energetic efficiency, biofuel production, energetic plantations, EROEI

Andrzej WASIAK, Olga ORYNYCZ***

EFFECTS OF FIELD'S TOPOLOGY ON ENERGETIC EFFICIENCY OF RAPESEED PLANTATION FOR BIOFUEL PRODUCTION

Abstract

The model, developed earlier, have been designed to the studies of energy gain in the biofuels production, as compared to the sum of energy inputs on various production steps, and in processes enabling biomass conversion to energy. The present paper shows application of that model towards estimation of the contribution of energy used for commuting between agricultural production sites for a chosen example of plantation's topological characteristics. Algorithm for computations is elaborated, and numerical example is shown. The sizes of the fields as well as distances between them determine the amount of energy spend for the agricultural work in addition to the tillage technologies being applied.

1. INTRODUCTION

Problems connected with the use of various types of biomass as the source of energy are widely discussed in literature [1–6]. Among others, the energy balance consisting of energy inputs to the biofuel production as compared to the energy gain was also considered [7–9]. Some of the papers have taken into account also transportation terms [9, 10] as well as embedded energy content in agricultural machines and transportation means. Tis matter was also discussed in earlier papers written by present Authors [11–13], but in the actual analysis it was temporarily neglected. In earlier papers, mentioned above, present Authors have published a theoretical model of energetic efficiency of agricultural plantation designed for production of biomass for biofuels. The model includes the most important contributions to energy efficiency, and permits calculations for any

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[*] Bialystok University of Technology, 15-351 Białystok, Wiejska Str. 45A, tel. 85-746-9842, e-mail: a.wasiak@pb.edu.pl

[**] Bialystok University of Technology, 15-351 Białystok, Wiejska Str. 45A, tel. 85-746-9844, e-mail: o.orynycz@pb.edu.pl

practical situation, as well as analysis of some dependencies. Although transporttation terms corresponding to commuting between fields, and between fields and external sites e.g. industrial ones, have been incorporated in the above model – general conclusions are possible only in limited scope, and conclusion was made that particular solutions have to be established for clearly specified field topologies. This task, based upon computer simulation, is a subject of the present work.

The aim of the present work is to estimate effects of energy inputs into subsidiary processes enabling production e.g. agricultural operations, transportation of machinery, and goods between fields as well as from the fields to the external industrial sites, on the energy efficiency of plantation (practically defined in analogous manner as EROEI).

2. THE METHOD

An algorithm for numerical computations have been elaborated and implementted as well as computations were performed under specific assumptions with respect to plantation's topology. The program is quite general and "elastic" enabling computations for different topologies. Fig. 1 presents a flow chart of the program involving one agrotechnical operation subsequently for all fields considered. (index *n* numbers the fields, while index *k* numbers the subsequent days (when it is relevant – it is assumed that working time cannot exceed t_{max}. When t_{max} is reached work is terminated for the particular day, and machines drive to the base, and return next day, the corresponding route is added to the distance D_{out}). In the present computations we have adopted 5 identical fields, and operations performed in identical configurations of the machines, maximum working time is specified as t_{max}=10h. Consequently, the values of the total distances driven, as well as energy spend for all operations, both depend upon a number of operations. The results presented in the tables 1–11, and figures 1–4 concern only one agrotechnical operation, therefore:

$$\eta_1 = \frac{E_{bio}}{\left(E_{out}+E_{agr}\right)_1} \tag{1}$$

where: η_1 – is efficiency for one operation,

E_{bio} – is energy obtained in form of biofuel,

E_{agr} – is energy used for agricultural operation 1,

E_{out} – is energy spend for driving outside the fields associated with operation this particular operation.

Since it is assumed that all operations are performed in identical manner, the global energy efficiency for all I operations can be obtained as follows:

$$\eta_{tot} = \frac{E_{bio}}{\sum_{i=1}^{I}\left(E_{out}+E_{agr}\right)_i} \tag{2}$$

Therefore the efficiency for all I operations equals:

$$\eta_{tot}=\eta_i/I \tag{3}$$

In general, algorithm permits computations to be performed for linear structure of the production system with the topology of the fields shown on Fig. 2. The algorithm can be easily modified to be used for other structures e.g. star-like, etc. It represents a number of fields separated by some distances from each other, and separated from the main base. Dimensions of the fields, as well as distances between them are being introduced as primary data. Also the width of strip of land being elaborated during single ride, and velocity of the machine, is given for each of the agricultural operations.

