Acta Agroph., 2016, 23(2), 331-345

ENERGY ASSESSMENT OF *MISCANTHUS×GIGANTEUS* CULTIVATION BASED ON H.T. ODUM'S ENERGY VALUE THEORY*

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A b s t r a c t . The subject matter of an emergy analysis was the environmental system of a model *miscanthus×giganteus* cultivation. Assessment of environmental work contribution to the cultivation of renewable biomass was performed based on the energy value theory (EVT) created by Howard T. Odum, which combines the principles of thermodynamics, ecology and economics by means of a single unit of measurement – emergy. The concept of emergy is based on energy transformation ratio between each elements of the ecosystem and emergy is a measure of quality differences between different forms and streams of energy. Flow of energy and materials between the environment and the model cultivation was determined. The analysis of emergy allowed the evaluation of all identified streams that power the analysed system, especially the ones which are omitted by traditional economics due to inability to price or to common availability. EVT, whose principles are based on transformation of primary solar energy that powers all systems within the cycle of life on our planet, opens the real environmental costs for assessment. In order to determine and consider the value of environment in the process of biomass production, a basic study was conducted for a model cultivation of miscanthus within the scope of elemental analysis of collected biomass and soil. An attempt was made at the assessment of environmental contribution into a renewable energy source, that is, biomass. The results showed that the contribution of soil components emergy in the creation of biomass was the most significant. Renewability of the analysed system reached 18%, which proves considerable instability of the system. Eighty two percent of environmental contribution into the formation of renewable biomass was constituted by non-renewable sources which may result in degradation of the local ecosystem over a short period of time. Cultivation requires to be supplied with basic nutrients in order to restore environmental balance. The cost of environmental contribution not considered by humans was circa 314 \$ year^{-1}.

K e y w o r d s : energy theory of value, biomass, *miscanthus×giganteus*, emergy, transformity

*The publication financed by the University of Agriculture in Cracow, Faculty of Production and Power Engineering, DS 3600.

INTRODUCTION

Nowadays, analysis of proper evaluation and management of natural resources forms the basis for sustainability. The system adaptation of values of economics to ecology and an attempt at a realistic assessment of the value of rain, high tide and low tide, energy of waves or wind etc. with an economic tool encounters a lack of understanding of the fact that economy is dependent on processes occurring within the natural environment, while the role of this environment is usually omitted in assessment of the value of natural resources, which leads to a clash. The emergy approach to assessment of natural resources ensures its independence from political and economic systems and supports greater objectivity within the scope of consumption and degradation assessment of natural resources. Free services of natural environment create an invisible foundation supporting societies and economies (Abramovitz 1997, Odum 1983).

One of the core advantages of emergy analysis is the ability to assess the environment, ecological services, technological processes etc. on a common ground based on solar energy unit. The premises for this theory are based on the transformation of basic energy powering all systems within the cycle of life on our planet, combining thermodynamics, ecology and economics, by means of a single measurement unit – emergy. EMA (Emergy Analysis) defines emergy as the amount of total energy used in the past to manufacture a product or service nowadays. It allows to take into consideration and calculate all contributions from nature, those provided by human economics, as well as interdependences and relations between the analysed systems and the environment, providing quantitative data on energy used, consumed, stored directly and indirectly in the manufactured product or service (Brown and Ulgiati 2009, Odum 1983,1996).

