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Carbon Footprint Determination When Using Residual Agricultural Biomass for Energy Production

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Abstract: At present, the focus is on distributed energy generation with low or negative carbon emissions as well as high conversion yields. In Romania, the renewable energy resource that can be used and produced when and wherever necessary is residual agricultural biomass with a potential of 31 million tons, which can produce over 40% of the national energy demand. Residual agricultural biomass is produced with an average energy efficiency of 6 kWh·bm/kWh input. The CHAB (combined heat and biochar production) concept produces high yield thermal energy as well as BC (biochar) with an average carbon footprint of 140 kg/ton biomass. If the energy produced is used to produce agricultural output, the negative carbon footprint increases by reducing the consumption of fossil fuels. It increases energy independence, the safety of agricultural production, the number of jobs, and regional economic development.

Key words: Waste biomass, energy, BC, CHAB, carbon footprint.

1. Introduction

Agriculture has been and remains the main source of raw materials for food and industrialization. The concept of sustainable development and evidence of climate change tends to tackle the issue of adapting efficient and sustainable agricultural production technologies to humanity in order to provide food for an ever-growing population fed by a declining global agricultural area.

Sustainable development of agriculture also involves increasing the energy independence of agricultural farms by reducing fossil fuel consumption, increasing and maintaining productive soil capacity, and reducing use of mineral fertilizers in favor of compost, which is linked to current ecological requirements and leads to the need to increase the level of use of residual biomass resulting from agricultural crops [1, 2].

At present, direct biomass burning, chopped, briquetted or pelletized is the majority procedure. As an alternative to current methods of thermal energy production from biomass, it is proposed the CHAB (combined heat and biochar production) concept which also includes the BC (biochar) generation. BC is a sterile organic material obtained from biomass pyrolysis in an oxygen-free environment or with a controlled gasification, with a neutral or alkaline pH. It has a carbon content of 75-90% and is characterized by high porosity and adsorption capacity [2, 4].

BC is used to improve the long-term fertility of agricultural soils, and secondarily as a filtering agent for air, gas and water. Built in soil, it is the most economical and ecological way of sequestering at least 25% of carbon, for extended periods between 100 and 1,000 years; it also has many other applications in the most diverse fields of human activity [3, 5, 6].

In order to evaluate how the waste biomass can be efficiently exploited, an energy balance and carbon mass analysis will be carried out, from which the carbon footprint can be calculated to determine the useful energy produced, and to create a base analysis and optimization of variants and energy conversion regimes.

In nature, spontaneous vegetation uses solar energy, carbon dioxide (CO_2) and soil fertility to produce a vegetal mass containing carbon Cb, which, through the natural carbon circuit, returns to the atmosphere.

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Vegetable crop production has as its main product a biomass destined for human and zootechnical consumption, which we call food biomass, as well as a by-product called waste biomass (Fig. 1). Solar energy, carbon dioxide (CO_2) in the atmosphere, soil fertility, as well as *E*cons energy consumed to carry out agricultural works contribute to the achievement of vegetal agricultural production. This produces an energy accumulation in agricultural products—*E*bal in the main product and Ebr in the wast biomass [7].

The efficiency of agricultural production is determined by the ratio of energy at exit *E*b and that of input *E*cons. Therefore energy efficiency is calculated with Eq. (1):

$$EFEN = \frac{Eb}{Econs} = \frac{Ebal + Ebr}{Econs} \quad (1)$$

Table 1 presents the energies produced and consumed for the main agricultural crops as well as the total energy efficiency EFEN, the main EFENp and the secondary EFENs [7].

It is noted that most of the agricultural production has an EFEN > 1 overall efficiency and many crops also have an EFENs secondary efficiency of more than 3, which confirms the conclusion that the agricultural crop production is also producing renewable energy with low costs and with a reduced CFPf (carbon footprint) [7].