As it was mentioned earlier the daily allowed distance, is computed as the product of allowed working time, t_{max}, and velocity of the machine. The t_{max} was assumed 10 hours, and velocity 6 km/h.

Energies consumed are computed basing on the distance driven and fuel consumption. Energy obtained from the field is estimated on the basis of crop yield from the unit area of field and fuel yield from the unit of mass of the crop.

At this stage of calculations the fuel yield is taken as an industrial average without distinguishing processing technology. Two values of the biofuel yield obtained from rapeseed grain related to the unit area of plantation (ha = hm^2) were accepted: a very small one that equals to 380 l/ hm^2, and much higher amounting to 1500 hm^2, which correspond to very efficient plantation. Values of energy required for agricultural operation, E_{agr}, as well as values of energy needed for transportation between fields, E_{out}, were computed using the values of average fuel consumption equal C=0,3 dm^3/km, and low caloric value of the fuel equal W_{fuel}=36MJ/dm^3.

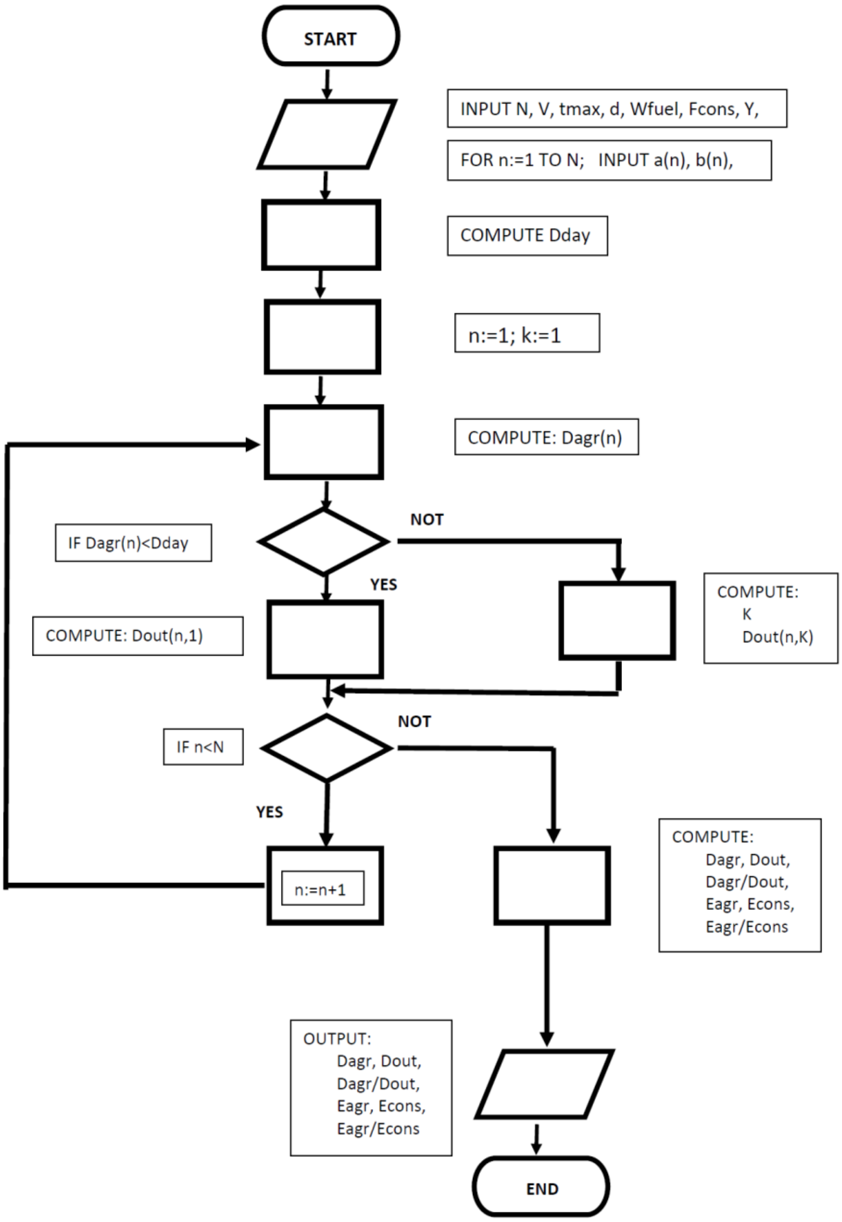

Fig. 1. Flow chart of computation algorithm for one operation [source: own study]