The approach based on the emergy value theory goes beyond the classical view on energy within the aspect of potential ability to perform work or obtain heat, creating another parameter which is not a function of state, describes energy from the perspective of its quality and takes the history and transition paths into consideration. The emergy value theory, by means of a universal unit of solar joule (sej), assigns all elements of the system a new value, a measure of the true wealth independent of existing economic systems. Emergy as **em**bodied en**ergy** is the sum of all streams energy in system incorporated or embodied in the system's products. Emergy is measured with the transformity (Tr) coefficient which defines its amount needed to manufacture one unit of production. Transformity also shows the position of an element within the biosphere thermodynamic scale by assigning a given system with a quality level perceived from the point of view of biosphere's dynamics (Brown and Ulgiati 2004, Odum 1983). The theory, which goes beyond the classical foundations of energetics, hierarchises the forms of energy taking their work capabilities on each concentration level into consideration. Generally accessible dispersed solar energy is characterised with different work capability than the same energy accumulated in the form of biomass. The result is that various forms of energy, such as solar energy, electrical energy, human thought or information show different work capability from the thermodynamic perspective. Determining the trasformity coefficient enables us to receive information on the "quality" of a given form of energy and therefore on transformation of solar energy through subsequent processes into output form of energy (Lefroy and Rydberg 2003). Emergy analysis enables us to determine environmental indices (Cavalett *et al*. 2006): renewability of environment (% R), ability to provide the amount of emergy required by the system (ELR), exchange rate (EER) (Brown *et al*. 2007, Cavalett *et al*. 2006, Lefroy and Rydberg 2003).

MATERIALS AND METHODS

For evaluation of work expenditure on renewable biomass of miscanthus giganteus, the emergy value theory (EMA) was used. Emergy analysis was executed in three stages. The first one was related to the construction of a diagram identifying all energy flows and storages within the system. The second stage included emergy assessment for the identified resources and energy streams. In the last stage, transformity was calculated and stability of the system was determined by means of environmental indices.

The subject of emergy analysis was the cultivation of power plant – *miscanthus*×giganteus, a perennial plant which belongs to C4 type of plants, characterised by increased CO_2 absorption and economic water management. The model cultivation was located on the premises of the University of Agriculture in Krakow. The aim of the analysis was evaluation of work contributed by the natural environment through the assessment of primary energy conversion during production process of renewable biomass energy, assessment of contribution and attempt at evaluating this contribution. The assessment method was based on the determination of the amount of environmental energy taken directly and indirectly by the cultivation. Transformity coefficient and energy concentration coefficient at a higher level were calculated and expressed in terms of primary solar energy, that is, the form of energy that drives all environmental systems.

For the purpose of emergy analysis, in order to arrive at reliable data, a number of tests on the basic parameters of the cultivation and soil were performed. Elemental analysis of soil and elemental analysis of biomass was performed. The balance was performed with emergy streams flowing through the system over an annual cycle taken into consideration, as well as with primary solar energy, wind kinetic energy, rain chemical energy, geothermal energy, and soil chemical energy being taken into account. Transformity coefficient (Tr) of the system and environmental indices are tabulated in Table 1 (Cavalett *et al*. 2006, Lefroy and Rydberg 2003).

Table 1. Indices used in environmental accounting

Index	Expression	Meaning
System emergy (Y) (Lefroy and Rydberg 2003)	Y = R+N	sum of emergy from renewable and non-renewable sources
System tranformity coefficient (Tr) (Abramovitz 1997)	Tr = Y/E	input emergy to output product energy quotient
Renewability of environment (%R) (Lefroy and Rydberg 2003)	%R =100(R)/Y	total contribution of renewable emergy
Eenvironmental loading ratio (ELR) (Lefroy and Rydberg 2003)	ELR = N/R	non-renewable emergy source input to renewable emergy source input quotient
Share of a given source in effects on the system	Ui = ui/Y	relative share of the i-th element in total energy stream
Energy exchange ratio (EER) (Lefroy and Rydberg 2003)	EER = Y/(($) (sej/$))	energy provided by the system to economy divided by the product of market value of the product and emergy value of money

Miscanthus giganteus

The cultivation of 121 m^2 area was established in 2008 and included 198 seedlings of *miscanthus×giganteus* planted in 11 rows of 18 seedlings, each spaced at 60-70 cm intervals. In 2014, in the fifth year of cultivation, an average amount of 1.9 kg of crops was collected from each root stem, 376 kg in total, which makes 31.1 t ha^{-1}. Harvest was carried out in March, owing to which the amount of dry matter in hay was increased, while sodium and potassium content, slagging ingredients and ingredients that influence the amount of ash during thermal processing were decreased (Brown *et al*. 2007). Biomass samples collected in 2014 were characterised by total moisture of 18.7%. Biomaterial was analysed for elemental composition, which is tabulated in Table 2.

