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ENERGY EFFICIENCY OF A BIOFUEL PRODUCTION SYSTEM

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Abstract

Manufacturing engineering is supposed to provide analyses related to various aspects of manufacturing and production in order to maximise technological, energy, and economic gains in relevant production processes. The present paper gives a recapitulation of several publications by present authors, presenting considerations of the energy efficiency of biofuel production. The energy efficiency is understood as the ratio of energy obtained from biofuels produced basing on crops from a particular area to the energy required to satisfy needs of all subsidiary processes assuring correct functioning of the production system, starting from operations aimed to obtain agricultural crops, and ending with the conversion of the crops onto biofuels.

Derived by the present authors, the mathematical model of energy efficiency of biofuel production is extended to a more general form, and applied to the analysis of quantitative relations between energy efficiency of sc. "energy plantations", and further elements of biofuel production system converting harvested biomass into biofuel. Investigations are aimed towards the determination of the role of biomass as a source of energy.

Keywords
energy efficiency, EROEI, biofuels, production systems.

Introduction

Contemporary world's economies encounter several problems associated with the harvesting of energy. Since carbon-containing fossil fuels are the major energy sources so far, the emission of carbon dioxide is considered as one of the most important factors affecting global warming. The other problem is the prediction of the exhaust of petroleum resources in a not very distant future. Consequently, the search for replacement must be considered. Biofuels derived from biomass are frequently considered [1] as actually the most important way to combat both i.e. global warming as well as future shortages of petroleum and other fossil fuels. This idea induces the search for biomass resources effectively convertible into biofuels, and for efficient technologies of biomass cultivation, and for conversion of biomass to fuel. Liquid biofuels especially are considered a good alternative for petroleum-derived ones. The materials of the biological origin, like vegetable oil, can be processed into biodiesel, while sugars, etc. provide bioethanol or biomethanol that can replace gasoline for Otto type engines. Several papers have been published dealing with cultivation methods of some plants e.g. [2, 3], and for processing of them to biofuels [4–6]. In addition, the question is whether such fuels may be produced with sufficient efficiency with respect to energy consumption occurring during production processes. It equally concerns agricultural as well as industrial operations in need of biofuels. Obviously, 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. The characteristic that provides a quantitative measure of that kind of efficiency was already established. This measure, called EROI or EROEI, which is the "energy return on energy invested" cf. e.g. [7, 8], is defined as follows:

$$\varepsilon = \frac{\sum\limits_{p=1}^{p} (E_{\text{out}})_p}{E_{\text{cr}} + \sum\limits_{p=1}^{p} (E_{\text{in}})_p + E_{\text{rem}}}, \tag{1}$$

where E_{out} is the total usable energy delivered by energy gathering system during the p-th year of its existence, E_{in} represents the total energy expended during that year, E_{cr} is the energy needed for the creation of that system, and E_{rem} is the energy needed for remediation of that system after the end of its life at the p-th year.

It should be pointed out that EROEI is different than the thermodynamic efficiency of the energy conversion that is expressed as:

$$\eta = \frac{E_{\text{out}}}{E_{\text{in}}} = \frac{E_{\text{out}}}{E_{\text{out}} + E_w}, \tag{2}$$

where E_{in} and E_{out} represent input and output energy to and from the converter, while E_w corresponds to the energy wasted (dissipated) by that converter.

The Eq. (1) describes the situation when the energy E_{in}, introduced to the production system is not directly converted into output. It is the energy consumed to maintain the production process. In some cases, E_{in} might be very small, while in the other cases – very large as compared to E_{out}; consequently, the range of the variation of this measure might extend in the limits $-\infty \leq h \leq \infty$. The Eq. (2) relates energies being directly converted one into the other, and it can be easily proved that changes of this characteristic occur only in the limits: $0 \leq \eta \leq 1$.