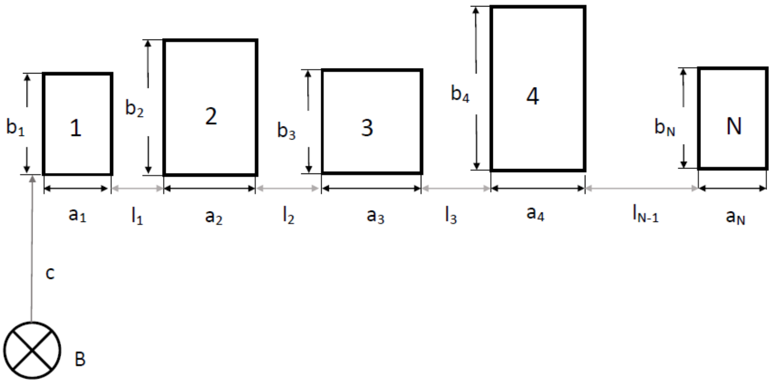

Fig 2. Field's topology (symbols denoting distances are indicated) [source: own study]

Computations were performed for the example consisting rapeseed plantation built of five fields of equal area, separated by equal distances. Several cases of plantation sizes and distances were considered. The initial data for computations are presented in Table 1.

Tab. 1. Values of parameters taken into computations [source: own study]

v= 6 km/h t_{max}=10 h						
$1 \le i \le n$ $a_i = b_i$						
n=5	a_i= 0,1 km			a_i = 0,5 km		
n=5	b_i= 0,1 km			b_i = 0,5 km		
c [km]=	1	5	10	1	5	10
l [km] =	0,2	0,2	0,2	0,2	0,2	0,2
l [km] =	0,4	0,4	0,4	0,4	0,4	0,4
l [km] =	0,6	0,6	0,6	0,6	0,6	0,6
l [km] =	1	1	1	1	1	1

3. RESULTS FOR RAPESEED PLANTATION

Results of computations indicate that obviously the distance driven on the fields depends upon the area of the field and the width of operation strip. The total distance, D_{agr}, driven on the fields for the case of field's area A=0,01 km^2, and strip width 4m equals to 12,5 km, while for the strip width 0,5m equals to 100 km. Similar calculation for the individual field size equal to 0,25 km^2 gives the total distance, D_{agr} , equal to 312,5 km for the strip width 4 m, and 2500 km for the strip width 0,5 m. It is clearly seen that the choice of working equipment seriously affects the driven distance.

Table 2. presents results of computations of distance outside of the fields D_{out} for the system of 5 identical fields, each of surface area, A, separated from themselves by a distance, *l*, and separated by the distance, *c*, from the base to the first field, and for working width equal to *d* = 4m. Two plantations are compared with sizes of individual fields each equal to 0,01 km^2 (1 hectare), and 0,25 km^2 (25 hectares).

The distances outside of the field obviously increase when the distances separating fields increase. It is also visible that those distances depend upon the size of the field. This dependence results of the need to return to the base after the allowed working time is reached, and next day drive again to the point where work stopped day before.

Tab. 2. Values D_{out} (in km) for the case when working width is *d* = 4m [source: own study]

A_i[km^2]=	**0,01**			**0,25**		
***c* =** / ***l* [km]**	**1**	**5**	**10**	**1**	**5**	**10**
0,2	2,6	6,6	11,6	17,7	43,3	75,3
0,4	3,2	7,2	12,2	20,0	45,6	77,6
0,6	3,8	7,8	12,8	22,4	47,9	79,9
1	5	9	14	27	52,6	84,6

Fig 1. shows the ratio of distances driven inside and outside of the plantation composed of 0,01 km^2 (1 hectare) fields for the case when operation width was assumed 4 m as function of the distances between fields and upon the distance between the base and the first field. The ratio $\underline{D_{out}/D_{agr}}$ assumes values between about 0.2 and 1.12, being affected by both distance between fields and the distance from the base. The later seems to show more pronounced effect.

