Model for optimization of biomass utilization of energy production by energetic and economic requirements

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Abstract. Biomass-energy use is not a new idea. Earlier the by-products of the production processes or naturally grown materials were mainly used for energy production. One of the answers to the contemporary problems is the deliberate as well as mass production of the biomass, furthermore the planned and systematic collection of the by-products, which is the source of the energy being able to replace a part of the fossil fuels. At the same time during the production of biomass the conventional sources of energy are being used (fuels, the embodied energy which is used in the production of the equipment, etc.) which are to be taken into account in determining the net energy production. The research aims to examine how to optimize production and use of biomass energy supply chain process in the energetic and the economic criteria system, how to impact the managing models of the processes to the energetic and economic parameters of the supply chain, what kind of criteria and how these identify the natural (environmental), economic and social sustainability, and how they will be implemented e.g. in frame an innovation cluster. This article describes a test model, analyzes the results of the model examinations and the conditions for compliance with sustainability criteria.

Keywords: sustainability, logistics, heating energy, local society, cluster

JEL Codes: C67, Q42, Q51

1. Introduction

The research carried out in the topic of biomass utilisation of energy production has had a long history of several decades in Hungary. Research primarily focused on the by-products of plant production in the 1980’s (e.g. Lehoczki and Takács 1981 and Lehoczki and Takács 1983 where the economic assessment of the experiments with KTB-R straw bale heating energy production was presented). Afterwards, in the 1990’s attention was mainly directed at plants utilised for energy production in many ways and the technologies of their utilisation (bio ethanol, biodiesel, hard-stemmed and non-hard stemmed resources). At that time the spread of the biomass-based alternative energy resource use was significantly hindered by the relatively low piece of fossil fuels and the relatively low returns on the technologies of producing biomass-based energy resources. Nowadays the price of fossil fuels has considerably been raised and the competitiveness of alternative energy resources has greatly improved due to the fact that the political leaders of different
governments were ready to accept the researchers’ views and also action plans were drafted to decrease the extent of environmental pollution. The need for sustainable development has also become stronger.

The complex system of sustainability has necessitated the application of such multi-criteria decision making models that help select the optimal decision making alternatives by arguing criteria. Due to the general system of points of view on the implementation of projects it is necessary to examine technical, financial and economic feasibility alike. The evaluation of the points of view is usually hierarchic, i.e. technical feasibility (the availability of equipment, suitable technology and licenses to implement the given project at the given place and time) is the prerequisite of the examination of economic feasibility (return) which is the necessary (but not at all satisfactory) condition for financial feasibility (the availability of financing sources and funds). The parts of the system of conditions are correlated as technical feasibility affects the cost of the project, the possible revenue; the compounds of the funds has an impact on their costs that affect return and, at the same time, the economic risks detected while analysing returns influence the cost of funds (credit spread risk).

The traditional system of points of view can actually include compliance with environmental-economic-social sustainability. Furthermore, their simultaneous examination in an explicit way has not been carried out. At the same time, there is a need for such an optimising model that are suitable for arguing for natural sustainability directly (e.g. energy balance (return), or aggregated CO₂ emission) or indirectly (e.g. by minimising the environmental pollution of transportation). Moreover, the model includes social sustainability as an impact factor together with employment as well as the impacts of organisation structures on performance, instrument efficiency and capital investment requirement (how many and what types of instruments are necessary to solve the task).

The model can be used to solve all types of optimisation problems when it comes to

- designating transportation areas,
- selecting the optimal site of the plant,
- evaluating the energy payback ratio and the impacts on aggregated CO₂ emission of the sporadic biomass for energetic purpose as well as
- analyzing the economic impacts of organisational solutions.

A complex system of indicators is used for optimisation where the widely used investment-economic criterion is supplemented by transport optimising and energy efficiency and possibly an aggregated CO₂ emission optimising component.

The issue of energy payback is detailed by the dimensions of the optimising model. Energy utilisation and energy payback were modelled by the concept of mass flow models. The concept of mass flow models are described by the equations of raw material extraction/production-processing-utilisation-losses.

In the case of pure mass flow (when mass is not transformed into energy) the weight of all the masses in the system equals the amount of masses accumulated in the system and those leaving the system as losses on the basis of the law of conservation of mass.