Perspectives of biofuel production in several countries, as well as various conversion technologies, have also been discussed in several publications [8–15] including the review [12] concerning various approaches to production and the use of biofuels. Some works refer to the energy efficiency of biofuel production, e.g. the analysis given in [16] shows that exergyoss that occurs in the process of biodiesel production is rather low, yet chances of the further decrease can be available due to improvements in technology. In contrast, bioethanol production [17] seems not to fulfil requirements of sustainability, i.e. the energy yield in bioethanol production is insufficient.

The paper [16] discusses the effect of the scale of a techno-system emphasising that at various scale levels, different processes determine the efficiency. Empirical investigations of the energy efficiency of agriculture in general [16–19], as well as that of individual plantations especially dedicated to "energy" crops [20–26], are also available. Those works might be considered as the sources of important sets of data enabling the analysis of the factors that decide on the energy efficiency of biofuel production systems. A slightly different approach to the scale of a techno-system is given in the paper [27] discussing the feasibility analysis with respect to the size of the production system. Despite the rather abundant literature, few papers discuss the energy effectiveness of biofuel production systems, in relation to production conditions and technologies. To contribute to the filling of this gap, the Authors proposed a model directly involving technological parameters into the evaluation of effectivity characteristic [28–31].

The present paper is a summary of several earlier publications and is aimed at the presentation of the model describing the effects of subsidiary processes that occur at individual steps of a biofuel production system on the energy efficiency of that system. The paper also presents results of numerical computations giving the estimation of the main effects related to the real production conditions. The paper directly concerns the agricultural part of the production subsystem and indirectly considers the influences of the industrial subsystem.

Method

The scientific problem discussed in this as well as in previous papers [29–31] is to investigate the relationships between various technological conditions and energy effectiveness of biofuel production systems.

The main tool chosen for finding solutions is mathematical and numerical modelling. The aim of the modelling is to describe the behaviour of the investigated system, as well as to predict its properties. Computations are made in a wide range of variables involved, frequently wider than actually accessible for real measurements. The formulation should permit the limitation of the desired accuracy of description to the most pronounced effects at first, and later enable the extension of the treatment by adding (not necessarily in the arithmetic sense of addition) other more subtle effects.

The approach to the design of the mathematical model of the production system is based on several assumptions. The first step is the analysis of details of physical and technical phenomena that are responsible for particular production processes. Recognising and understanding such fundamental relations is necessary to make the next step, namely, to form mathematical relationships. In the next step, some attempts are made to analytically resolve at least parts of the problem. Finally, the numerical model is constructed using relationships created in the previous stage. Various attempts can be made as further steps.

A realistic set of data can be used for the validation of the model or to demonstrate the behaviour of a "virtual" case study. For each particular independent variable, a set of subsequent values can be assigned in order to show the functional dependence.

Model of the energy effectiveness

According to the assumptions made, the structure of the biofuel production system is built of two subsystems connected by flows of materials and energy, as well as interacting with the surroundings. It can be represented by a scheme shown in Fig. 1. The involved subsystems are agricultural and industrial, connected by internal transport. Arrows (1), (2), (3), and (4) represent energy flows arriving from the outside of the system, i.e. solar as well as fluxes of energy derived from fossil fuels. The arrow (5) shows the flux of energy obtained from own production biofuel, and being returned to the system. The arrow (6), in turn, represents the main flux of biomaterial produced in the agricultural subsystem and transported to the industrial one. Material fluxes (7) and (3) are the fluxes of by-products and wastes that are rejected outside of the system, and not converted into energy. The flux (9) is the material returned to the agricultural fields to be used there. All those processes require the input of energy, and, therefore, contribute to the decrease in the energy efficiency of the system.