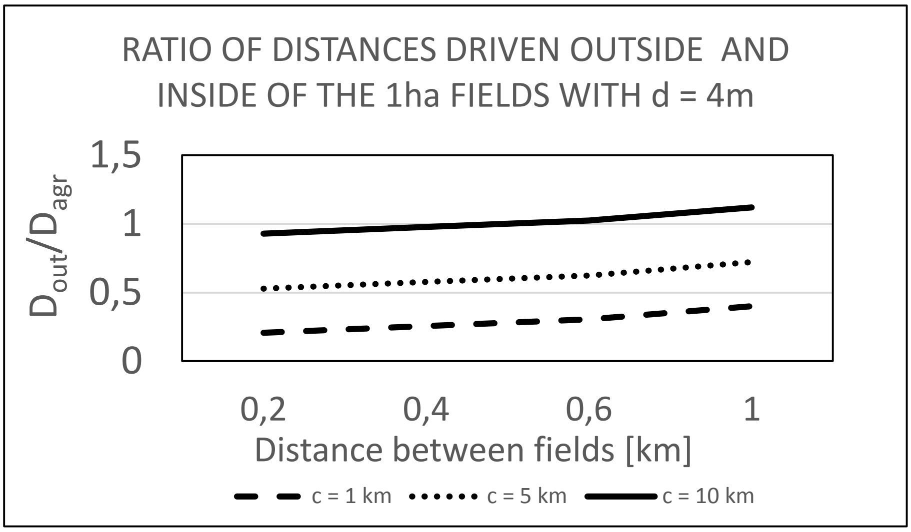

Fig. 1. Computed ratio of distances driven outside and inside of the plantation in the case when operation width was assumed 4 m [source: own study]

Similar results for the individual field size equal to 0,25 km^2 (25 hectare) are shown in fig. 2. In this case the values of the ratio D_{out}/D_{agr} are between 0,057 and 0,271. These values are smaller than previous ones, and do not exceed value of one. In this case there are also slightly dependent upon distances between fields, and rather stronger depend upon the distance between base and the first field.

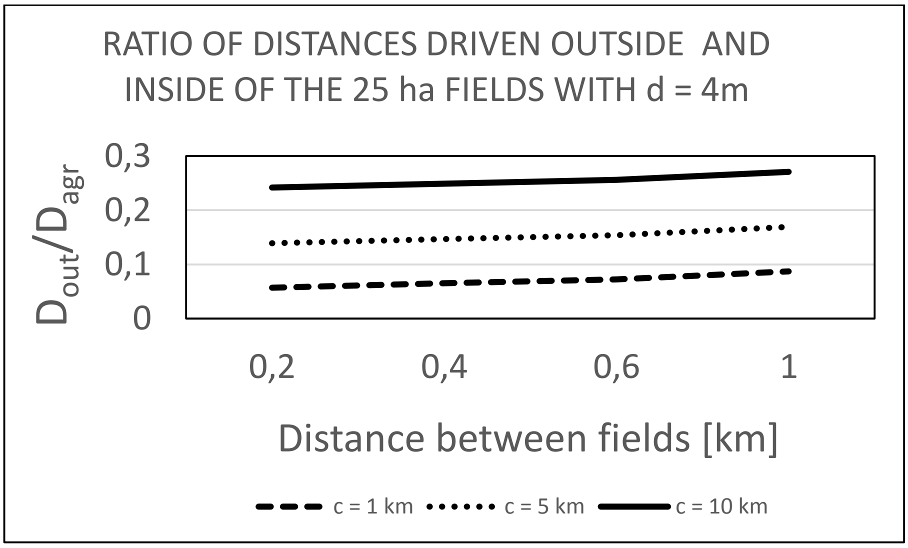

Fig. 2. Computed ratio of distances driven outside and inside of the plantation [source: own study]

Table 3. in turn, presents results for the case when the working width is 0.5 m. It is clearly seen that bigger field area contributes to substantial increase of D_{out}. The distances driven outside the larger fields are much higher than those for the small field area.

