) to satisfy needs and legislation (in lt/annum)
\( \text{C}_{c} \): Production cost for biofuel j locally produced (not including the cost of raw materials, €/lt)
\( \text{C}_{C} \): Cost of imported biofuel (€/lt)
\( \text{CR}_{c} \): Production cost of raw material (€/kg)
\( \text{CR}_{c} \): Cost of imported raw material (€/kg)
\( \text{P}_{c} \): Price of exported raw material (€/kg)
\( \text{P}_{c} \): Selling price of biofuel j locally produced and consumed (€/lt)
\( \text{P}_{c} \): Selling price of biofuel i locally produced but exported (€/lt)
\( \text{W}_{i} \): Raw materials specific water consumption, i.e. quantity of water demand for the cultivation of raw material i (in m\(^3\) of water demand/kg of raw material i being cultivated)
\( \text{W}_{i} \): Biofuels production specific water consumption, i.e. quantity of water demand for the production of biofuel j (in m\(^3\) of water demand/lt of biofuel j domestically produced)
\( \text{W}_{i} \): Maximum water availability for raw material i (in m\(^3\) of water)
\( \text{W}_{i} \): Maximum water availability for biofuel j (in m\(^3\) of water)