Table 2. Parameters of *miscanthus×giganteus* biomass

Parameter	Symbol	Unit	Analytic state	Work state
Analytical moisture	W^a	%	9.36	8.39
Transient moisture	W_{ex}	%	–	10.30
Total moisture	W_t^r	%	9.36	18.70
Heat of combustion	Q_s	MJ kg^{-1}	18.20	16.16
Calorific value	Q_i	MJ kg^{-1}	16.35	14.41
Carbon C	C	%	44.31	39.74
Hydrogen H	H	%	6.34	5.69
Oxygen O	O	%	34.40	30.85
Nitrogen N	N	%	0.35	0.31
Ash A	A	%	5.20	4.66

Calorific value and heat of combustion were calculated based on the elemental analysis of miscanthus performed with the LECO analyser. The calculated values did not differ from values determined based on analysis in calorimetric bomb.

Also chemical analysis of soil samples collected up to 30 cm under the cultivation (sample M) and soil from non-cultivation areas (sample O) was performed. Tables 3 and 4 present the analysis of soil samples – particle size distribution and elemental analysis: organic carbon, total nitrogen, potassium, phosphorus, magnesium, pH and density.

Table 3. Soil analysis – particle size distribution

Parameter	Soil under cultivation sample M	Control soil sample O
Particle size distribution	%	%
Sand 0.05-2 mm	73.0	73.5
Large dust particles 0.02-0.05 mm	10.5	10.0
Fine dust particles 0.02-0.002 mm	14.1	14.0
Clay < 0.002	2.4	2.5

Table 4. Soil analysis – chemical composition

Parameter	Soil under cultivation sample M	Control soil sample O
Total nitrogen N_{tot}, g kg^{-1}	0.5	0.6
Phosphorus P, mg kg^{-1}	80.6	83.4
Potassium K, mg kg^{-1}	87.0	96.0
Magnesium Mg, mg kg^{-1}	10.4	10.9
pH(kcl)	5.4	5.7
Organic carbon content C_{org}, g kg^{-1}	7.1	7.5
Wet bulk density* ρ, g cm^{-3}	2.14	2.16

* determined by using a ring or cylinder method – according to PN-88/B-04481 pts. 5.2.6. for sample: concentrated, on the structure of disturbed and natural humidity

Cultivation of miscanthus which constitutes a part of a larger environmental system undergoes continuous energy flows, the use of which helps it to build its structure. Energy streams originating from the sun, rain, wind, and soil in the form of geothermal heat stream or streams of minerals obtained from the soil flow through the system. All of the above-mentioned streams combined make up the environment's work, without which no cultivation, production or services would be possible. The task was to evaluate the value of the environment's work, its renewable and non-renewable resources used directly or indirectly in the production of renewable biomass of *miscanthus×giganteus*.

The first stage of the analysis was to examine the paths of energy flow in the processes that occur within the system. The analysis formed the basis for determining relations among the system's main components. Main streams of energy were identified and interpreted visually based on systemic modelling language rules (Brown *et al*. 2007, Odum 1996, Lewandowski and Heinz 2003). Identified flows allowed the determination of total emergy of the system and of environmental indices related to environmental load and resource renewability. A diagram (Fig. 1) depicts energy flows (expressed in J year^{-1}) for a model cultivation of *miscanthus*×*giganteus*.