The law referred to above also holds true for the production of biomass for energetic purposes. At the same time, the amount of energy deriving from nature (decisively i.e. solar energy) plays a significant part of producing the utilisable amount of energy although significant amount of hidden energy also accompanies the process of production (embodied in the instruments of production, materials used and energy taken in through production) together with overt energy (taken in the process by means of fuel). However, instruments do not only pass down their economic value (see amortisation) to products via several production cycles but also energy that is necessary for their creation.
Regarding energy payback we have to measure the extent (frequency) of payback of the direct and indirect fossil energy source based energy taken in the system in the energy amounts produced within its lifespan. To measure this, EPR (Energy Payback Ratio) energy payback ratio was worked out that examines the relationship between total net energy yield and total energy payback by means of lifecycle analysis. [White and Kulcinski, 2000].

\[
EPR = \frac{E_{n,L}}{E_{mat,L} + E_{con,L} + E_{op,L} + E_{dec,L}}
\]

where \(E_{n,L}\) is total net energy (J) produced during the lifespan (L) of the establishment
\(E_{mat,L}\) is total energy (J) taken in by the materials during the lifespan (L) of the establishment
\(E_{con,L}\) is total net energy (J) taken in instruments and the establishment during the lifespan (L) of the establishment
\(E_{op,L}\) is total net energy (J) taken by its operation and fuels during the lifespan (L) of the establishment
\(E_{dec,L}\) is total energy (J) necessary for stopping the establishment after its lifespan (L)

Estimating the energy footprint of the instruments, i.e. their embodied energy is a modern approach of measuring energy efficiency through which a real picture can be obtained about the usefulness of the single solutions aimed at saving energy. The name of the approach is the Input-Output Embodied Energy analysis model by Leontief, which is the adaptation of the neoclassical theory of general balance. [Leontief, 1966] (NB also Wikipedia: Embodied energy, 2012.)

The research and examinations that make a try to define the energy equivalence of the different masses and instruments play a significant role in the practical application of the model. The activity of the research team of the University of Bath (UK) is outstanding who worked out the embodied energy per unit in different types of masses as well as their CO₂ equivalence. [Hammond, Jones 2008] The definition of the energy equivalence of a machine, equipment, building or establishment is a complex task. According to estimations, e.g. the energy equivalence of an average Australian car is 0.22-0.27 TJ. During the lifespan the relative weight of the single components vary, which must be taken into consideration in the examinations (e.g. in our calculation the car has a share of 64%, road construction 21% and running a car 15% of the energy equivalence in the first year while by the end of the lifespan (after 40 years) running a car represents 62%, car manufacturing and running 28% and road construction 10% of the total 6.572 TJ energy equivalence (embodied energy). [Treloar et al. 2004]

At the same time, we have to consider that the energy efficiency of certain activities will improve due to the technical development and improvement, which stresses the necessity of revising the standard values of modelling from time to time. [The NEED Project 2011]

The spread of the external costs of biomass-based energy production is significant in different European countries (the typical value is 1-2 euro cent but there are countries where it can even each 5-6 euro cent). [A villamosenergia termelés externális költségei…. 2010] This directs our attention to the importance of analysing the cost component.

The energy payback ratio of the biomass-based energy production is 15-30 times higher, which is a very favourable value in the comparison of single power plant technologies. However, we must bear it in mind that the aggregated CO₂ emission indicator can be relatively unfavourable as predicted by high GWP values. [Lund and Biswas 2008] GWP (Global Warming Potential) is an indicator to express the impacts of greenhouse gases numerically that defines the extent of the greenhouse impact of the given gas compared to the same amount of carbon dioxide for a certain period (usually for 100 years). Obviously, the GWP of carbon dioxide is 1 according to the definition.
The objective of the research is to create a multi-factor model of evaluation by arguing for sustainability criteria that assist in designating the site of the furnace of burning biomass, setting the frontiers of its region together with ranking decision making alternatives.

2. Material and methods

OPTILOG© model is a multi-factor comparative method in which logistic costs, energy payback, CO₂ emission and economic return will simultaneously be assessed and the optimal is the one in which the factors are the best balanced.