Biomass produced has an Etotal energy for which Econs was consumed from fossil fuels. It is assumed that the fuel used is diesel fuel having a CFPf = 0.0815 kg/kWh footprint for base energy. The overall diesel fuel efficiency is estimated at $\eta_f = 0.864$, which results in a positive footprint in the CFPatm atmosphere (kg·C/kWh) for residual biomass:

$$CFPatm = \frac{1}{EFEN}\frac{CFPf}{\eta_f} = 0.0944 \quad (2)$$

Since for the production of Econs fossil fuels are consumed in the atmosphere, a quantity of *C*f0 = *E*cons·CFPf is released.

Table 1 presents the energy efficiency values for the main crops in Romania. It is noticed that the majority of agricultural crops produce residual biomass with an EFENs >> 0, so they are economically and

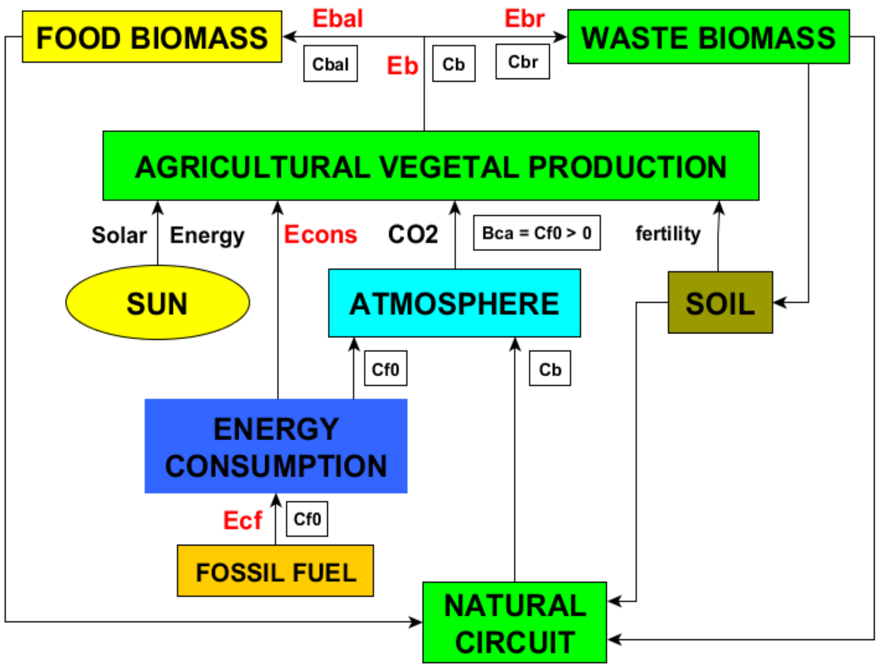

Fig. 1 Agricultural crop production general model.

Table 1 Energies produced, consumed and energy efficiency for the main agricultural crops.

Crops	Energy produced			Energy consumed	Energetic efficiency		
	*E*total	*E*bal	*E*br	*E*cons	EFEN	EFENp	EFENs
	kWh/ha	kWh/ha	kWh/ha	kWh/ha			
Corn	91,029	41,054	49,975	5,163	17.63	7.95	9.68
Winter wheat	41,017	16,773	24,244	5,764	7.12	2.91	4.21
Beans	21,227	10,585	10,642	3,254	6.52	3.25	3.27
Sunflowers	19,807	4,970	14,837	4,982	3.98	1.00	2.98
Soy	29,517	18,550	10,967	4,643	6.36	3.99	2.36
Plum	23,981	12,775	11,206	12,833	1.87	1.00	0.87
Vineyard	17,547	8,381	9,167	16,028	1.09	0.52	0.57
Apple	22,372	14,467	7,906	17,383	1.29	0.83	0.45

Table 2 Carbon footprints and the utilization yields for the main fuels entering the energy production processes of the waste biomass.

