ENERGETIC EFFICIENCY OF AGRICULTURAL PLANTATIONS DEDICATED FOR BIOFUEL PRODUCTION

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Abstract: A deterministic model of "energetic" plantation aimed towards biofuel production is formulated in order to evaluate fluxes of energy occurring during subsequent agro-technical operations. The agro-technical production system, in general, is considered as a part of larger system that includes also industrial part dedicated to processing of crops to biofuel, at present stage of research it is, however, considered separately. The scale of production, resulting of the demand of industrial part of the system, is implicitly considered. The derived efficiency indicator, that principally corresponds to EROEI, indicates that one of the most important factors decreasing energetic efficiency of plantation is transportation of goods and machinery outside of cultivated fields. Contribution of transport term depends upon the distances driven outside of the fields, and therefore depends upon the size of production – controlled by the demand from the industrial part. (Because it seems impossible to find continuous field of required size). The other factors are the yield of plantation and technical characteristics of machinery being used.

Keywords: biofuels, transportation, production system, energetic efficiency, EROEI

1. Introduction

Fuels based on biological resources are considered as important contribution to world's energy balance [1]. This is due to both: the recognition of threats to natural environment, and expectation of future shortages of fossil fuels. Both factors force the search for a new, alternative source of energy, mainly those based on renewable resources. The trend to use biomass as the source of energy is politically promoted [2,3], and widely discussed [4,5]. Some problems are also indicated, mostly referring to the competition between food production and industrial exploitation of biomass (as energy or materials resource). This competition concerns equally non-food use of edible crops, as well as land use for cultivation of plants for industrial purposes. As pointed out in [1] the efficiency of plantations designed for food production increases due to the progress in agricultural technology, also it is indicated that in many regions of the world there are still large reserves of unexploited land as well as the level of efficiency of land use in those areas appears to be below world's average – consequently some degree of freedom is available. The situation differs depending upon climatic zone, type of soil, availability of water, as well as political, economic and technological development of particular country. In recent literature several papers discuss perspectives of biofuel production and its use in relation to the situation in chosen countries [6-10]. Excellent review discussing various approaches to production as well as use of biofuels is given in [11].

Concerning biofuels as a replacement for fossil ones, the "energetic" plantations require special attention with respect to energetic efficiency of plantation itself, as well as of the complete system of biofuel production, that involves combination of agricultural and industrial processing subsystems. A problem of this kind is discussed in several recent papers giving insight into thermodynamic bases of biofuel production. The exergy flow analysis performed in [12] for the case of biodiesel production, indicated low exergy loss in the process, and still existing possibilities to its decrease with the improvement of technology. Similar analysis is performed [13] for the case of bioethanol production. Referring to sustainability the paper mentioned states that not always bioethanol production fulfills the requirement of sustainability i.e. that the bioethanol production is not always sufficiently efficient. The paper mentioned [13] introduces also 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 of global size. Several studies are also concerned with empirical studies on energy efficiency in agriculture in general [14-18] as well as especially dedicated to "energetic" plantations [19-23]. Those papers provide important sets of data that enable more general analysis of the factors deciding on the energetic efficiency of biofuel production systems. Slightly different approach to the scale of a techno-system is given in paper [24] discussing feasibility analysis with respect to the size of the production system. Summarizing achievements presented in the cited literature, as well as in many other sources one can list the following: biofuels are considered as important contribution to world's energy balance, especially when applied as the source of energy for transportation. Energetic efficiency of particular type of biofuel depends upon many factors, like local climate, availability of water, tillage strategy applied in agricultural production, type of plant used, as well as technology of conversion of biomass to fuel including the way of byproducts treatment. The recently published paper [25] gave, based on several scenarios, analysis of EROEI factor for soybean production as a source for biofuel indicating relatively strong dependence upon technical as well as other factors.

The present paper extends the results given in [26] aiming towards construction of a model describing the effects of processes occurring in the individual elements of biofuel production system on energetic efficiency of that system. This part concerns agricultural part of the production system including transportation terms between different production sites as well as energy embodied into production means (tools).

1.1. The aim and methodology of the research

Biofuel production is realized in a production system of specific structure. First of all it is composed of two interacting subsystems substantially differing form each other. Those are: agricultural and industrial subsystems. They strongly interact: namely each one poses specific requirements and boundary conditions towards the other. Coupling between them may be achieved according to various strategies affecting the structure of the whole system. The common features are inputs of mass and energy to particular elements, flow of the mass through all elements, conversion of mass to another form or to energy. Individual elements of each subsystem perform functions enabling occurrence of predetermined processes, frequently differing in the specific time scales of the processes occurring in various elements. Each of elements requires some amount of energy to perform its function. Sum of amounts of energy consumed by each process compared to energy obtained in form of the biofuel determines the efficiency of the system. In the present studies it is attempted to form mathematical model describing behavior of the system, and enabling investigation how variations of parameters controlling particular element of the system's structure affects the effectiveness of the whole system.
The main assumptions are made as follows:

– Structure of the production system, understood as specific order of elements, types of elements, and kinds of links between them, determine performance of the whole system
– Deterministic description of functionalities of system's elements can offer a tool for analysis of the whole system behavior.

