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The Effects of Plantation Size and Internal Transport on Energy Efficiency of Biofuel Production

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***Abstract*—**Mathematical model describing energetic efficiency (defined as a ratio of energy obtained in the form of biofuel to the sum of energy inputs necessary to facilitate production) of agricultural subsystem as a function of technological parameters was developed. Production technology is characterized by parameters of machinery, topological characteristics of the plantation as well as transportation routes inside and outside of plantation. The relationship between the energetic efficiency of agricultural and industrial subsystems is also derived. Due to the assumed large area of the individual field, the operations last for several days increasing inter-fields routes because of several returns. The total distance driven outside of the fields is, however, small as compared to the distance driven inside of the fields. This results in small energy consumption during inter-fields transport that, however, causes a substantial decrease of the energetic effectiveness of the whole system.

***Keywords*—**Biofuel, energetic efficiency, EROEI, mathematical modelling, production system.

I. INTRODUCTION

EMISSION of carbon dioxide is considered as one of the most important factors affecting global warming. The other problem of contemporary global economy is the prediction of exhaust of petroleum resources. Consequently, a replacement has to be taken into account.

Biomass derived biofuels are frequently considered [1] as one of the possible ways to combat both, i.e. shortages of petroleum as well as global warming. This idea motivates the search for most effective biomass resources, and technologies of their cultivation as well as technologies for conversion of biomass to energy. Several papers have been published dealing with cultivation methods of several plants [2], [3] and processing of them to biofuels [4]-[6]. Together with this trend another question can be raised: whether or not biomass derived fuels may be produced with sufficient efficiency with respect to energy consumption during production processes, equally in agricultural, and industrial operations are necessary to obtain biomass, and convert it to energy. It means that the amount of energy gained from biomass must be substantially greater than the amount of energy consumed during all processes facilitating production of biomass and conversion of it to energy. Characteristic that provides quantitative measure of that kind of efficiency was already established. This measure, called "energy return on energy invested" (EROI or EROEI), cf. e.g. [7], [8], is defined as:

$$H = \frac{\sum_{p=1}^{p} \left(E_{out}\right)_p}{E_{cr} + \sum_{p=1}^{p} \left(E_{in}\right)_p + E_{rem}} \qquad (1)$$

where: E_{out} is the total energy obtained during the *p-th* year from energy gathering system, E_{in} denotes the total energy used during that year, E_{cr} is the energy consumed to create the system, and E_{rem} is the energy needed for maintenance of that system, and finally liquidation after the end of its life at *p-th* year.

EROEI index is different than thermodynamic efficiency of energy conversion that is expressed as:

$$\eta = \frac{E_{out}}{E_{in}} = \frac{E_{out}}{E_{out} + E_w} \qquad (2)$$

where E_{in} is the input energy to the converter, E_{out} is the output of energy, that is directly converted form the input, and E_w denotes the energy dissipated (lost) by the converter.

In contrast, the energy, E_{in}, contained in (1), that is provided to the production system is not converted into the output. It is only used to support production process. The energy, E_{in}, depending upon particular situation, may be very small or even very large as compared to E_{out}. This means that the range of variation of the parameter, h, may extend in the limits $-\infty \leq h \leq \infty$. The thermodynamic efficiency, η, relates energies being converted one into the other, and therefore, the variation of this characteristic occurs only within the limits: $0 \leq \eta \leq 1$.

Perspectives of biofuel production in several countries have recently been discussed in several publications [2], [9]-[11]. Excellent review concerning various approaches to production as well as use of biofuels is given in [12]. Some of the papers refer to energetic efficiency of biofuel production. For example, analysis given in [13] shows that exergy loss, in the process of biodiesel production, is rather low, and still there are possibilities of further decrease due to predictable improvements of technology. For the case of bioethanol production, however, arguments presented [14] that the requirements of sustainability are not always fulfilled, i.e. bioethanol production methods are not sufficiently efficient from view point of energy yield.

The mentioned earlier paper [13] introduces a notion of the scale of the techno-system showing different processes determining efficiency at various scale levels. The highest level in this approach is that of the global size, while the next

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ones are subsequently more and more local. Empirical studies on energy efficiency of agriculture in general [13]-[17], as well as plantations, especially dedicated to "energetic" crops [18]-[24] are also available. Those works might provide the data enabling detailed analysis of the factors determining the energetic efficiency of real production systems. The role of the scale of a techno-system is discussed in the paper [25], providing feasibility study of various size production systems. In spite of quite abundant literature, there exist not so many papers discussing energetic effectiveness of agricultural part of biofuel production systems, and relating it to production conditions and technologies. To contribute to fulfilling of this gap, the present authors have proposed a model directly involving technological parameters for the evaluation of effectivity characteristic [26]-[30].