Feature	Symbol	UM	Value	Notes
Diesel fuel foot print	CFPdf	kg·C/kWh	0.0815	
Corn stalk foot print	CFPbr	kg·C/kWh	0.0873	Corn stalk
Corn stalk pellets foot print	CFPcp	kg·C/kWh	0.0873	Corn stalk pellets
Carbon foot print for peleting	CFPcpr	kg·C/kWh	0.0082	
Syngas foot print [CFPsg]		kg·C/kWh	0.1059	From gasifier
Conversion yeld for diesel burning	Kconv·f	adim	0.864	
Conversion yeld for BM burning	Kconv·bm	adim	0.786	
Conversion yeld for syngas burning	Kconv·g	adim	0.746	
Global BM footprint	CFPbmu	kg·C/kWhu	0.112	
Global diesel footprint	CFPfu	kg·C/kWhu	0.095	
Global syngas footprint	CFPgu	kg·C/kWhu	0.142	

ecologically productive renewable energy resources, mainly the corn and wheat crops that offer biomass for pelleting. These aspects regarding the fruit cuttings and of the vines were presented in the works [2, 8]. Further analysis will be developed for corn crop, which has the highest energy efficiency, for pellets produced from corn stalks.

For the energy and carbon balance, Table 2 shows the carbon footprints and the utilization yields for the main fuels entering the energy production processes of the waste biomass: diesel fuel, corn stalk biomass, corn stalk pellets, biochar and syngas [3, 4, 9, 11].

From the calculation of the carbon footprint produced using the primary energy of the residual corn mass, taking into account the part of the carbon footprint due to the energy input at the system entry, it results that for 1 MWh of the residual corn stalk consumed 56.7 kWh at input with a carbon footprint of max. 4.623 kg·C/MWh.

2. Energy Conversion System with Burning Process

To perform the analysis, a model (Fig. 2) of a corn stalk pellet energy production system was designed using burning processes. The conversion of the energy biomass into useful energy is achieved with a biomass energy system block, which enters an Ecs.inp energy consisting of Ebre as a Kbe part of the pellet biomass that has been pelletized and a carbon content Cbre. To perform the conversion process, an Ecs.act power is also introduced with a CFPcons footprint.

The output energy Ecs.out consists of the energy emitted in Ecs.ev environment and a useful energy that can be divided: one *E*cs.c part can be consumed directly for the production of the vegetal agricultural production and another *E*cs.u that feeds the energy consumers external to the analyzed system. Part of the input energy, which represents the losses of *E*cs.ev, is