Tab. 3. Values D_{out} for the case when working width is d = 0,5m [source: own study]

A_i[km^2]=	0,01			0,25		
c = / l [km]	**1**	**5**	**10**	**1**	**5**	**10**
0,2	2,4	6,4	11,4	92,2	234,6	412,6
0,4	2,8	6,8	11,8	103,3	245,7	423,7
0,6	3,2	7,2	12,2	114,3	256,7	434,7
1	4	8	13	136,5	278,9	456,9

Such an increase of D_{out} with the increase of field area results of the necessity of return to the base after daily allowed working time is reached, The plots of D_{out}/D_{agr} presented in fig 3 and fig. 4 show similar shape of dependencies (a slight increase with the distance between fields, as well as an increase with increasing distance from the base). In this case there is no substantial difference beteween the values observed for different sizes of individual fields in the plantation. The values of $D_{out}/D_{agr,}$ in both cases are smaller than one. This result is mostly due to the high distance driven on the field when the working width is small (0,5m) –with respect to which the distances outside the fields do not contribute too much.

The most important question in this work concerns the amount of energy consumed during agricultural, and transportation operations as compared to the amount of energy obtained in the form of biofuel. Obviously, the amount of energy spend during plants cultivation depends upon the distance driven in, and outside the fields. Consequently it depends on the same factors as the distances driven. The amount of energy obtained from the field is easy to estimate from the crop yield (and also depends upon efficiency of the industrial system, which is not analysed in the paper), for which, two limiting values are accepted. Values of energy consumption by various machines, as well as possible field yields are taken from literature and practical sources of information [14-17]. An estimate of energy spend on driving the distances outside the fields for the case when working width is 4m, is given in Table 4.

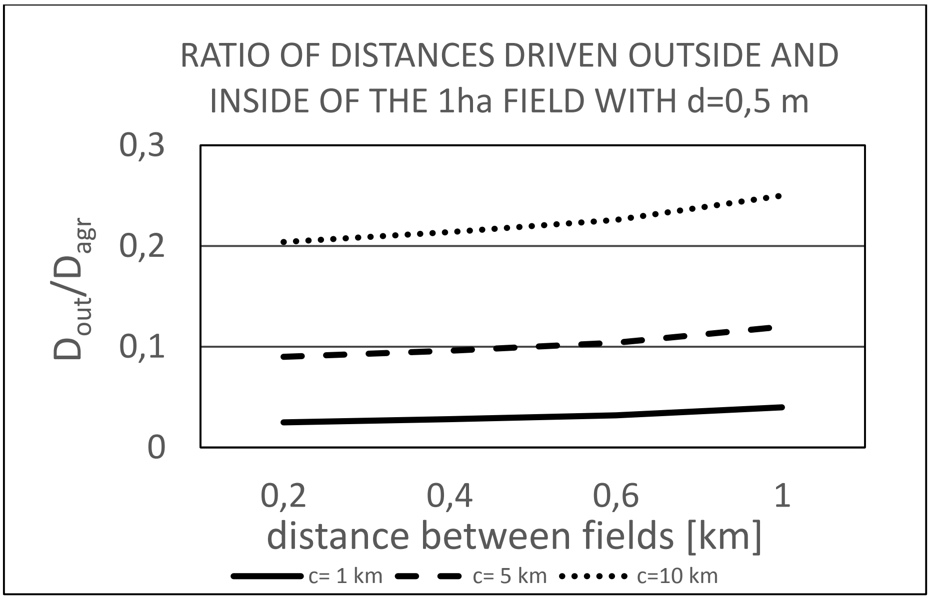

Fig. 3. Computed ratio of distances driven outside and inside of the 1hm^{2}field in the case when operation width was assumed 0,5 m [source: own study]