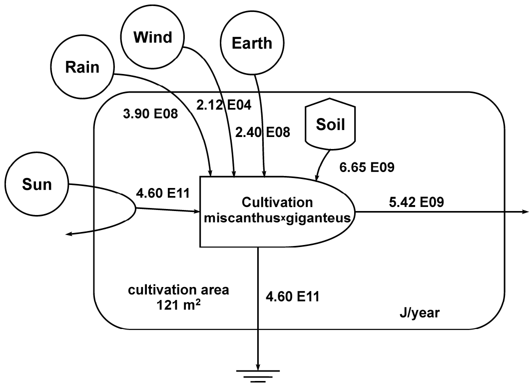

Fig. 1. Diagram of model cultivation of *miscanthus*×*giganteus* system located at the premises of University of Agriculture in Krakow, depicting energy flow to and from the system expressed in J year^{-1}

Table 5 compiles the division of emergy flows used in environmental accounting (Cavalett*et al*. 2006) modified slightly for the purpose of the system in question.

Table 5. Marking of emergy flows used in environmental accounting

Symbol	Input	Description
R	renewable environmental resources (Lefroy and Rydberg 2003)	sun, rain, wind, geothermal heat
N	non-renewable environmental resources (Lefroy and Rydberg 2003)	soil – mineral components
Y	total system emergy (Lefroy and Rydberg 2003)	sum of the system's renewable and non-renewable emergy
Ui	emergy share of the i-th component with a significant influence on the system	yN – nitrogen emergy yC– organic carbon emergy y(rain) – rain emergy y(geoterm) – geothermal heat energy

The next stage included the compilation of all available data on energy streams marked in a diagram of miskanthus×giganteus cultivation. Emergy of each type was assessed by means of formulas used or created for the purpose of individual input calculations. Calculation formulas, collected data and obtained results are compiled in Tables 6-9. Table 6 contains data on basic calculation of input streams from renewable sources.

Table 6. Calculation formulas for the amount of energy flowing through the system from renewable sources R

Item	Item	Reference
1	Sun	Odum 1996
	Intensity of solar exposure = 2890 W h m^{-2} day^{-1}	NASA Langley Research Center 2014
	Unit conversion 1 h = 3600 s	
	(intensity of solar exposure) (unit conversion) (cultivation area)	
	energy = 4.6E11 J $year^{-1}$	
2	Wind	Lorenc 1996
	Mean annual wind speed = 3.2 m s^{-1}	GUS 2013
	Air density ρ = 1.225 kg m^{-3}, for temperature t = 15°C, p = 1013 hPa	
	Cultivation area = 121 m^2	
	unit conversion 1 year = 3.156 E07 s	
	0.5 (air density) (wind speed)^3 (time) (cultivation area) 2.778 E-07	
	energy = 2.12 E04 J $year^{-1}$	
3	Rain – geopotential energy	Odum *et. al*. 2000
	mean annual precipitation = 619 mm $year^{-1}$	GUS 2013
	unit conversion 1 mm = 1.0 E-03 m	
	gravitational acceleration = 9.81 m s^{-2}	
	mean altitude = 233 m AMSL	
	surface runoff 10%	
	water density = 1000 kg m^{-3}	
	(area) (surface runoff) (mean annual precipitation) (mean altitude AMSL) (gravitational acceleration) (unit conversion) (water density)	
	energy = 1.7 E07 J $year^{-1}$	
4	Rain – chemical energy	Odum 1996
	mean annual precipitation = 619 mm $year^{-1}$	GUS 2013
	unit conversion 1 mm =1.0 E-03 m	
	Gibbs's chemical potential G = 4.94 E06 J m^{-3}	Odum 1996
	(cultivation area) (mean annual precipitation) (unit conversion)·G	
	energy = 3.7 E08 J $year^{-1}$	
5	Geothermal soil energy	Odum 1996
	mean heat stream of soil = 0.063 W m^{-2}	Tytko 2009
	time conversion 1 year = 3.15 E07 s	
	(mean heat stream of soil) (cultivation area) (time conversion)	
	energy = 2.4 E08 J $year^{-1}$	

The amount of solar emergy flow was assessed in two ways: by assuming an average annual total solar exposure for Poland as determined over 22 years of observation, from database for Cracow, latitude 50.060°N and longitude 19.959°E, as well as based on data on the intensity of solar exposure read from maps (NASA Langley Research Center 2014, GeoModel Solar 2011) from whose range of 900-1100 kWh m^{-2} for Cracow area the value of 1080 kWh m^{-2} $year^{-1}$ was adopted. Comparable values were obtained. The present application adopted the former one.