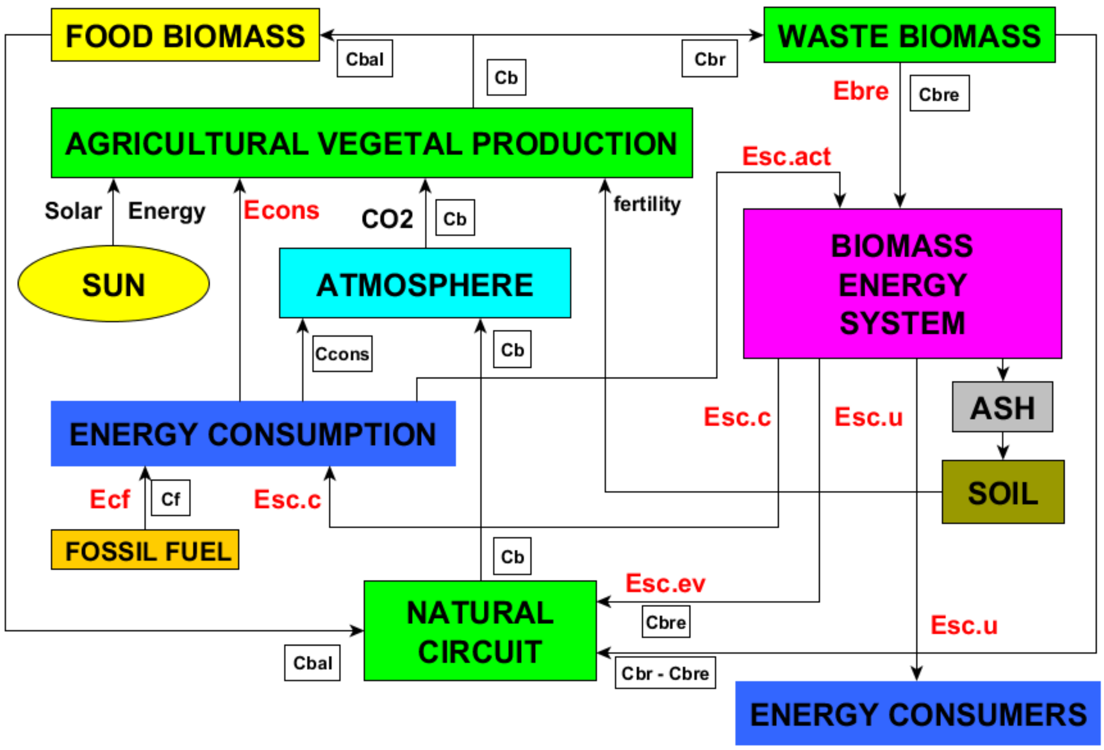

Fig. 2 Model of biomass energy system with burning process.

evacuated in the case of Cbre. Also comes the ASH without energy and carbon, which is incorporated into the soil.

The energy balance is:

$$\Delta Ebes = Ecs.inp - Ecs.out = 0 \tag{3}$$

Input energy is:

$$Ecs.inp = Ebre + Ecs.act \tag{4}$$

Energy for system consumption is:

$$Ecs.act = Ecs.pr + Ecs.ard + Ecs.he = Kact\cdot(Kbe\cdot Ebre) \tag{5}$$

where in the analyzed case, $Kact \approx 0.17$, resulting for Ecs.inp the relation:

$$Ecs.inp = Kbe\cdot Ebr + Kact(Kbe\cdot Ebr) = (1+Kact)(Kbe\cdot Ebr) \tag{6}$$

The output energies are: *Ecs*.ev—exhaust gas energy from the heat exchanger; *Ecs*.u—energy usable in external applications to the system; *Ecs*.c—energy consumed for the system by energy consumption. The energy relationship at the output is:

$$Ecs.out = Ecs.ev + (Esc.u + Ecs.c) = (1-\eta_{cs})Ecs.out + (Esc.u + Ecs.c) \tag{7}$$

$$where \quad \eta_{cs} = \eta_{pr}\cdot\eta_{ard}\cdot\eta_{he} = (1/1.1)\cdot 0.96\cdot 0.9 = 0.7855 \cong 0.78 \tag{8}$$

The energy *Ecs*.c consumed in the system is determined by the take-off *K*bc in the useful energy at the exit:

$$Ecs.c = Kbc(Ecs.out - Ecs.ev) = Kbc\cdot\eta_{sc}\cdot Ecs.inp = Kbc\cdot\eta_{sc}\cdot(1+Kact)Ebre = Kbc\cdot Kconv\cdot(Kbe\cdot Ebr) \tag{9}$$

$$where \quad Kconv = \eta_{sc}\cdot(1+Kact) \tag{10}$$

The carbon balance shows that since the carbon footprint for *Ecs*.c + *Ecs*.u is incorporated into the exhaust outlet, it follows that:

$$\Delta Cbes = Cbre - Csc.ev = 0 \quad (11)$$

It is noticed that Cbre re-enters the atmosphere through the combustion gases exhausted at the exchanger outlet. It follows that the carbon footprint for *E*cs.u and *E*cs.c is zero.

Another important block is the energy consumption subsystem. In block is the *E*cf energy produced from fossil fuels with Cf carbon content and *E*cs.c energy from the energy produced by the system with a zero footprint. The exit is *E*cons = cnt. used directly for agricultural crop production and *E*cs.act for the energy conversion system. The energy balance is:

$$\Delta Eec = (Ecf + Ecs.c) - (Econs + Ecs.act) = 0 \quad (12)$$

*E*cf energy from fossil fuels produces a positive carbon footprint.

$$Ecf = (Econs + Ecs.act) - Ecs.c$$

$$where \quad Econs = \frac{Etotal}{EFEN} \cong \frac{Ebr}{EFENs} \quad (13)$$

The carbon balance is:

$$\Delta Cec = Cf - Ccons = Ecf \cdot CFPf - Ccons = 0$$

$$and \quad Ccons = Cf \quad (14)$$

For atmosphere carbon balance is:

$$\Delta Catm = (Ccons + Cb) - Cb = Ccons \quad (15)$$

Carbon footprint in atmosphere is:

$$CFPatm = \frac{Ccons}{Econs + Ecs.c} =$$

$$\frac{Cf}{Ebr / EFENs + Ecs.c} = Ecf \frac{CFPf}{Ebr / EFENs + Ecs.c} \quad (16)$$