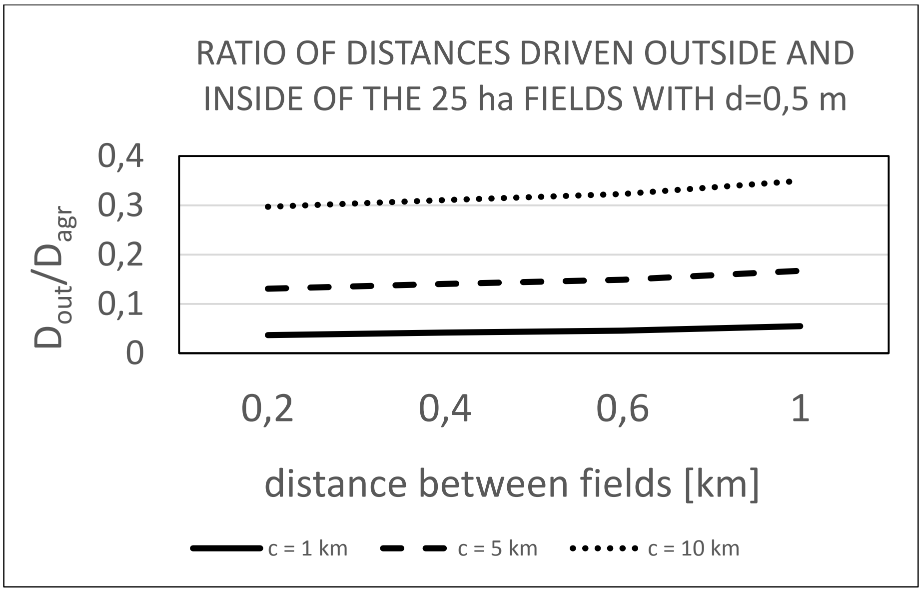

Fig. 4. Computed ratio of distances driven outside and inside of the 25hm^{2}field in the case when operation width was assumed 0,5 m [source: own study]

Tab. 4. Energy, E_{out} [MJ], spend for movements outside for the case when working width is d = 4m [source: own study]

A =	0,01			0,25		
c = l [km]	1	5	10	1	5	10
0,2	28,1	71,3	125,3	191,4	467,9	813,4
0,4	34,6	77,8	131,8	216,4	492,9	838,5
0,6	41,1	84,2	138,2	241,5	517,9	863,6
1	54	97,2	151,2	291,6	568,1	913,7

It is seen, that the energy, E_{out}, spend outside the fields depends on both distances, *l* – between fields, and *c*- distance from the base, and first of all depends upon the size of fields. Again, this later dependence can be rationalized as the result of returns after the allowed working time is reached.

Similar results for the working width equal to 0,5m are presented in Table 5. For both sizes of plantation the energy spend outside of the fields depends on the distances between fields and the distance from the base. The biggest effect is, however, produced by field's size, which again can be interpreter as being due to returns after daily allowed working time limit is reached. The number of days, and consequently the number of returns is much higher when narrow strip is elaborated – what substantially increases the distance driven outside the fields.

Tab. 5. Energy, E_{out} [MJ], spend for movements outside of the fields for the case when working width is d = 0,5m [source: own study]

A =	0,01			0,25		
c = l [km]	1	5	10	1	5	10
0,2	25,9	69,1	123,1	995,5	2533,5	4455,9
0,4	30,2	73,4	127,4	1115,2	2653,1	4575,5
0,6	34,6	77,8	131,8	1234,9	2772,8	4695,2
1	43,2	86,4	140,4	1474,2	3012,1	4934,5

Tables 6 and 7 give the sum of energy spend during operating on the field and energy spend during driving outside fields. Values presented in Table 6 show not very strong dependence upon the distance between fields, *l*, as well as upon the distance, *c*. Important difference is visible when values for small plantation is compared to values for large one. The later values are much higher. This difference is much more pronounced in the case of the narrow width of working strip (table 7).

Basing on the values presented in above tables the energetic efficiency for individual agro-technical operation is computed according to eq. 1.

Tab. 6. Sum of energies, E_{out} and E_{agr}, spend for individual agrotechnical operation for the case when working width is d = 4m [source: own study]

A =	**0,01**			**0,25**		
c = **l [km]**	**1**	**5**	**10**	**1**	**5**	**10**
0,2	164	207	261	3567	3843	4189
0,4	170	213	267	3592	3868	4214
0,6	177	220	274	3617	3893	4239
1	189	233	287	3667	3944	4289

Tab. 7. Sum of energies, Eout and Eagr, spend for individual agrotechnical operation for the case when working width is d = 0,5m [source: own study]