Model variations:
A) Dimensions of the three dimensional OPTILOG© model:
   1. Net transportation (logistic) cost
   2. Energy payback ratio (EPR)
   3. Net present value (NPV)

B) Dimensions of the four dimensional OPTILOG© model:
   1. Net transportation (logistic) cost
   2. Energy payback ratio (EPR)
   3. Aggregated CO₂ emission
   4. Net present value (NPV)

Optimisation criteria: the area covered by the triangle or square by the standardised values of the criteria should be maximum on the three-or four-dimensional ray diagram.

Steps of optimisation:
1. Preparing the tables with the basic data
2. Preparing the parameters of the alternatives
3. Calculating the values of dimension variables per alternative
4. Standardising result values
5. Calculating OPTILOG© optimum criterion value
6. Evaluating results

2.1. Calculating the values of dimension variables

Dimension 1: Transportation arrangement optimum

Optimisation takes place by trying to find the shortest distance of transportation or the cheapest way of transportation by using the method of the smallest squares.

Designating the site of the optimal furnace on the basis of the cheapest transportation costs in the case of a single mass flow
Condition: different means of supply with different costs and substantially different amounts

\[ C_j = \sqrt{\frac{\sum_{i=1}^{n} \sum_{j=1}^{n} c_i^j \cdot m_{ij} \cdot d_{ij}}{\sum_{j=1}^{n} n_j}} \]

where  
\( C_j \) is the average transportation cost weighed by the amount of goods to be transported and the distance between the sites of the resources and j site of usage (Ft)  
\( c_i \) is the transportation cost of the amount to be transported from i site of resource (Ft/km)  
\( m_{ij},i \) is the weight to be transported between i site of resource and j site of usage in y year (t)  
\( d_{ij} \) is the distance between i site of resource and j site of usage (km)  
\( n_j \) is the number of resource sites
$k$ is the number of potential sites of usage

Optimum:

$$\min_{j \in [1,k]} \sum_{j} C_j$$

If the site of the furnace and the site of energy utilisation differ or there are several alternatives, optimisation takes place by considering the cheapest input supply cost and output cost of further transportation. Condition: different means of supply with different costs and substantially different amounts and different transportation costs of energy (heating, steam...) to the site of usage.

Optimum:

$$\min_{j \in [1,k]} \left( C_j + C_{j}^{E} \right)$$

where $C_j$ is the average transportation cost weighed by the amount to be transported and the distance between the sites of resources and $j$ potential furnace (Ft) $C_{j}^{E}$ is the energy transportation cost between $j$ potential furnace and the site of usage (Ft/km) $k$ is the number of sites of resources

**Dimension 2: Energy payback on the basis of the Energy Payback Ratio (EPR)**

Energy payback is defined by analysing the project lifecycle by comparing the amounts of utilisable/utilised energy and directly or indirectly utilised energy created during the years of operation (Y). It is calculated as follows:

1. estimating the amount of utilisable energy produced during the lifespan of the project
2. estimating the amount of directly utilised energy (fuels) or indirectly utilised energy (embodied energy, the size of the energy footprint produced during the lifespan of the project
2.1. estimating the amount of energy embodied in the instruments invested during the lifespan of the project to meet its objectives
2.2. estimating the value of energy embodied in the instruments partly meeting the objectives of the project per performance unit during the lifespan of the project by considering the conditions of the use of instruments
2.3. estimating the performance of instruments that partly meet the objectives of the project
2.4. estimating the value of energy utilised during the lifespan of the project
2.5. equivalence of energy necessary for the infrastructure connected to the operation of the project
2.6. equivalence of energy necessary to meet the basic demands of the labour force who operate the project
2.7. estimating the energy necessary to stop the project by the end of its lifecycle

The next correlation describes the estimation of net energy that can be produced by operating the project during its lifespan on the basis of the projected energy production.