The present paper is aimed towards short presentation of the model describing the dependence of energetic efficiency of biofuel production system upon auxiliary energy inputs, that are consumed by processes supporting biofuel production. Also, the paper presents results of computations giving estimation of the main effects related to the real production conditions. Although agricultural part of the production system is a subject of present analysis, the indirect influence of industrial subsystem is also taken into account.

II. The Model

The main idea used in developing of the model is to identify factors playing role in determining the energy efficiency of the system, and to describe their contributions in a mathematical language. Further development is to define functional relationships and to perform numerical computations taking into account possibly realistic range of independent variables.

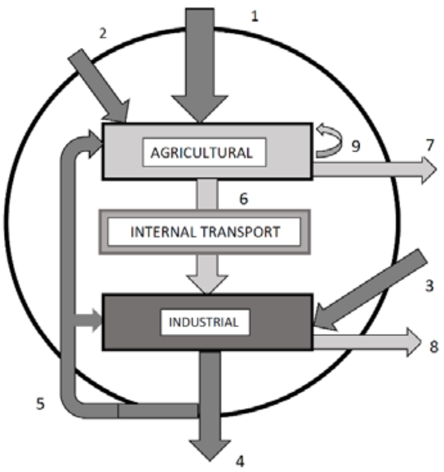

Fig. 1 The biofuel production system's structure

According to the assumptions made, the structure of biofuel production system is built of two subsystems connected by flows of materials and energy. The system is open, in the sense of exchange some flows with the surrounding. The structure of the system is shown in Fig. 1. The two subsystems, i.e. agricultural and industrial, are connected by internal transport. Arrows **1**, **2**, **3**, and **4** represent energy flows arriving from outside of the system; those can be solar, as well as fossil fuels derived fluxes of energy. The arrow **5** shows the flux of energy obtained from own production biofuel. The arrow **6** corresponds to the main flux of biomaterial produced, and being transported to the industrial subsystem. Fluxes **7** and **8** denote byproducts and wastes being rejected outside of the system, and consequently do not undergo conversion to energy. The flux **9** is the biomaterial used in the fields for agricultural reasons. The figure does not show the transportation processes inside of the agricultural, as well as industrial subsystems, nevertheless they have to be considered. Computations of the energy consumed for transportation outside of the field as compared to energy consumed in agricultural operations is performed in the present work.

Several processes are realized in the biofuel production system:

In agricultural subsystem, the start with tillage is accompanied by fertilizing and crop protection procedures. Simultaneously several transportation processes are executed, mainly related to machinery, but also to some other goods. Finally, the crop's collection, separation of various parts of plants, and transport of the crop are performed.

In the industrial subsystem, in turn, operations like drying, grinding, conducting chemical reactions, followed by cleaning, storage and transportation of biofuel occur. It should be mentioned that all of those processes require input of energy, and therefore contribute to the decrease of energetic efficiency of the system.

The energetic effectiveness, ε, related to one year of production of agricultural subsystem, can be expressed as:

$$\varepsilon = \frac{E_{bio}}{E_{ex} + E_{tr} + E_{emb}} \tag{3}$$

where E_{bio} is the energy obtained from the field, E_{ex} is the energy expended on tillage operations, E_{tr} is the energy used for transportation of biomass outside of the fields, E_{emb} is a fraction of energy embodied in the production means, that is consumed in tillage and transport operations within the production year.

The energies above mentioned can be presented as follows:

Energy contained in biofuel obtained from the plantation amounts to:

$$E_{bio} = A \times M_{crop}\left(c_f, c_w, c_{cp}, \ldots\right) \times \gamma \times \sum_{k=1}^{n} \alpha_k \times W_{bio,k} \tag{4}$$

where A denotes the plantation area, M_{crop} $(c_f,\ c_w,\ c_{cp},)$ – the crop yield, which, in turn, depends upon concentrations: c_f – fertilizer, c_w – water, c_{cp} – crop protection means, supporting cultivation. The function describing this dependence can only be estimated basing empirical studies, γ – the general mass fraction of biofuel in the crop, α_k – mass fraction of k-species of biofuel, $W_{bio,k}$ – low calorific value of k-species of biofuel.