The present paper gives general formulation of the model describing agricultural subsystem and present conclusions that can be derived from the model on several levels of approximation. Subsequent papers will show the model of industrial system and numerical analyses, computed for realistic ranges of parameters basing on the derived formulas. Although the main goal of the agricultural subsystem is to accumulate solar energy and convert it into biomass, the flux of solar energy is not explicitly considered in the present calculations. The proposed model concerns fluxes of energy introduced by human activity (production) in order to facilitate the conversion mentioned above.

2. The efficiency of energetic plantation

Tillage of energetic plants includes the number of agro-technical operations, every one of which requires some input of energy - first of all in the form of liquid fuel for agricultural machines. The quantity of fuel consumed in each operation depends on the length of the route driven on the given field. Depending on its design, and principle of operation every machine in a single course can cover strip of land of specific width, *d*. The whole surface of the field is worked through the multiple, subsequent movements of the machine in parallel strips or simultaneous parallel movements of a number of machines.

In the previous paper [26] we have shown that for the field of a form of parallelogram, independently of its shape, and of the direction of movement, the length of the route depends only upon area, $A=L\times D$, of the field (L, and D - are the field's dimensions), and width of operation, *d*, that determines the number of parallel runs, *n*, necessary to cover the whole area.

The total distance will be:

$$Dr = \frac{A}{d} = \frac{L\times D}{d} \tag{1}$$

The amount of energy expended in *m* tillage processes can be expressed:

$$E_{ex} = \sum_{i=1}^{m} \frac{L\times D}{d_i} \times \omega_i \times W_{fuel} \tag{2}$$

after extraction of constants before the sign of the sum expression assumes form:

$$E_{ex} = W_{fuel} \times A \times \sum_{i=1}^{m} \frac{\omega_i}{d_i} \tag{3}$$

where:

ω_i - the fuel consumption per unit of the distance passed during the individual agro-technical process,

d_i - width of the land strip operated in the single course of *i*-th operation

W_{fuel} - the low caloric value of the fuel used for operations (might be fossil fuel or biofuel),

m - the number of the agro-technical operations (in each one of the operations the width of the worked field, d_i, and the consumption of fuel, ω_i , can be different).

The energetic efficiency of the plantation can be expressed as E_{bio} / E_{ex} . Component E_{bio}, that is the total quantity of energy contained in all forms biofuels got from the given plantation, can be expressed as:

$$E_{bio} = A \times M_{crop} \times \gamma \times \sum_{k=1}^{n} \propto_k \times W_{bio,k} \tag{4}$$

where:

A - the surface area of plantation,

M_{crop} -the mass of crop on the unit of area of plantation,

γ – general mass fraction of biofuel in the crop,

α_k - mass fraction of k species of biofuel,

n - a number of biofuel species obtained from the plantation

$W_{bio,k}$ – low caloric value of k-species of biofuel.

Basing of equations (3) and (4) one can formulate a first approximation of the dependence E_{bio}/E_{ex} expressing efficiency of a plantation

$$\frac{E_{bio}}{E_{ex}} = \frac{M_{crop} \times \gamma \times \sum_{k=1}^{n} \propto_k \times W_{bio,k}}{W_{fuel} \times \sum_{i=1}^{m} \frac{\omega_i}{d_i}} \tag{5}$$

Eq. (5) although incomplete, gives crude approximation of reality leading to the conclusion, that (at least in situations where it would be valid with enough accuracy) the efficiency of plantation does not depend on the surface area of the field, and is mainly governed by factors like the crop yield, M_{crop} , characteristics of machinery (ω_i , d_i) being used, and a number of operations performed. It can be easily recognized that an increase of caloric value of the fuel used for agricultural operations, W_{fuel} , as well as an increase of the number of operations or fuel consumption, ω_i , or decrease in, d_i , always lead to a decrease in energetic efficiency.