A =	**0,01**			**0,25**		
c = **l [km]**	**1**	**5**	**10**	**1**	**5**	**10**
0,2	1106	1150	1204	27996	29534	31456
0,4	1111	1154	1208	28116	29654	31576
0,6	1115	1158	1212	28235	29773	31696
1	1124	1167	1221	28475	30013	31935

Tab. 8. Ratio of energy contained in biofuel to the sum of energies, E_{out} and E_{agr}, spend for individual agrotechnical operation for the case when working width is d = 4m. The case of field yield 380 dcm^3/hm^2 [source: own study]

A =	**0,01**			**0,25**		
c = **l[km]**	**1**	**5**	**10**	**1**	**5**	**10**
0,2	403	318,7	252,6	460,7	427,6	392,3
0,4	387,6	308,9	246,4	457,5	424,8	390
0,6	373,4	299,8	240,6	454,4	422,1	387,7
1	347,8	283,1	229,7	448,2	416,7	383,2

Table 9. Ratio of energy contained in biofuel to the sum of energies, E_{out} and E_{agr}, spend for individual agrotechnical operation for the case when working width is d = 0,5m. The case of field yield 380 dm^3/hm^2 [source: own study]

A =	0,01			0,25		
c = / l [km]	1	5	10	1	5	10
0,2	59,5	57,2	54,7	58,7	55,7	52,3
0,4	59,2	57	54,5	58,5	55,5	52,1
0,6	59	56,8	54,3	58,2	55,2	51,9
1	58,6	56,4	53,9	57,8	54,8	51,5

In these computations two values of energy yield from plantation, E_{bio}, are taken into account. Those are 380 dcm^3/hm^2 and 1500 $dcm^3/hm^{2.}$. Results for the case of low yield of plantation are presented in Tables: 8 and 9 giving data computed for working width 4m and 0,5m correspondingly. The resulting η_1 values vary from about 230 to about 460 for various combinations of parameters in the case of 4m wide working strip. Similar results for the case of 0.5m strip width give much lower values between about 54 and about 60.

Table 10. Ratio of energy contained in biofuel to the sum of energies, E_{out} and E_{agr}, spend for individual agrotechnical operation for the case when working width is d = 4m. The case of field yield 1500 dcm^3/hm^2 [source: own study]

A =	0,01			0,25		
c = / l [km]	1	5	10	1	5	10
0,2	1591	1258	997	1819	1688	1549
0,4	1530	1220	973	1806	1677	1540
0,6	1474	1184	950	1794	1666	1531
1	1373	1118	907	1769	1645	1513

Values of η_1 obtained for the other extreme case, of high crop yield equal to 1500 dcm^3/hm^2, and working width equal to 4 m, as indicated in Table 10, vary from around 900 to around 1800, depending on plantation structure (fields sizes, and distances between them). Corresponding values of efficiency η_1 are bigger for larger fields. As it is seen in Table 11, the values of efficiency for the case of working width 0,5m are much smaller than those for 4m operation width, and also the differences between different field's sizes, and inter-field distances are much less pronounced.

Table 11. Ratio of energy contained in biofuel to the sum of energies, E_{out} and E_{agr}, spend for individual agrotechnical operation for the case when working width is d = 0,5m. The case of field yield 1500 dcm^3/hm^2 [source: own study]

A=	**0,01**			**0,25**		
c = **l [km]**	**1**	**5**	**10**	**1**	**5**	**10**
0,2	235	226	216	232	220	207
0,4	234	225	215	231	219	206
0,6	233	225	215	230	218	205
1	231	223	213	228	217	204

It was mentioned earlier that computations performed according to eq. 1 give the values of efficiency, η_1 ,corresponding to full yield of fuel, but only one agro-technical operation performed during cultivation of plants. It is never the case in real situations. Usually several tillage operations are necessary. Each of operations might require assumption of different conditions concerning e.g. working width, fuel consumption etc. For the case of simplicity, in the present paper, it was assumed that the same conditions are applied in all operations. Therefore eq. 3 could be used for estimation of final result. The examples of results of computations of energy efficiency, η, as function of a number of operations, for both cases, of field's yields, and for chosen sets of parameters of operations are given in Tables 12 and 13. Obviously results presented in those tables are smaller than those given in previous tables. Evidently the yield of plantation contributes very strongly to the efficiency. The higher the crop yield, the higher is the efficiency η. An increase of the number of operations evidently decreases efficiency. Strong effect is also shown by a decrease of technological parameter, e.g. width of working strip (determining machine's productivity), which also causes a decrease of efficiency. Characteristics of the plantation also play a role in defining efficiency. Factors, like field size, distances between fields or distance from the base show evident (10% to 40%), but less pronounced effects than the above mentioned (crop yield and productivity of the machinery).