If we want to get a zero fingerprint, CFPatm = 0, then *E*cf = 0 and an *E*cs.c energy is required in the system with the value:

$$Ecs.c = Econs + Ecs.act =$$

$$Ebr / EFENs + Kact \cdot (Kbe \cdot Ebr) =$$

$$Ebr(1 / EFENs + Kact \cdot Kbe) \quad (17)$$

If an *E*cs.u useful power is required for applications, it is necessary to determine which *K*be quota of residual biomass to be harvested should be used.

$$Ecs.u = (1 - Kbc) \cdot Kconv \cdot (Kbe \cdot Ebr)$$

$$from\ where \quad Kbc = 1 - \frac{Esc.u}{Kconv \cdot (Kbe \cdot Ebr)} \quad (18)$$

$$Ecs.c = (1 - \frac{Esc.u}{Kconv \cdot (Kbe \cdot Ebr)}) \cdot Kconv \cdot (Kbe \cdot Ebr) =$$

$$Kconv \cdot (Kbe \cdot Ebr) - Esc.u \quad (19)$$

And using Eq. (9) results:

$$Ecs.c = Kconv \cdot (Kbe \cdot Ebr) - Esc.u =$$

$$Ebr(1 / EFENs + Kact \cdot Kbe) \quad (20)$$

It is shared with *E*br and it follows:

$$Kconv \cdot Kbe - Esc.u / Ebr =$$

$$1 / EFENs + Kact \cdot Kbe \quad (21)$$

In order to ensure the *E*cs.u value required for the *K*be harvested waste biomass, it must be greater than:

$$Kbe \geq \frac{1}{Kconv - Kact}\left(Kbu + \frac{1}{EFENs}\right)$$

$$where \quad Kbu = \frac{Esc.u}{Ebr} \quad (22)$$

Table 3 shows the values of the *K*be coefficient according to the *K*bu share of the energy demand.

Table 3 *K*be coefficient according to the *K*bu of the energy demand.

*K*bu	0.100	0.200	0.300	0.400	0.512
*K*be ≥	0.330	0.493	0.655	0.818	1.000

3. Energy Conversion System with CHAB Concept

As previously described, the application of the CHAB concept leads to the production of energy and biochar. Fig. 3 presents a model for a system that produces bio-fuel and energy from pyrolysis or gasification processes from residual biomass [2, 4, 9, 10, 12].

Tables 4 and 5 show the energies and carbon content of the input and output products.

The model shown in Fig. 3 has a biochar output with *C*bch carbon content and contains an *E*bch energy.

For energy from biomass CHAB system energy balance is:

$$\Delta Ebes = Ecs.inp - Ecs.out = 0 \tag{23}$$

Input energy is:

$$Ecs.inp = Ebre + Ecs.act \tag{24}$$

$$Ecs.inp = Kbe \cdot Ebr + Kact(Kbe \cdot Ebr) = (1 + Kact)(Kbe \cdot Ebr) \tag{25}$$

The relationship for the output energy is:

$$Ecs.out = Ecs.ev + (Esc.u + Ecs.c) + Ebch = (1 - \eta_{cs})(Ecs.out - Ebch) + (Esc.u + Ecs.c) + Ebch \tag{26}$$

Because at the carbon balance the carbon footprint for *E*cs.c + *E*cs.u is included in the exhaust outlet it results that:

$$\Delta Cbes = Cbre - (Csc.ev + Cbch) = Cbre - (Csc.ev + Kbch \cdot Cbre) = 0 \tag{27}$$

$$Csc.ev = Cbre(1 - Kbch) \tag{28}$$

In this case for atmosphere carbon balance is:

$$\Delta Catm = (Ccons + Cb - Cbch) - Cb = Ccons - Cbch \tag{29}$$

Table 4 Energies and carbon content of the input products.