Table 7. Calculation formulas for the amount of energy flowing through the system from non-renewable sources N

Item	Item	Reference
1	Humus layer of non-cultivated soil	GUS 2013
	organic carbon content in soil = 7.5 g kg^{-1}	own research
	mean depth of soil sample collection = 0-30 cm ~ 0.15 m	
	unit conversion = 1 E06 cm^3 m^{-3}	
	soil density = 2.16 g cm^{-3}	own research
	soil's calorific value = 5.4 kcal g^{-1}	GUS 2013
	conversion of calories into Joules 1 kcal = 4186 J	
	(organic carbon content) (mean depth of soil sample) (soil's calorific value) (calories to Joules conversion) (unit conversion) (soil density) (cultivation area)	
	energy = 6.65 E09 J $year^{-1}$	
2	Minerals – loss	
	P – phosphorus content – sample O = 83.4 mg kg^{-1}	own research
	K – potassium content – sample O = 96 mg kg^{-1}	own research
	N_{tot} – total nitrogen content – sample O = 0.6 g kg^{-1}	own research
	Mg – magnesium content – sample O = 0.5 g kg^{-1}	own research
	P – phosphorus content – sample M = 80.6 mg kg^{-1}	own research
	K – potassium content – sample M = 87 mg kg^{-1}	own research
	N_{tot} – total nitrogen content – sample M = 0.6 g kg^{-1}	own research
	Mg – magnesium content – sample M = 10.4 mg kg^{-1}	own research
	mean soil density = 2.16 g cm^{-3}	own research
	(mineral content sample O – mineral content sample M) (cultivation area) (depth) (soil density) (unit conversion)	
	ΔP = 2.2 E02 g $year^{-1}$	
	ΔK = 7.0 E02 g $year^{-1}$	
	ΔN_{og} = 7.8 E03 g $year^{-1}$	
	ΔMg = 39 g $year^{-1}$	
3	Soil – organic carbon loss	
	carbon content sample zero =7.5 g C_{org} kg^{-1}	
	carbon content sample cultivation = 7.1 g C_{org} kg^{-1}	
	wet soil bulk density =2.16 g cm^{-3}	
	depth = 0.3 m	
	area = 121 m^2	
	(cultivation area) (depth) (soil density) (C_{org} content sample O – C_{org} content sample M)	
	ΔC_{org} = 3.1 E04 g $year^{-1}$	

Kinetic wind energy was calculated taking into consideration the mean wind speed observed in this region according to data of the Central Statistical Office (GUS 2013, Lorenc 1996).

For calculation of rain chemical potential, mean annual precipitation for Cracow and Lesser Poland Voivodeship region according to the Central Statistical Office was adopted (GUS 2013).

Soil chemical energy was determined based on analysis of soil composition for basic elements.

Geothermal energy stream of soil that flowed through the model cultivation was assessed with the use of mean geothermal stream. Table 7 compiles detailed calculations of soil environment parameters treated as a non-renewable source.

Table 8 contains calculations of seedling potential and collected biomass based on market prices in 2013.