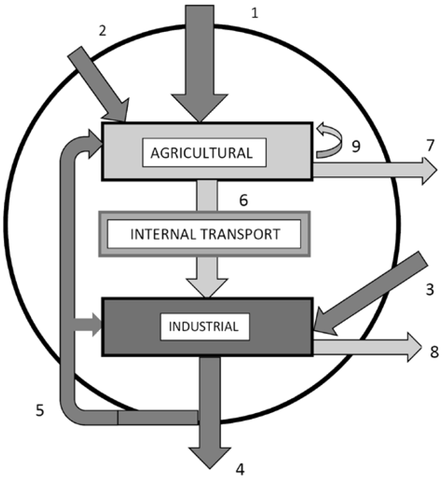

Fig. 1. Assumed structure of biofuel production system.

The figure does not show the transportation processes inside the agricultural or industrial subsystems; nevertheless, they have to be considered. Computations of the energy consumed for transportation outside of the field as compared to the energy consumed in agricultural operations are performed in the present work.

Considering critical remarks [19, 20] made towards the determination of EROEI index used in the literature, the new model of the energy efficiency of the biofuel production system was introduced in [28]. The model expresses the energy effectiveness ε related to one year of production in any of subsystems:

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

where E_{bio} is the final energy obtained from the system as a whole, E_{ex} is the energy expended for operations in a particular subsystem, E_{tr} is the energy consumed for transportation outside of a subsystem considered, E_{emb} is a fraction of embodied energy contained in production means, that is spent during technological operations and transport executed during the production year in the particular subsystem.

Such approach gives the possibility to estimate the energy efficiency, ε_{tot}, of the whole system built of several subsystems, connected in series, e.g. agricultural and industrial subsystems, using a simple and easy to derive formula:

$$\frac{1}{\varepsilon_{\text{tot}}} = \sum_{i=1}^{I} \frac{1}{\varepsilon_i}, \tag{4}$$

where ε_1, ε_2, ε_I are the values of efficiency determined for subsystems (related to the final energy yield from the system as a whole).

For the case of the agricultural subsystem, the contributing energies are further expressed as follow.

The energy obtained from the plantation equals to:

$$\begin{gathered} E_{\text{bio}} = A \times M_{\text{crop}}(c_f, c_w, c_{cp}, \ldots) \\ \times \gamma \times \sum_{k=1}^{n} \alpha_k \times W_{\text{bio},k}, \end{gathered} \tag{5}$$

where A is plantation area, M_{crop} (c_f, c_w, c_{cp}) is crop yield dependent upon concentrations: c_f – fertiliser, c_w – water, and c_{cp} – crop protection means, maintained during cultivation. This dependence should be estimated based on the empirical field studies. γ – the general mass fraction of biofuel in the crop, α_k – the mass fraction of k-species of biofuel, $W_{\text{bio},k}$ – low calorific value of the k-species of biofuel.

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

$$E_{\text{ex, agr}} = W_{\text{fuel}} A \times \sum_{i=1}^{m} \left[\frac{\omega_i}{d_i}\right] + \sum_{i=1}^{m} \sum_{k=1}^{K} \gamma_k \times Em_{ik}, \tag{6}$$

where ω_i – the fuel consumption per unit of the distance passed during an individual agro-technical process, d_i — the width of the land strip operated in the single course of the i-th operation, W_{fuel} — the low calorific value of the fuel used for operations (fossil fuel or biofuel), m – the number of the agro-technical operations (in each of the operations, the width of the worked field strip, d_i, and the consumption of fuel, ω_i, can be different), γ_k is a fraction of embodied energy contained in one of the k-technical means employed at the i-th operation (machines, fertilisers, etc.). E.g., it may be estimated as the ratio of the time of a particular operation to the total expected lifetime of particular equipment. Em_k is embodied energy contained in the k-th technical mean.