$$E_N^{\text{i}} = \sum_{y=1}^{Y} E_{V,y}^{\text{i}} + E_{H,y}^{\text{i}} + E_{M,y}^{\text{i}}$$

where $E_N^{\text{i},y}$ is net (utilizable) energy (J) that can be produced during the lifespan by $i$ project alternative $E_{V,y}^{\text{i}}$ is the amount of electric energy (J) in $y$ years in the case of $i$ project alternative $E_{H,y}^{\text{i}}$ is the amount of geothermal energy (J) in $y$ years in the case of $i$ project alternative $E_{M,y}^{\text{i}}$ is the amount of energy (J) embodied in the mass for sale in $y$ years in the case of $i$ project alternative $Y$ is the lifespan of the project (year)
Estimating the energy footprint (embodied energy) of the project

\[ E^E = \sum_{y=1}^{Y} E_{i,y}^{E_i} + E_{i,y}^{E_{ij}} + E_{i,y}^{E_{ij}} \]

where \( E_{i,y}^{E_i} \) is the amount of energy (J) embodied in the mass for sale in \( y \) years in the case of \( i \) project alternative
\( E_{i,y}^{E_{ij}} \) is the energy embodied in the instruments meeting the objectives of the project in \( y \) year per unit during the lifespan of the project by considering the conditions of the use of instruments in the case of \( i \) project alternative accounted for once a year when the use of their utilisation for the project began (J)
\( E_{i,y}^{E_{ij}} \) is estimating the value of energy embodied in the instruments partly meeting the objectives of the project per performance unit during the lifespan of the project in the case of \( i \) project alternative in \( y \) year every year accordingly to the use of the given year (J)

Energy value of running

\[ E_i^O = \sum_{y=1}^{Y} E_{i,y}^{O_{i,y}} + E_{i,y}^{O_{i,y}} \]

where \( E_{i,y}^O \) is the equivalent of total energy value of running by using \( i \) project alternative during the lifespan, which is in accordance with the energy footprint (embodied energy) of the amount of materials and energy resources utilized (J)
\( E_{i,y}^{O_{i,y}} \) is the equivalent energy of the materials and energy resources utilized by \( i \) project alternative in \( y \) year of running that is accounted for annually in accordance with the energy footprint (embodied energy) of the amount of materials and energy resources utilized (J)

Energy equivalence of restoring the condition prior to the project and destruction

The energy equivalence of restoring the condition prior to the project is estimated to be 10-30% of the energy embodied in the establishments of the project.

Calculation of energy payback

\[ EPR = \frac{E_i^N}{E_i^E + E_i^O + E_i^R} \]

where \( EPR \) is the energy payback ratio for the lifespan of the project (–)
\( E_i^N \) is the estimated value of net (utilizable) energy for \( i \) project alternative for the project lifespan (J)
\( E_i^E \) is the estimated amount of energy embodied in the instruments of \( i \) project alternative for the project lifespan (J)
\( E_i^O \) is the equivalence of the energy of materials, energy, labour, embodied energy utilized in \( i \) project alternative for the project lifespan (J)
\( E_i^R \) is the estimated equivalent energy of restoration in the case of \( i \) project alternative at the end of the project lifespan (J)

Dimension 3: Present value of revenue realised in the period of lifespan

The process of calculating revenues realised in the period of years (Y) is the following:

1. Estimating cash-flow for the whole project lifespan
   1.1. timing of investments, estimating investment costs at fixed prices (there might be a need for another supply of logistic instruments and some technological equipment for the project lifespan (Y year)
   1.2. estimating running costs at fixed prices
1.3. estimating revenues realised in the years of operation at fixed prices
1.4. estimating the residual value of instruments at the end of the period
1.5. estimating the costs of destruction and restoring the original state at the end of the period

2. estimating alternative rate of interest
3. calculating net present value

Due to the constraints of the present paper the parts of cash-flow and calculating NPV indicator will not be dealt with as they can be found with details in the professional literature.

**Dimension 4: Calculating aggregated CO\textsubscript{2} emission**

Aggregated CO\textsubscript{2} emission can be defined by analysing project lifecycle like in the case of Dimension 2 and 3 by defining CO\textsubscript{2} equivalence embodied in the instruments and materials realised or indirectly utilised during the project lifespan (Y). Its calculation is analogue with defining embodied energy, which is now not detailed, either due to the limitations of the present paper.