The other term is the energy consumed on the field during agro-technical operations:

$$E_{ex,agr} = W_{fuel} A \times \sum_{i=1}^{m} \left[\frac{\omega_i}{d_i} \right] + \sum_{i=1}^{m} \sum_{k=1}^{K} \gamma_k \times Em_{ik} \quad (5)$$

where ω_i is the amount of fuel consumed per unit of the distance driven during the individual agro-technical operation, d_i is the width of the land strip machined in the course of *i-th* operation, (both characteristics d_i , and, ω_i may differ in subsequent operations), W_{fuel} is the low calorific value of the fuel used for agro-technical operations, *m* is the number of the agro-technical operations, γ_k is a fraction of energy embodied in the one of the *k*-technical means used in the *i-th* operation. It may be evaluated e.g. as a ratio of the time of given operation to the total expected life time of particular equipment. Em_k is the energy embodied in *k-th* of technical means.

Equation (6) gives used energy for transportation of goods outside of the fields. This energy is especially important for large plantations arranged in several fields frequently separated by quite long distances. It is given as:

$$E_{tr} = \sum_{p=1}^{p} L_p \times \left\{ \beta_p \times W_{fuel,tr} + Emt_p \right\} \quad (6)$$

where L_p is a distance driven outside of the field in *p-th* route, β_p is the fuel consumption during *p* route, $W_{fuel,tr}$ is low calorific value of the fuel used in transport, Emt_p is the corresponding to the unit of distance driven, fraction of energy embodied in the given item of transportation means.

Energies, E_{bio}, and $E_{ex,agr}$, are explicit functions of plantation area, *A*, while, E_{tr}, does not. Also embodied energies, Em_{ik}, and Em_{tr}, apparently do not depend on the area, *A*. Some contributions to those energies might, however, introduce such dependency (e.g. energy embodied in crop protection means or fertilizers, and the additional driving outside of the fields caused by organizational reasons). In consequence, the efficiency, ε, might depend upon the size of plantation in a complex manner. Numerical computations reported below give better feeling of relations between characteristics introduced in the model. It should be also mentioned that significant contribution of the energy consumed for transportation can be expected, especially in the cases when the distance between plantation and industrial processing facilities is sufficiently long.

E_{bio} is the amount of energy contained in the biofuel that is delivered at the end of the whole production system, but obtained from crops raised in corresponding agricultural subsystem. Such approach gives the value characterizing the agricultural subsystem's energy efficiency related to the final yield of energy. Defining the energy efficiency of the other components of production system in analogous way, it is possible to derive the expression for energy efficiency of the total system containing a series of several subsystems, e.g. agricultural and industrial ones, in the following form:

$$\frac{1}{\varepsilon_{tot}} = \sum_{i=1}^{l} \frac{1}{\varepsilon_i} \quad (7)$$

where ε_1, ε_2, ε_l are the values of efficiency determined for subsystems.

III. Numerical Computations

The aim of numerical computations was to establish dependencies of energetic efficiency upon realistic technical parameters occurring in agricultural operations. The formulas given above were incorporated to the program (macro) defined in the EXCEL spreadsheet. As indicated in [30], consideration of relatively large plantations required an additional component to be taken into account in the computations. This was the time needed to perform particular operation. Assumption of the maximum admissible daily working time as compared to the time needed for operation gave the number of days necessary to perform particular operation on a given field. The other assumption of organizational nature was that, after reaching the assumed maximum daily time, the equipment is moved back to the base. This requirement causes an increase of the distance driven outside of the field. Fig. 2. presents the scheme of assumed topological structure of the plantation.

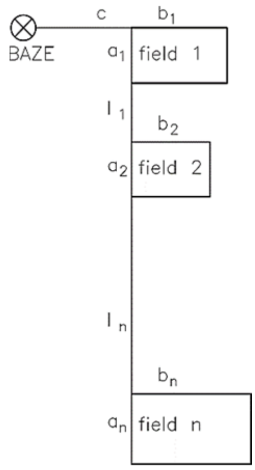

Fig. 2 Schematic view of assumed topological structure of plantation

According to derivation given in [30], the distances driven outside the field each day increase by a distance, a_i/J.

The first driven distance is *c* for driving to the field, and $c+a_1/J$ for driving back on the end of the first day. The distance driven next day to the field is $c+a_1/J$. After the second day, return to the base needs the distance equal to $c+2a_1/J$. Similar increase of distance driven outside of the field is observed during each subsequent day of work. Obviously during each subsequent day, the daily driven distance is increased by contribution of the corresponding distance, l_i, between subsequent first.