The last term concerns the transportation of goods (including crops) outside of the field. This term is especially important for big plantations that must be arranged into several fields, sometimes separated by rather long distances. It is expressed as:

$$E_{\text{tr}} = \sum_{p=1}^{p} L_p \times \{\beta_p \times W_{\text{fuel, tr}} + Emt_p\}, \qquad (7)$$

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

As seen from the above formulas, individual contributions to the energy efficiency depend on various factors. E_{bio}, and $E_{\text{ex, agr}}$ depend on the plantation area A, while E_{tr} does not. Also, the embodied energy terms Em_{ik} and Em_{tr} do not depend on A, in spite that some contribution to it (e.g. energy embodied in crop protection means or fertilisers) might depend upon the plantation area. It means that the efficiency, ε, depends on the size of a plantation in a complicated manner, affected by various relationships. Numerical computations were performed to get a deeper insight into relations described in the model. The contribution of transport is also significant when crops must be transported a long distance to industrial facilities for processing.

Numerical computations

Numerical computations using equations given above were aimed towards establishing dependencies of energy efficiency on technical parameters of agricultural operations. Computations were performed in EXCEL (Microsoft) using an especially designed macro. Some calculations and graphs were made in ORIGIN (Microcalc).

Results presented here are the extension of the results given in [28, 29]. Since the consideration of relatively large plantations was assumed, the computations additionally included the calculation of time needed for any operation, and under the assumption of maximum daily working time, the number of days needed to perform an operation on a particular field was evaluated. Moreover, it was assumed, that after reaching this maximum time, the equipment was transferred back to the base. This obviously increased the distance driven back and forth outside of the field, and introduced the dependence of the distances driven outside of the field as well as energy consumed on this distance, on the field's area. The schematic view of the assumed plantation's topological structure is given in Fig. 2.

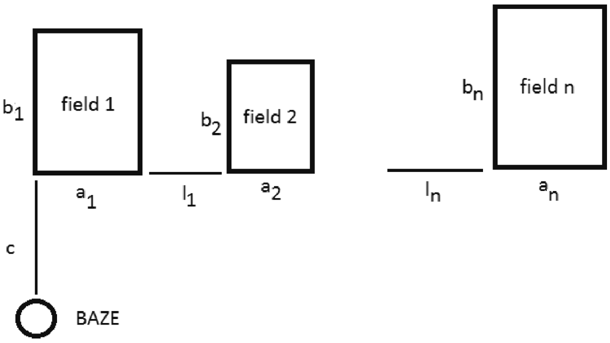

Fig. 2. Schematic view of the assumed topological structure of a plantation.

The analysis of the situation shows that after starting, the work equipment is moved from the base driving the distance, c, and drives back and forth on the field till the maximum working time is reached. At this moment, it returns to the field border closest to the base, and being on the distance from the base equal to the sum $c + a_1/J$. The fraction of the distance, a_1, is determined by the number of days, J, needed for the elaboration of the whole field. The distance, which must be driven next day before the operation on the field can be started, is $c + a_1/J$. The return to the base after the second day's work requires the distance $c + 2a_1/J$. Similarly, each next day of work is associated with an analogous increase of distances driven outside of the field. On some subsequent day, this daily driven distance is increased by the contribution of the distance, l_1, between the first and second fields, etc. Finally, the sum of all contributions for the fields can be expressed as:

$$\begin{aligned} D_{\text{out}} = 2c\sum_{1}^{N} J_n + 2\sum_{1}^{N-1}\left[(a_n + l_n)\sum_{n+1}^{N} J_n\right] \\ + D_{\max}\sum_{1}^{N} J_n^2 \frac{d_n}{b_n}, \end{aligned} \qquad (8)$$

where d_n, denotes the width of the operation strip on the field, n, and, N, denotes the total number of fields.

Computations were performed assuming the plantation structure composed of five fields of equal sizes with dimensions $b = 0.5$ km, and a – the variable separated by the distance, $l = 0.2$ km, and the distance from the base equal to $c = 5$ km. Values of the width of the operation strip, ω, were assumed, namely, equal to 0.5 m, 1 m, 1.5 m, 2 m, and 2.5 m. The low calorific value of the fuel used for running machines was taken as 36 MJ/dm^3, and for biofuel 34.6 MJ/dm^3. The fuel consumption by agricultural machines was assumed as 0.3 dm^3/km.The machine speed was estimated as 6 km/h, since the maximum daily allowable working time was assumed as 10 h, the resulting daily working distance driven on the field was equal to 60 km.