Tab. 12. Comparison of the ratio of energy contained in biofuel to the sum of energies, E_{out} and E_{agr}, as a function of the number of operations, for the case when working width is d = 4m, and field yields 380 dcm^3/hm^2 and 1500 dcm^3/hm^2 [source: own study]

Strip width= 4 m		**Field yield = 380**				
A=	0,01			0,25		
c=	1	5	10	1	5	10
l [km]=0,2	403	318,7	252,6	460,7	427,6	392,3
Number of operations						
2	202	160	127	231	214	197
3	135	107	85	154	143	131
4	101	80	64	116	107	99
5	81	64	51	93	86	79
Strip width= 4 m		**Field yield = 1500**				
A=	0,01			0,25		
c=	1	5	10	1	5	10
l [km]=0,2	1591	1258	997	1819	1688	1549
Numer of operations						
2	796	629	629	910	844	775
3	531	420	420	607	563	517
4	398	315	315	455	422	388
5	319	252	252	364	338	310

Tab. 13. Comparison of the ratio of energy contained in biofuel to the sum of energies, E_{out} and E_{agr}, as a function of the number of operations, for the case when working width is d = 0,5m, and field yields 380 dcm^3/hm^2 and 1500 dcm^3/hm^2 [source: own study]

Strip width= 0,5 m		**Field yield = 380**				
A=	0,01			0,25		
l [km]/c=	1	5	10	1	5	10
0,2	59,5	57,2	54,7	58,7	55,7	52,3
Number of operations						
2	30	29	28	30	28	27
3	20	20	19	20	19	18
4	15	15	14	15	14	14
5	12	12	11	12	12	11
Strip width= 0,5 m		**Field yield = 1500**				
A=	0,01			0,25		
l [km]/c=	1	5	10	1	5	10
0,2	235	226	216	232	220	207
Number of operations						
2	118	113	108	116	110	104
3	79	76	72	78	74	69
4	59	57	54	58	55	52
5	47	46	44	47	44	42

4. CONCLUSIONS

Presented result show that amount of energy obtained from biofuel might substantially exceed the sum of energy, which is needed as inputs to facilitate processes of biomass production and conversion to energy. The effectiveness of the biofuel production system is defined as a ratio of energy obtained in form of biofuel to the sum of energy inputs in all subsidiary processes enabling biomass production and its conversion to the biofuel. The present work is confined to the investigation of agricultural subsystem, while the industrial one is considered as constant represented by industrial average. According to the model presented, this effectiveness varies from 10-th to several hundreds depending on various characteristics of the system and ongoing processes. Among those characteristics the main effect is shown by productivity of agricultural machines, and the biofuel yield from the unit of plantation. Although the dependence between biofuel yield and types of agricultural operations might exist, but the data are scarce, and consequently it rather requires further studies. Therefore in this work two extreme values were accepted for computations, giving chance to estimate limiting values characterizing the effect. Variation of the other parameters, characterizing the structure of plantation (in this case assumed as linear one) affect the resulting effectiveness in the range of 10% to 40%. depending on the actual case. One of the phenomena that play substantial role is the dependence of the total distance driven outside of the fields upon the size of the fields, and operational width. This dependence results on the assumption that machines return to the base after allowable working time is reached. The other assumption concerning organization of the work e.g. machines remain on the field, and only people are transported to the base, would bring somehow different results. The expected differences should not be extremely large, since they would be a part of those effects estimated here as being between 10% to 40%. Also changing the structure of plantation to e.g. star-like could bring some differences in the results. Consequently, optimization of the agricultural part of biofuel production system should first of all include proper choice of performance of machinery, assuring as high as possible specific yield of the fields as well as reasonable engineering of work organization and transportation of goods. Some other aspects like industrial sub-system itself and coupling between agricultural and industrial subsystems will be the topic of separated studies.

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