The resulting total distance driven outside of the fields can be given as:

$$D_{out} = 2c\sum_1^N J_n + 2\sum_1^{N-1}[(a_n + l_n)\sum_{n+1}^N J_n] + D_{max}\sum_1^N J_n^2 \frac{d_n}{b_n} \quad (8)$$

where d_n denotes the width of operation strip.

IV. Results and Discussion

Computations were performed assuming plantation structure as composed of five field of equal sizes with dimensions b = 0.5 km, and a – variable, separated by the distance, l = 0.2 km, and the distance from the base was taken as: c = 5 km. Several values of the width of operation strip, d, were assumed, namely equal to 0.5 m, 1 m, 1.5 m, 2 m, and 2.5 m.

The low calorific value of 36 MJ/dm^3 for fossil fuel, and 34.6 MJ/dm^3 for the case of biofuel were accepted. The agricultural machines moving at the speed 6 km/h were assumed to consume 0.3 dm^3/km. The other factor, taken into account, was 10h of the maximum time of work during one day. Such assumption limited the working distance driven daily on the field to 60 km. An example of computed distances driven on the field and outside of the field is given in Fig. 3.

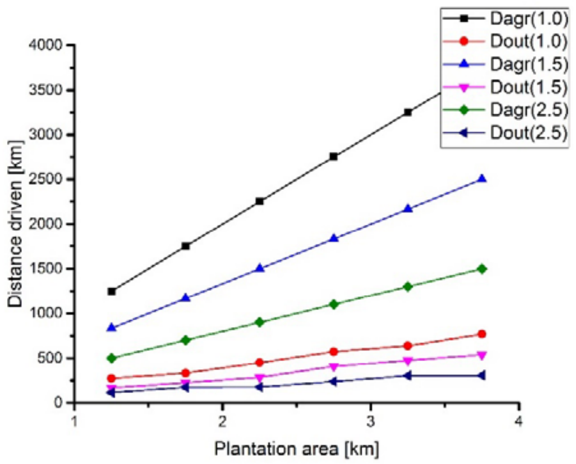

Fig. 3 Distances driven on and outside of the fields for three values of operation width, d = 1.0 m, d = 1.5 m and d = 2.5 m, as functions of total plantation area

It is seen that the distance driven on the field is substantially bigger than that driven outside. It is also clear that the wider is operational strip the shorter both distances are. Also, both are increasing functions of plantation area.

Tables I-III give the energy effectiveness, ε, dependening upon plantation area for various widths of the operation strip. The values of ε are given for several arbitrarily chosen values of specific energy yields obtained from the unit of plantation area (in GJ/ha). These values cover the range of specific energy yields that can be obtained from different s.c. "energetic plants (as an example, about 20 GJ/ha is typical for wheat plantation dedicated to bioethanol production, around 30 GJ/ha can be obtained in form of biodiesel produced from rapeseed plantation, while almost 80 GJ/ha is the amount of energy that can be derived in form of bioethanol from sugar beet plantation).

Table I gives the values for very narrow operation strip, whereas the next two are for gradually wider ones.

TABLE I
VALUES OF ENERGETIC EFFICIENCY, ε, FOR SEVERAL FIELD AREAS AND OPERATION WIDTH d = 0.5 M

A [km^2]	a [km]	Energy yield from plantation area [GJ/ha]						
		20	30	40	50	60	70	80
1.25	0.5	77.7	116.5	155.3	194.2	233	271.8	310.6
1.75	0.7	78.1	117.1	156.1	195.2	234.2	273.2	312.2
2.25	0.9	78.2	117.3	156.4	195.5	234.6	273.7	312.8
2.75	1.1	77.5	116.3	155	193.8	232.5	271.3	310
3.25	1.3	77.6	116.4	155.2	193.9	232.7	271.5	310.3
3.75	1.5	77.6	116.4	155.2	193.9	232.7	271.5	310.3

TABLE II
VALUES OF ENERGETIC EFFICIENCY, ε, FOR SEVERAL FIELD AREAS AND OPERATION WIDTH d = 1.5 M

A [km^2]	a [km]	Energy yield from plantation area [GJ/ha]						
		20	30	40	50	60	70	80
1.25	0.5	231,9	347,8	463,7	579,7	695,6	811,5	927,4
1.75	0.7	233,7	350,5	467,3	584,1	700,9	817,7	934,5
2.25	0.9	227,4	341	454,7	568,3	682	795,6	909,3
2.75	1.1	228,1	342,1	456,1	570,1	684,2	798,2	912,2
3.25	1.3	228,5	342,7	456,9	571,2	685,4	799,6	913,8
3.75	1.5	231,9	347,8	463,7	579,7	695,6	811,5	927,4

It can be seen from Tables I-III that energetic efficiency is not too much affected by plantation area, but strongly depends on the width of operation strip. This result clearly suggests important role of the choice of adequate equipment, i.e. the appropriate agricultural technology.