The results show that for all cases, the distance driven on the field was substantially greater than that driven outside. It is also clear that a machine with a wider operational strip assured both shorter distances. Also, both distances increased with an increase in the plantation area.

An example of computed distances driven on the field and outside of the field is given in Fig. 3. It is seen that the distance driven on the field is substantially greater than that driven outside the field. It is also clear that the wider is the operational strip, the shorter are both distances, as well as the difference between the distance driven on the field, and the distance driven outside of the field becomes shorter when the width of the operation becomes wider. Also, both are increasing functions of the plantation area.

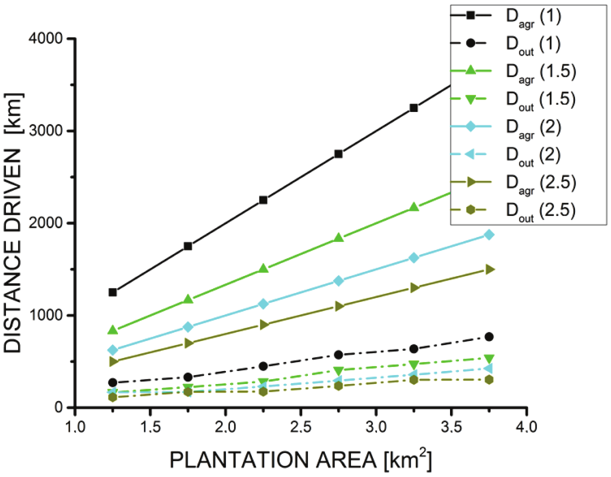

Fig. 3. Distances driven on and outside of the fields for four values of operation width, $d = 1.0$ m and $d = 1.5$ m, $d = 2.0$ m, $d = 2.5$ m as functions of the total plantation area.

Tables given below show the dependence of the energy effectiveness, ε, as a function of the plantation area and the width of the operation strip. The values of ε are computed for several values of the energy yield from the unit of the plantation area (in GJ/ha). The considered values correspond to the approximate energy yields obtainable for various "energetic" plants (about 30 GJ/ha can be obtained from a rapeseed plantation, a little bit smaller value one obtains from a wheat plantation for bioethanol production, while about 80 GJ/ha may be achieved in bioethanol produced from sugar beet). Values of energy efficiency presented in tables below are computed for *five agricultural operations* performed on the fields under the assumption of equal energy consumption for each operation. Subsequent tables show values of energy efficiency for different operational width, d, of the machines used.

Table 1
Values of the energy efficiency, ε, for several field areas and the 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	15.5	23.3	31.1	38.8	46.6	54.4	62.1
1.75	0.7	15.6	23.4	31.2	39.0	46.8	54.6	62.4
2.25	0.9	15.6	23.5	31.3	39.1	46.9	54.7	62.6
2.75	1.1	15.0	23.3	31.0	38.8	46.5	54.3	62.0
3.25	1.3	15.5	23.3	31.0	38.8	46.5	54.3	62.1
3.75	1.5	15.5	23.3	31.0	38.8	46.5	54.3	62.1

Table 2
Values of the energy efficiency, ε, for several field areas and the operation width $d = 1.0$ m.

A [km^2]	a [km]	Energy yield from plantation area [GJ/ha]						
		20	30	40	50	60	70	80
1.25	0.5	30.4	45.6	60.8	76.1	91.3	106.5	121.7
1.75	0.7	31.2	46.7	62.3	77.9	93.5	109.0	124.6
2.25	0.9	30.9	46.3	61.8	77.2	92.6	108.0	123.5
2.75	1.1	30.7	46.0	61.3	76.6	92.0	107.3	122.6
3.25	1.3	31.0	46.5	61.9	77.4	92.9	108.4	123.9
3.75	1.5	30.7	46.1	61.5	76.9	92.2	107.6	122.9

Table 3
Values of the energy efficiency, ε, for several field areas and the operation width $d = 2.0$ m.