Table 8. Calculation formulas for energy of obtained biomass and seedlings

Item	Item	Reference
1	Value of existing cultivation – *Miscanthus×giganteus*	
	Price per seedling = 0.85 PLN	
	(number of seedlings) (price per seedling)	
	198 pcs. 0.27 \$ = 53.46 \$ year^{-1}	
	Value of existing cultivation = 53.46 \$ year^{-1}	
2	Collected biomass	
	calorific value 14.41 E06 J kg^{-1}	own research
	collected mass = 376 kg year^{-1}	own research
	(collected mass) (calorific value)	
	energy = 5.42 E09 J year^{-1}	
	market value of agro biomass for a power plant, purchase prices, 2013, 8 \$ GJ^{-1}	
	(biomass calorific value GJ t^{-1}) (price per 1GJ)	
	14.41 GJ t^{-1} 8 \$ GJ^{-1} 0.376 = 43.35 \$	

Energy streams and mass was multiplied by appropriate transformity coefficients Tr_i to calculate emergy of a given stream.

Largest emergy flows for renewable resources (R) were related to evapotranspiration and rain chemical potential (item 3, Table 9) and soil energy (item 5, Table 9). Whereas, for non-renewable resources (N), the shares of emergy flows were the largest for organic carbon contained in soil (item 1, Table 10) and nitrogen content (item 2, Table 10).

Macroeconomic value of each flow was calculated to determine the purchasing power of the local economy. Total emergy of Poland’s economy in 2013, estimated as 2.5 E23 sej (own calculations), was divided by gross domestic product (PKB), which reached 519.4 billion USD in 2013. If we take Poland's geopolitical location and its environmental resources into consideration, we may conclude that in 2013 the basic monetary unit 1 PLN (3.095 $) cost the environment emergy contribution of 1.52 E11 sej. In other words 1 $ cost the environment emergy contribution of 4.7 E11 sej. Detailed methodology of valuation calculations for renewable and non-renewable environmental resources are included in Tables 9 and 10.

Table 9. Emergy assessment of model cultivation of miscanthus giganteus – renewable resources

Item	Renewable energy sources R	Transformity Tr* sej J^{-1}	Energy J $year^{-1}$	Emergy sej $year^{-1}$	Economic valuation \$ $year^{-1}$
			Renewable resources R		
		1	2	1x2	2 $(1.52\ E11)^{-1}$ (3.095^{-1})**
1	sun	1	4.60 E11	4.60 E11	0.98
2	wind kinetic energy	2450	2.12 E04	5.19 E07	
3	evapotranspiration and rain chemical potential	31000	3.70 E08	1.15 E13	24.45
4	rain geopotential energy	47000	1.70 E07	7.99 E11	1.70
5	geothermal energy	58000	2.40 E08	1.39 E13	29.55
	total R			2.67 E13	56.68

* transformity – source transformity Odum 2000; **dollar exchange rate according to NBP rate table 25/A/NBP/2014

Table 10. Emergy assessment of model cultivation of miscanthus giganteus – non-renewable resources

Item	Non-renewable energy sources N	Transformity Tr * sej g^{-1}	Mass g $year^{-1}$	Emergy sej $year^{-1}$	Economic valuation \$ $year^{-1}$
			Non-renewable resources N		
		1	2	1x2	2 $(1.52\ E11)^{-1}$ (3.095^{-1}) ***
1	soil organic carbon loss	1.68 E09 *	3.10 E04	5.24 E13	111.38
2	minerals – loss				
	phosphorus P	2.99 E10 *	2.20 E02	6.60 E12	14.00
	potassium K	2.92 E09 *	7.00 E02	2.00 E12	4.25
	nitrogen N	7.73 E09 *	7.80 E03	6.00 E13	127.54
	magnesium Mg	6.14 E09 **	3.90 E01	2.40 E11	0.51
	total N			1.20 E14	257.68

* source transformity Odum 2000; ** source transformity Brown *et. al*. 2007; *** dollar exchange rate according to NBP rate table 25/A/NBP/2014.