Feature	UM	Corn stalks pellets	Biochar	Pyrolysis gas
Relative masse	real	1.00	0.237	0.763
Carbon	real	0.4053	0.7267	30.55
Oxygen	real	0.3905	0.489	49.66
Hydrogen	real	0.0540	0.0126	6.69
Ash	real	0.0502	0.2118	0
Humidity	real	0.10	0.00	13.11
L.H.V	MJ/kg	14.98	25.60	11.68
Carbon content	%	100	42.0	58.0
Energy content	%	100	40.50	59.50
CO_2 footprint	kg·CO_2/kWh	0.357	0.375	0.345
Carbon footprint	kg·C/kWh	0.097	0.102	0.094

Table 5 Energies and carbon content of the output products.

Feature	UM	Corn stalks pellets	Biochar	Gasified biomass
Relative masse	real	1.00	0.157	0.843
Carbon	real	0.4053	0.6316	0.3632
Oxygen	real	0.3905	0.032	0.4573
Hydrogen	real	0.054	0.0167	0.0609
Ash	real	0.0502	0.3197	0
Humidity	real	0.100	0.00	0.1186
L.H.V	MJ/kg	14.98	20.20	14.01
Carbon content	%	100	21.17	78.83
Energy content	%	100	24	76
CO_2 footprint	kg·CO_2/kWh	0.357	0.413	0.342
Carbon footprint	kg·C/kWh	0.097	0.113	0.093

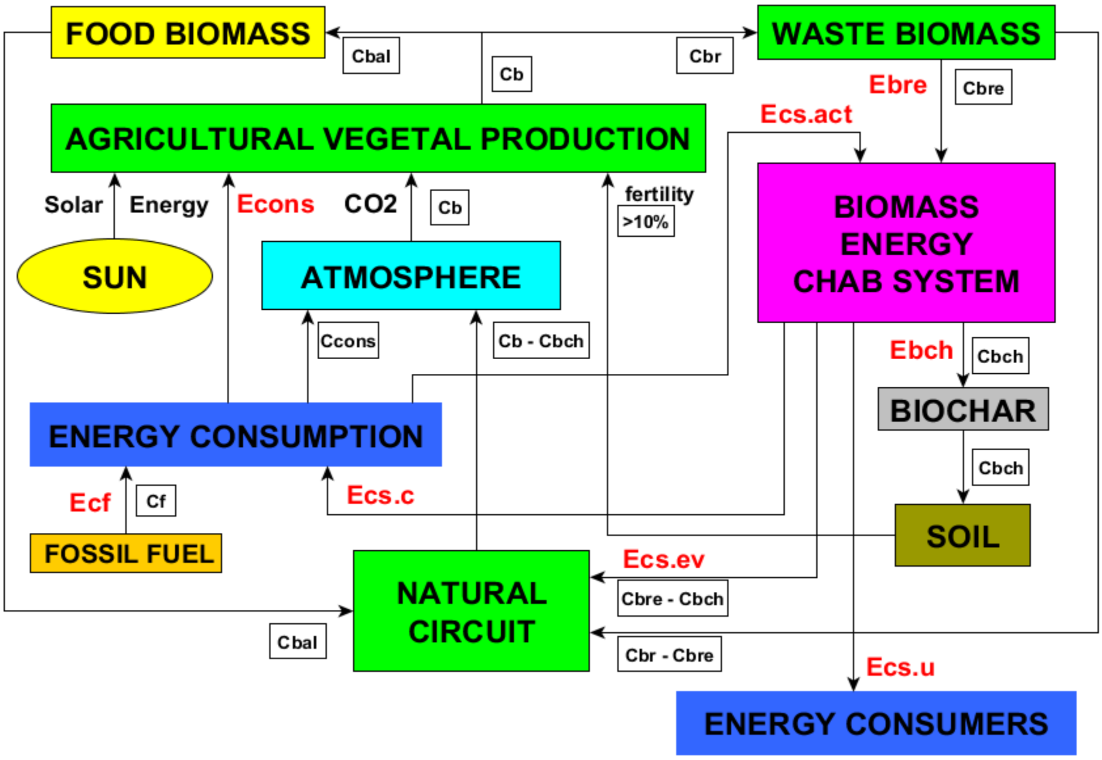

Fig. 3 Model of biomass energy system with CHAB concept.