A [km^2]	a [km]	Energy yield from plantation area [GJ/ha]						
		20	30	40	50	60	70	80
1.25	0.5	58.4	87.6	116.8	146	175.2	204.4	233.6
1.75	0.7	62.0	93.1	124.1	155.1	186.1	217.1	248.2
2.25	0.9	61.5	92.2	123	153.7	184.5	215.2	246.0
2.75	1.1	61.1	91.6	122.1	152.7	183.2	213.7	244.3
3.25	1.3	60.7	91.1	121.4	151.7	182.1	212.4	242.8
3.75	1.5	60.4	90.6	120.7	150.9	181.1	211.3	241.5

It can be easily recognised that the values presented in the Tables, rather slightly depend on the plantation area but are strongly dependent upon the width of an operation strip. Consequently, the appropriate choice of equipment has a substantial role in creating energy efficiency of a plantation. Obviously, they also strongly depend on the energy yield from an area unit of the plantation, i.e. the kind of plants being cultivated. Each kind of plant requires, however, different procedures for converting it into biofuel. The factors neglected in the present analysis are the energy embodied in production means (machines, tools, crop protection substances, fertilisers, etc.). It seems that this contribution is not very high but needs further studies.

Values of the energy efficiency presented in the Tables above vary between 15 and 250 depending on the type of plants cultivated, the distance between the fields, and the size of the plantation (the later contributions are rather small). The further reduction of the energetic efficiency should be expected to occur in the industrial part of the production system where the conversion of biomass to biofuel occurs, and due to the energy needed for the transportation of biomass to an industrial facility, which may be rather energy consuming because of possibly large distances and large amounts of biomass that undergoes transportation. As indicated in [26], estimations based on the lifecycle analysis show that the biodiesel production from palm oil requires two to three times more energy than the cultivation of plants and oil extraction, while in the case of bioethanol, which is produced from cassava fruits, the amount of energy needed for conversion is four times greater than the energy demand for the agricultural processes. This means that the energy efficiency would be reduced by 20% to 50% in industrial conversion operations. The energy demand is obviously dependent on specific plants and specific climatic conditions, so those proportions may vary depending on the localisation of a plantation, and is also dependent on the technology of conversion. Consequently, one can expect the efficiency of biofuel production system being between 5 and about 100, depending mainly on the type of plant cultivated, the amount of energy spend during agricultural operations and the energy consumption during the industrial conversion into biofuel. The appropriate choice of agricultural, industrial, and technologic optimisation of logistics inside as well as outside of the plantation is, therefore, important for achieving high energy efficiency.

The problem of the appropriate choice of equipment is not only associated with a decrease in the energy efficiency, but also with the time required to perform agricultural operations. Table 4 gives an example illustrating a variety of cases.

Table 4
Number of days (*) needed to perform one agricultural operation, as a function of the plantation size and the operation width, d, of the equipment.

A [km^2]	Number of days for one operation				
	$d=0.5$ m	$d=1.0$ m	$d=1.5$ m	$d=2.0$ m	$d=2.5$ m
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

(*) unrealistic values are shadowed.

It can be recognised that at several choices of the operation width, d, an individual agricultural operation takes too long. Each operation in the production systems requires some "time window", which in agriculture is determined mainly by climatic and biological requirements. Operations that last too long are simply not acceptable. In such cases, more efficient machinery is needed.

Effect of the internal transport

Biomass produced in an agricultural subsystem has to be converted into biofuel at an appropriate industrial facility. The present paper considers the industrial conversion rather than individual, and small-scale production of biodiesel for in-house use. Consequently, the biomass should be transported from the plantation to the industrial facility.