**2.2. Defining the optimum of the model**

The optimum is at the maximum of the area covered by the standardised model values of the factors (dimensions) (see Figure 1). The order of the axes is discretionary in the case of three dimensions whereas in the case of four dimensions it is fixed; clockwise (1) standardised logistic costs, (2) energy payback, (3) aggregated CO\textsubscript{2} emission, (4) indicator of revenue after the project lifespan.

In a professional sense, the indicators are favourable even if costs are the lowest possible (LC=\(C\)), ERP is the highest possible, aggregated CO\textsubscript{2} emission is the lowest possible and revenues (NPV) are the highest possible.

Optimum: the area bordered (defined) by the standardised values of the criteria should be maximum. The area of the polygon is calculated by using the area of the triangles that make it up.

As the standardised values can also be negative, their common vertex comprises the smallest standardised value so the length of the side of the triangle (D) is as follows:

In the case of logistic costs:

\[
D_{j}^{LC} = \left( -SD_{j}^{LC} - \min(-SD_{j}^{LC}) \right)
\]

The lower logistic costs are, the more favourable so by multiplying them by (-1) they are transformed in the similar reference values.

In the case of energy payback:

\[
D_{j}^{EPR} = \left( SD_{j}^{EPR} - \min(SD_{j}^{EPR}) \right)
\]

In the case of aggregated CO\textsubscript{2} emission:

\[
D_{j}^{CO_{2}} = \left( -SD_{j}^{CO_{2}} - \min(-SD_{j}^{CO_{2}}) \right)
\]

The lower aggregated CO\textsubscript{2} emission is, the more favourable so by multiplying it by (-1) they are transformed in the similar reference values.

In the case of return on investment:

\[
D_{j}^{NPV} = \left( SD_{j}^{NPV} - \min(SD_{j}^{NPV}) \right)
\]

where \(D_{j}^{LC}\) is the transformed, standardized value of the logistic costs of \(j\) alternative for the project lifespan (-)
\(SD_{j}^{LC}\) is the standardized value of the logistic costs of \(j\) alternative for the project lifespan (-)
\(D_{j}^{EPR}\) is the transformed, standardized value of the energy payback indicator of \(j\) alternative for the project lifespan (-)
$SD^{EPR}_{j}$ is the standardized value of the energy payback indicator of $j$ alternative for the project lifespan (-)

$D^{CO_{2}}_{j}$ is the transformed, standardized value of the aggregated CO$_{2}$ emission of $j$ alternative for the project lifespan (-)

$SD^{CO_{2}}_{j}$ is the standardized value of the aggregated CO$_{2}$ emission of $j$ alternative for the project lifespan (-)

$D^{NPV}_{j}$ is the transformed, standardized value of net present value income generation of $j$ alternative for the project lifespan (-)

$SD^{NPV}_{j}$ is the standardized value of net present value income generation of $j$ alternative for the project lifespan (-)

The size of the area designated by values in the case of three dimensions:

$$T_j = \frac{\sqrt{3}}{4}(D_j^{LC} \cdot D_j^{EPR} + D_j^{EPR} \cdot D_j^{NPV} + D_j^{NPV} \cdot D_j^{LC})$$

The size of the area designated by values in the case of four dimensions:

$$T_j = \frac{1}{2}(D_j^{LC} \cdot D_j^{EPR} + D_j^{EPR} \cdot D_j^{CO_{2}} + D_j^{CO_{2}} \cdot D_j^{NPV} + D_j^{NPV} \cdot D_j^{LC})$$

where $T_j$ is the area covered by the standardised criteria values (-)

Optimum:

$$\max T_j \quad j \in [1, k]$$

where $T_j$ is the area covered by the standardised criteria values (-)

3. Results

Five possible scenarios have been outlined (Table 1) to test the model that were evaluated by input data based on professional estimation.