It seems, however, that eq. (5) includes the most important contributions to the energetic efficiency. To estimate the accuracy of this approximation one should attempt to consider other factors affecting the efficiency, but neglected in derivation of the above formula. There are several such factors. The group of factors strictly connected to agricultural operations contain fertilizing, watering and applying of means of crop protection. It can be expected that crop yield from the unit of plantation area, M_{crop}, may depend on frequency and intensity of the factors mentioned – indicating an increase at least in some range of the applied treatment. Consequently should be considered as function of several variables:

$M_{crop}(cf, cw, ccp, ...)$, where e.g. *cf* – fertilizer, *cw* – water, *ccp* –crop protection concentration maintained during plan cultivation. This dependence can be estimated on the basis of empirical field studies.

The same factors, affecting crop yield, give also contributions to the expended energy. This contribution may be taken into account through consideration of embodied energies contained in corresponding means (like fertilizer or e.g. insecticide). The embodied energy contained machines should also be taken into account. Since such contribution is only a fraction of energy consumed in particular operation, one can write:

$$E_{ex,1} = \sum_{i=1}^{m}\{[\varepsilon_i \times W_{fuel} A \times \frac{\omega_i}{d_i}] + (1-\varepsilon_i)\sum_{k=1}^{K}\gamma_k \times Eemb_k\} \quad (6)$$

where:

ε_i - is a fraction of energy consumed in form of fuel during i-th operation

γ_k - is a fraction of embodied energy contained in the *k*–th of the *K* technical means employed (machines, fertilizers, etc.) being consumed in individual operation.

Obviously

$$\sum_{k=1}^{K}\gamma_k = 1$$

$Eemb_k$ - is embodied energy contained in *k*-th technical mean

The other factor, that in frequent situations plays important role, is transportation outside of the cultivated fields. It is related to transportation of various good, including machines, from some base to the plantation, as well transportation between various fields belonging to the same plantation (this especially applies to very big plantations, in which fields might be separated by quite long distances). Transportation energy is again composed of the contribution resulting of consumed fuel and embodied energy contained in transportation means. Consequently it can be written in the form:

$$E_{tr} = \sum_{p=1}^{P}\{\lambda_p \times L_p \times W_{fuel,tr} + (1-\lambda_p) \times Eembtr_p\} \quad (7)$$

where

$Eembtr_p$ - is embodied energy contained in one of the transportation means

λ_p - is fraction of energy consumed in form of fuel during *p*-th course

Consequently:

$$E_{ex,tot} = E_{ex,1} + E_{tr} \quad (8)$$

and finally:

$$\frac{E_{bio}}{E_{ex,tot}} = \frac{M_{crop}(cf, cw, ccp, \ldots) \times A \times \gamma \times \sum_{k=1}^{n} \propto_k \times W_{bio,k}}{\sum_{i=1}^{m}\{[\varepsilon_i \times W_{fuel} A \times \frac{\omega_i}{d_i}] + (1-\varepsilon_i)\sum_{k=1}^{K}\gamma_k \times Eemb_k\} + \sum_{p=1}^{P}\{\lambda_p \times L_p \times W_{fuel,tr} + (1-\lambda_p) \times Eembtr_p\}} \quad (9)$$

It is seen in the formula (9) that, in contrast to eq. (5) plantation surface area does not reduce, what results in dependence of energetic efficiency on the size of plantation. Plantation's size is determined by the size, and required output of cooperating industrial installation. It is seen that the transportation term causes substantial reduction of the total efficiency. This reduction will depend on topology of paths connecting elements of plantation. The type of agricultural operations might increase the mass of the crop, and the amount of energy obtained, but on the other hand it decreases energetic efficiency through contribution of corresponding embedded energies. It should be mentioned that the efficiency characteristic given by eq. 9 corresponds to EROEI factor used in many publications. Detailed estimation of the effects requires further studies, and numerical computations based on realistic sets of data, what will be the subject of the next publication.

3. Conclusions

The results of present study indicate that in a crude approximation (eq. 5), which under some circumstances might be applicable to a very small scale fuel production, (e.g. for own use in the farm, in which energy required for transportation could be neglected), the energetic efficiency depends only on characteristics of the machinery used, and is independent of the area of cultivated field. The achieved efficiency might be higher than one, i.e. giving the real contribution to energy production, when yield of the crop is high, and machinery used does not consume too much of energy. This case may be considered, as an upper limit of the efficiency. As seen in eq. 9, the term most strongly affecting efficiency is one determined by the energy consumed for transportation – the higher is this term the lower will be energetic efficiency of the plantation. The size of plantation depends upon demand for biomass from cooperation industrial facilities, while topology of plantation results of land availability. The term concerned with embodied energy in technical means directly involved in production, contained in eq. 6, also decreases efficiency, but most probably it is relatively small, and to some extend may be compensated by an increase of plantation yield upon various treatments applied. Further investigations of ranges of variability of individual components of consumed and produced energy, as well as of their mutual dependencies will contribute to optimization of biofuel production.

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