For example, the transportation concerns rapeseed grain separated from the straw, while utilisation and distribution of scraps resulting from the processing (straw), is not taken into account in the energy balance.

The analysis is made under consideration of several transportation means and various plantation sizes, which gives various crop sizes. The characteristics of transportation means are given in Table 5.

Table 5
Characteristics of transportation trucks.

Truck size	Load capacity		Fuel consumption	Ratio load capacity to fuel consumption	
	mass	volume		mass	volume
	Mg	m^3	l/km	Mg/l/km	m^3/l/km
3t	3	28	0.12	26	234
8t	8	45	0.24	34	188
24t	24	80	0.72	34	112

The data presented in Table 5 are taken from various catalogues, internet sites, etc. The fuel consumption is assumed based on the average taken from various sources.

The transportation of rapeseed grains between the plantation and the industrial facility for small plantations obviously shows incomplete filling of trucks. The amounts of courses (or trucks) for large plantations is shown in Table 6. It can be seen that a large number of trucks (or, correspondingly, a large number of courses at a smaller number of trucks) is needed for the transportation of rapeseed grain between the large plantation and the industrial facility.

Table 6
Number of trucks for the transportation of grain from large fields.

Field's area [ha]	Grain		Number of trucks		
	mass [Mg]	volume [m^3]	3 ton truck's	8 ton truck's	24 ton truck
100	300	458	16.4	10.2	5.8
200	600	916	32.8	20.4	11.5
300	900	1374	49.1	30.6	17.2
400	1200	1832	65.5	40.8	23
500	1500	2290	81.8	50.9	28.7
600	1800	2748	98.2	61.1	34.4
700	2100	3206	114.6	71.3	40.1
800	2400	3664	130.9	81.5	45.9
900	2700	4122	147.3	91.7	51.6
1000	3000	4580	163.6	101.8	57.3

Obviously, the bigger trucks are used, the smaller number of trucks or courses is needed.

The plot, which is not shown here, also indicates a linear dependence of the number of trucks upon a field size.

Figure 4 shows the comparison between the energy, E_{bio}, that is obtained from the field, and the energy consumed.

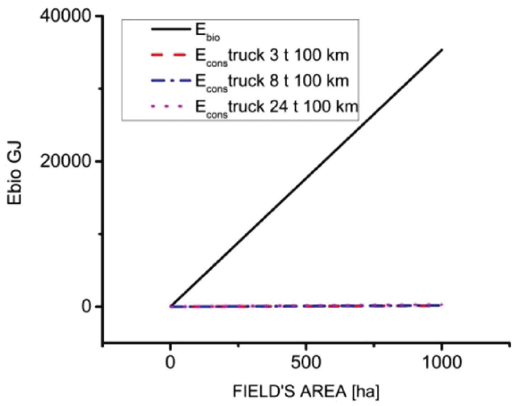

Fig. 4. Energy produced vs. the energy consumed by trucks on the distance of 100 km.

Since the plots for different trucks are not distinguishable on this plot, the consumed energy by different trucks is also presented in Fig. 5. It is visible that less energy is consumed as compared to the amount of energy produced.

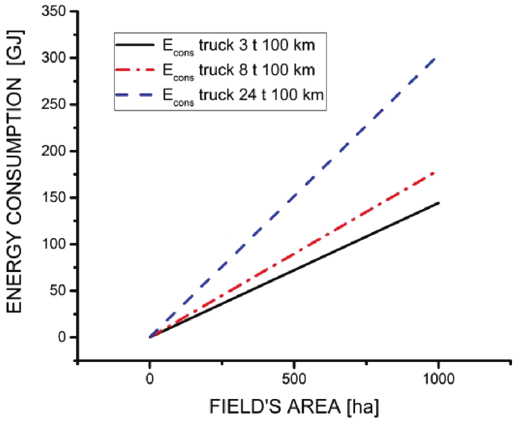

Fig. 5. Energy consumed for transportation on the distance of 100 km.