**Table 1: General characteristics of scenarios**

<table>
<thead>
<tr>
<th>Code of the scenario</th>
<th>Characteristics of the basic material supplying district</th>
<th>Characteristics of machinery</th>
<th>Organisational characteristics</th>
<th>Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>The sampling district covers the geographic area modelled, roadworks density is balanced.</td>
<td>Modern machinery with average utilization.</td>
<td>Ocasional cooperation, not coordinated decision making</td>
<td>2 3</td>
</tr>
<tr>
<td>B</td>
<td>The sampling district goes beyond the geographic area modelled, roadworks density is favourable.</td>
<td>Modern machinery with above the average utilization.</td>
<td>Cooperating participants, coordinated decision making mechanisms</td>
<td>1 2</td>
</tr>
<tr>
<td>C</td>
<td>The sampling district is smaller than the geographic area modelled, roadworks density is not balanced.</td>
<td>Machinery of low performance with above the average utilization and significantly extra capacity.</td>
<td>Not cooperating participants, weak machinery performance, not coordinated decision making</td>
<td>5 5</td>
</tr>
<tr>
<td>D</td>
<td>The sampling district is smaller than the geographic area modelled, roadworks density is not balanced.</td>
<td>Modern machinery of high performance with below the average utilisation and extra capacity.</td>
<td>Not cooperating participants, weak machinery performance, not coordinated decision making</td>
<td>4 4</td>
</tr>
<tr>
<td>E</td>
<td>The sampling district goes</td>
<td>Old fashioned machinery of low</td>
<td>Cooperating participants,</td>
<td>3 1</td>
</tr>
</tbody>
</table>
beyond the geographic area modelled, roadworks density is favourable. performance with above the average utilization and above the average environmental pollution. coordinated decision making mechanisms

<table>
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<tr>
<th>AT</th>
<th>EPR</th>
<th>NPV</th>
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Source: own construction

After standardising the criteria values of the scenarios and calculating the three-and four-dimensional OPTILOG© indicator (Figure 1) the indicators obtained were suitable for ranking the alternatives. Excluding the aggregated CO₂ emission from the criteria made some changes at the top of the rank in this particular situation. However, the three-dimensional examination also supplies proper information to omit the least favourable scenarios. As a consequence, preparatory procedures can be reduced by means of a two-stage examination that consists of a preliminary selection and working out the values of the fourth dimension is also carried out in the case of the reduced alternatives.

The results of the tests proved that the optimisation model served as a proper decision making instrument in selecting between the alternatives in the case of a multi-criteria problem. However, the application of the model requires significant knowledge capital for which the cooperation between producers, consumers and the institutions that provide intellectual capital is inevitable. Due to the constraints of this study it cannot be explained in details but rather it is the cluster model that is the most suitable for meeting this requirement as from certain aspects it is better at integrating the interests and roles of the participants than the classical models of cooperation and alliance. Our experience in this field reflects the observations of Maciejczak [2012] in Poland. Károly Róbert College takes part in several regional clusters (among others to utilise renewable energy resources) as a governmental organisation and has experienced the birth of such synergies which prove that the efficient application of our model worked out to compare the biomass utilisation alternatives for energy production and its necessary maintenance triggered by technological and technical changes can be the most efficient within the framework of a cluster model cooperation. As a further argument for this, our experience that reflect that of Maciejczak and Szczupska [2012] transaction costs are favourable in a cluster model, which is also an important economic point to consider.

4. Discussion, conclusions
The complexity of economic and social processes requires a complex approach in the processes of evaluation. Arguing for the environmental-economic-social sustainability among the criteria of the model for evaluation is not possible at all times by means of direct indicators - that is why indicators that are suitable for expressing, describing or estimating observations in numbers can and must be selected while taking the essential relations between the process elements into consideration at the same time.

The research focussed on the biomass utilisation for energy production that results in utilisable energy on the one hand although the process directly or indirectly consumes energy and also has external impacts on the environment (heat emission, CO\textsubscript{2} emission) that are unfavourable.

The acquisition of input is not only a question of logistics but also influences the volume of the two factors stressed above (energy embodied in utilised instruments, infrastructure, CO\textsubscript{2} emission while transportation etc.)

It has also to be stressed that the efficiency of using the instruments, the level of cooperation describing the quality of social contacts influence return on energy as well as the volume of externalities as higher level cooperation and more efficient use of instruments improve return on energy and reduce environmental pollution.

Adding the criteria of sustainability to the traditional return on economy shows a longer-term way of managerial thinking. However, it also supports making better grounded decisions.

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6. References