RESULTS AND DISCUSSION

Annual cost of environmental work, not included in economic balance, in production of 376 kg of collected biomass in the form of hay of energy plant miscanthus giganteus was 314 $ for the analysed system. As much as 257.68 $ was contributed by non-renewable soil-related resources, while 56.68 $ was contributed by renewable energy sources. The economic value of the obtained material estimated in a traditional way according to market prices of agro biomass for an energy crop in 2013 is 43.35 $. The cost of natural environment's work contributed to produce 1GJ of energy of renewable biomass from miscanthus in the model cultivation in 2013 was 58 $. Primary environmental energy, of low quality but huge resources whose usage was initiated for the purpose of this cultivation, was transported with the environment's work to a higher energy concentration level.

The diagram in Fig. 2 presents a summary of emergy flows in the analysed ecosystem. The analysed cultivation consumed 14.67 E13 sej over a year to produce 5.42 E09 J of energy.

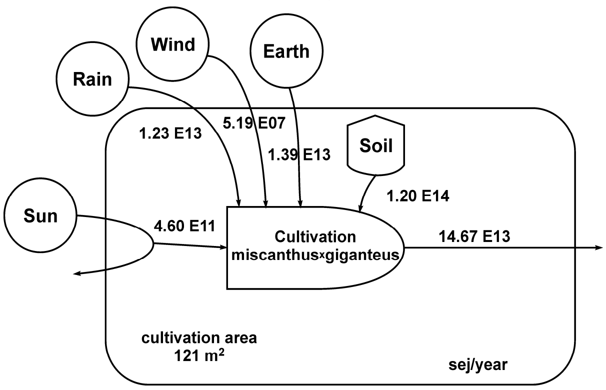

Fig. 2. Diagram showing emergy flow through the system of the model *miscanthus×giganteus* cultivation. The total emergy stream is 14.67 E13 sej year

The environment renewability rate (%R) obtained for the analysed system was 18.16%, which means that almost 82% of emergy used up by the cultivation is non-renewable. The activity of miscanthus cultivation caused environmental stress (ELR). Collected biomass upset the balance of the environment and impoverished it. Introduction of mineral and organic nutrients next year will improve the stability of the system. Systems of higher renewability level are also more durable (Brown and Ulgati 2004, Lefroy and Rydberg 2003) which suggests that the balance of the cultivation's ecosystem was disturbed considerably. The analysed system had not been supported by human activity in any possible way in previous years. The biomass produced by the environment was collected each year. All environmental indices calculated are compiled in Table 11.

Table 11. Index values used in environmental accounting for model cultivation

Index	Value	Unit
Y = R+N	14.67 E13	sej $year^{-1}$
Tr = Y/E	2.71 E04	sej J^{-1}
%R = 100 (R)/Y	18.16	%
ELR = N/R	4.49	–
$U_N = y_N /Y$	0.41	–
$U_C = y_C /Y$	0.357	–
$U_{(rain)} = y_{(rain)}/Y$	0.078	–
$U_{(geotherm)} = y_{(geotherm)}/Y$	0.095	–
EER = Y/(($) (sej/$))	1.73	–

The value of 4.49 obtained for the environmental load index (ELR) is comparable to ELR of similar production systems of 2.49-5.63 (Brown and Ulgiati 2004, Ulgiati *et al*. 1994). When ELR falls below 2, the environment is able to cover the system's emergy demand. When the index falls within the range of 3-10, the influence of the model cultivation on the environment is moderate. ELR values above 10 show that the system's effect on the environment is severe and if too large amounts of non-renewable energy are taken from the environment, resources may become degraded.

Also the shares of individual emergy streams in environmental work for the purpose of renewable biomass production were assessed. Nitrogen compounds, converted to total nitrogen, had the largest share of 41%. A share of circa 35% was related to organic carbon emergy stream, 7.8% to rain emergy and evapotranspiration processes, while 9.5% was related to the geothermal heat emergy stream. The shares of other emergy streams totalled 6.7%.