Basing on the data contained in Fig. 5, the energy efficiency of the internal transport between the fields in the plantation was computed [32]. As an example, values of ε_i for selected trucks, and the driving distance of 100 km are given in the third row of Table 7.

Table 7
Resulting energy efficiency of an agricultural subsystem coupled with the internal transportation system, both of various individual contributions.

$\varepsilon_{\mathrm{agr}}$		Internal distance of 100 km		
		3 ton truck's	8 ton truck's	24 ton truck's
	$\varepsilon_i =$	245	197	116
10	$\varepsilon =$	97	96	93
50	$\varepsilon =$	416	399	35
100	$\varepsilon =$	711	664	538
200	$\varepsilon =$	1102	993	735

Finally, to estimate the influence of the internal transport on the total energy efficiency of the production system, the resulting efficiency was calculated with the use of Eq. (4). As an example, the values of energy efficiency of the agricultural plantation being between 10 and 200 depending on particular conditions of the production technology, were taken from Tables 1 to 3. The final results are given in Table 7. Despite the energy consumption by transport between the agricultural subsystem and the industrial facility being relatively small as compared to the energy consumption in tillage operations or the final energy yield, it, however, gives a rather pronounced reduction in the global energy efficiency of the production system. The reduction is especially evident when contributing values are very different.

It seems, therefore, important that all types of operations should be carefully selected considering the lowest possible energy consumption.

The general question might be posed, i.e. how efficient can the biofuel production be? As seen in Tables 1–3, there is no universal answer to such question. The energy efficiency of a plantation depends strongly upon the type of plants being cultivated. Considering that values presented in Tables 1–3 are computed for five tillage operations, it can be expected that a reduction in the number of operations or a reduction in the energy consumption in, at least, some of the operations may increase the energy efficiency of the plantation by a factor of 2 or maybe 3. Also, the choice of a plant of the highest energy yield will give a higher global efficiency. However, it has to be considered that not all fuels can be derived from any plant, and also that a conversion of biomass into biofuel will also consume energy, and, consequently, contribute to a further decrease in the energy efficiency of the production system as a whole. It also indicates the need for a further development of industrial conversion technologies. The problem of the energy efficiency of the industrial subsystem will be the subject of further studies. It can be roughly estimated that a contribution of the industrial subsystem might also cause a reduction in the efficiency by a factor of 2 or more.

Conclusions

The calculations conducted using the data corresponding to realistic situations in the production systems indicate:

The energy efficiency of an agricultural subsystem depends upon:

a) the technical parameters of applied machines,
b) the distance travelled on the field during agricultural operations, which is mostly contributing to the energy consumption,
c) the number of operations (and, consequently, the production technology),
d) the distances travelled between fields (which depends on the degree of dispersion of the plantation and upon the sizes of individual fields as very big fields force an increase in the movement of machinery outside the field; it, however, appears to give a smaller contribution to the energy consumption than the distances driven on the fields, and also not very strong influence on the final energy efficiency,
e) the distance between the plantation and the processing installation – the transportation of biomass. This transport, showing not as big absolute values of energy consumption, substantially affects the total energy effectiveness of the production system. The energy consumption depends on the characteristics of transportation means, mainly the ratio of the volume capacity to fuel consumption per unit of the distance.

The scale of the industrial production subsystem extorts the suitable scale (size) of the plantation and affects the consumption of fuels (energy) during the agro-technical operations and transportation.

The estimated values of energy efficiency are mostly dependent upon the energy yield from a particular plant being cultivated. The most pronounced technical factor is the efficiency of agricultural machines since the distance driven on the field is the most contributing to the energy consumption.

Production organisation might also influence the energy efficiency, especially by a correct choice of logistic solutions applicable inside and outside the plantation.

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