TABLE III
VALUES OF ENERGETIC EFFICIENCY, ε, FOR SEVERAL FIELD AREAS AND OPERATION WIDTH d = 2.5 M

A [km^2]	a [km]	Energy yield from plantation area GJ/ha						
		20	30	40	50	60	70	80
1.25	0.5	377,7	566,5	755,3	944,1	1133	1322	1510
1.75	0.7	371,5	557,2	742,9	928,6	1114	1300	1486
2.25	0.9	387,8	581,7	775,6	969,5	1163	1357	1551
2.75	1.1	380,9	571,4	761,8	952,3	1143	1333	1524
3.25	1.3	375,6	563,4	751,2	939	1127	1314	1502
3.75	1.5	384,9	577,3	769,7	962,2	1155	1347	1539

The presented values are overestimated since they have been computed as the whole production would be performed in the only one operation. This is never the case. Having, as usual, several operations, one has to compute resulting values using reciprocal additivity rule, expressed in (7). If all operations applied have the same energetic characteristics (the same energy consumption), (7) reduces to simple division of the value from Tables I-III by the number of operations. Other factors that are neglected in the present computation are: the possible differences in fuel consumption when different operation strips are used, the effects of energy embodied in production means, as well as possible differences in biomass yield due to differences in treatment. All those factors require further investigations.

The energetic efficiency of a complete production system should be expected to be reduced by contribution of industrial part where the conversion of biomass to biofuel also requires inputs of some energy. Also, energy needed for transport of biomass to industrial facility might require substantial energy consumption because possibly large distances, and large amounts of biomass that have to be transported, should contribute for further reduction of energy efficiency.

The correct choice of equipment is not only important from the viewpoint of a decrease of energetic efficiency, but also because such choice determines the time required to perform agricultural operations. Table IV gives an example illustrating variety of cases. In the cases of small operational width and large plantation, operation time becomes unrealistic. In practice, each operation can be characterized by some 'time window" or "operation window" which, in agriculture, from biological reasons cannot last too long, and has to be placed in a very specific time of the year. The figures placed in the table in bold face characters might be considered as being within, while those in italics are rather outside this "time window" and therefore unrealistic. As a kind of remedy, one might propose to use multiple machines to shorten operation time. This is true from the viewpoint of fuel consumption – it seems equivalent to use one machine during some time or two machines during half of the former time. The difference that intuitively leads to the reduction of energetic efficiency is a substantial increase of energy embodied in machines.

TABLE IV
NUMBER OF DAYS NEEDED TO PERFORM ONE AGRICULTURAL OPERATION, AS A FUNCTION OF PLANTATION SIZE, AND OPERATION WIDTH OF THE EQUIPMENT

A[km^2]	J (0.5)	J(1)	J(1.5)	J(2)	J(2.5)
1.25	*45*	*25*	**15**	**15**	**10**
1.75	*60*	*30*	**20**	**15**	**15**
2.25	*75*	*40*	*25*	**20**	**15**
2.75	*95*	*50*	*35*	*25*	**20**
3.25	*110*	*55*	*40*	*30*	*25*
3.75	*125*	*65*	*45*	*35*	*25*

V. CONCLUSIONS

Concluding, one should mention that performed computations, based on the developed model give an insight into dependence of energetic effectiveness of the use of biomass for biofuel production. With appropriate choice of equipment, one might achieve quite large values of energetic efficiency. The efficiency would increase with reduction of a number of operations, with an increase of performance of machines, and with minimization of their use. Energetic efficiency can also be affected by the choices of organizational nature, especially the distances driven outside of the fields can be reduced if for example machines would remain on the field instead driving to the base after the working day is finished. Achieving as high as possible energetic efficiency plays substantial role in creation of sustainable agriculture because it might assure at least energetic independence of agriculture without decreasing its potential in other production areas.

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