Carbon footprint in atmosphere is:

$$CFPatm = \frac{Ccons - Cbch}{Ecf + Ecs.c} = \frac{Cf - Kbch \cdot Cbre}{Ecf + Ecs.c} =$$

$$\frac{Ecf \cdot CFPf - Kbch \cdot (Kbe \cdot Ebr) \cdot CFPbm}{Ecf + Ecs.c} \quad (30)$$

Two situations are analyzed: CFPatm = 0 or, for *Ecf* = 0, is obtained CFPatm < 0.

For condition CFPatm = 0:

$$Ecf \cdot CFPf - Kbch \cdot (Kbe \cdot Ebr) \cdot CFPbm = 0 \quad (31)$$

If *Ecs.c* = 0 of the balance results *Econs* = *Ecf*.

$$(Ebr / EFENs) \cdot CFPf -$$

$$Kbe \cdot (Kbch \cdot CFPbm) \cdot Ebr = 0 \quad (32)$$

To meet this condition, you must:

$$Kbe = \frac{CFPf}{CFPbm} \cdot \frac{1}{Kbch \cdot EFENs} \quad (33)$$

For gasification results $Kbe_g \geq 0.44$, and for pyrolysis $Kbe_p \geq 0.23$. When using gasification, more energy is available for external applications.

If the system energy *Ecs.c* ≈ *E*br/EFENs covers the energy requirement it results that *Ecf* = 0 and the carbon footprint is negative:

$$CFPatm = -\frac{Kbch \cdot (Kbe \cdot Ebr) \cdot CFPbm}{(Ebr / EFENs)} =$$

$$-Kbch \cdot Kbe \cdot CFPbm \cdot EFENs \quad (34)$$

For *K*be = 0.67 with gasification $CFPatm_g = -0.124$, and with pyrolysis $CFPatm_p = -0.814$. Pyrolysis has to be noted the high negative value of the footprint, but there is a very little energy for the outside.

4. Conclusions

(1) Original models for energy conversion systems of agricultural waste biomass were developed by burning, pyrolysis and gasification processes, for the determination of energy and carbon balance, as well as

of the carbon footprint in the atmosphere. A power conection of vegetable production with energy generated by the system has been introduced to reduce positive carbon footprint.

(2) The models were used to determine the regimes where the carbon footprint can be reduced to zero in the combustion process for different levels of useful energy needed for other applications.

(3) The simulation was performed for residual biomass from corn with the highest total energy efficiency EFEN = 17.63 and the energy-producing biomass for EFENs = 9.68. An energy use factor $K\mathrm{be} \in (0, 1)$ was used.

(4) In the system with burning process if 50% of the harvested residual biomass is used, for a zero footprint, is obtained useful energy for other thermal applications of about 80% of the biomass used.

(5) In system with gasification process for zero carbon footprint is necesary $K\mathrm{be}_g \geq 0.44$, and for a $K\mathrm{be}_g= 0.67$ is a negative footprint $\mathrm{CFPatm}_g = -0.124$ kg·C/kWh, relatively small, less biochor is obtained but available more power for other applications.

(6) In system with pyrolysis process for zero carbon footprint is necesary $K\mathrm{be}_p \geq 0.44$, and for a $K\mathrm{be}_p = 0.67$ is a negative footprint $\mathrm{CFPatm}_p= -0.814$ kg·C/kWh, is a remarkable value due to the production of more biochar with a higher content of carbon.

(7) Developed models are a useful tool for the design of energy conversion systems for biomass in general and especially for agricultural waste biomass. It is a very useful tool in the development of automated control systems, both as structure and optimal control algorithms.

(8) Economic aspects will also be attached to become the most complete tool for developing biomass energy conversion systems.

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