SUMMARY

Emergy analysis based on primary energy calculation shows how far solar energy has been transformed through a series of subsequent process into the output form of energy. In the analysed system annual amount of solar energy consumed by the model cultivation in 2013 totalled 1.47 E14 sej. The basic energy supply was provided by rain energy of 1.15 E13 sej and geothermal heat energy stream of 1.39 E13 sej within renewable resources and by non-renewable energy resources of 1.2 E14 sej. Transformity of the whole system was 2.71E04 sej J^{-1} and this value is comparable to results for biomass obtained by other researchers (Cohen *et al*. 2006) for systems which did not undergo any work. Low transformity proves high effectiveness in the use of energy which the system was supplied with. In order to obtain 1 J of energy accumulated in biomass of miscanthus giganteus, the environment performed work equal to 27100 sej.

The environment's added value not included in the economic balance was 314 \$ $year^{-1}$. The knowledge of the actual value of biomass based on the environment's biophysical work is useful in the assessment of system's stability, especially of the loss of natural resources (Cohen *et al*. 2006) in the form of mineral compounds or organic content, which was showed by a very low level of renewability index that proves excessive and unsustainable exploitation of the environment. In order to maintain the environment on a similar level the system would have to be supported by replacement of work performed by the natural environment with an artificial substitute for a year and provide at least a sum equal to the energy supplied.

Emergy analysis also allows early identification of processes that have negative effects on environmental balance and identification of parameters that change under environmental stress before the system becomes irretrievably degraded. System emergy assessment aims at providing additional information that is not usually perceived and taken into consideration in many environmental assessments but may appear helpful in sustainable use and management of environmental resources.

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ENERGETYCZNA OCENA UPRAWY *MISKANTHUS×GIGANTEUS* W OPARCIU O ENERGETYCZNĄ TEORIĘ WARTOŚCI H.T. ODUMA

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Streszczenie. Przedmiotem analizy emergetycznej był system środowiskowy modelowej uprawy rośliny energetycznej *miskanthus×giganteus*. Do oceny wkładu pracy środowiska na rzecz uprawy odnawialnej biomasy zastosowano energetyczną teorię wartości (ETW) stworzoną przez Howarda T. Oduma, łączącą zasady termodynamiki, ekologii i ekonomii za pomocą jednej jednostki miary – emergii. Koncepcja emergii opiera się na stopniu przetwarzania energii między poszczególnymi elementami ekosystemu oraz odzwierciedla ona różnice w jakości między różnymi formami i strumieniami bilansowanej energii. Dla systemu określono przepływy energii i materiałów między środowiskiem a modelową uprawą. Analiza emergii pozwoliła ocenić wszystkie wyróżnione strumienie zasilające analizowany system, a zwłaszcza te, które klasyczna ekonomia pomija z uwagi na niewycenialność lub powszechną dostępność. ETW opierając swoje założenia na transformacji i przekształceniu podstawowej energii słonecznej zasilającej wszystkie układy w cyklu życia naszej planety, stwarza możliwość oceny rzeczywistych kosztów środowiskowych. Celem określenia i rozważenia wartości środowiska w procesie tworzenia biomasy przeprowadzono badania podstawowe dla modelowej uprawy miskanta, w zakresie analizy elementarnej zebranej biomasy oraz gleby. Dokonano próby wyceny pracy środowiska na rzecz odnawialnego źródła energii w postaci biomasy. Wyniki wykazały, że największy udział w tworzeniu biomasy miała emergia składników gleby. Odnawialność analizowanego systemu kształtowała się na poziomie 18%, co świadczy o dużej nietrwałości systemu. Osiemdziesiąt dwa procent wkładu środowiska w budowę odnawialnej biomasy stanowią źródła nieodnawialne, co w krótkim terminarzu skutkować może degradacją lokalnego ekosystemu. Uprawa wymaga zasilenia w podstawowe składniki celem przywrócenia równowagi w środowisku. Koszt pracy środowiska, nieuwzględniany przez człowieka, wyniósł około 314 $ na rok.

Słowa kluczowe: energetyczna teoria wartości, biomasa, *miskanthus*×*giganteus*, emergia, transformity