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 (CO₂) and soil fertility to produce a vegetal mass containing carbon Cb, which, through the natural carbon circuit, returns to the atmosphere.
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 (CO₂) in the atmosphere, soil fertility, as well as Econs energy consumed to carry out agricultural works contribute to the achievement of vegetal agricultural production. This produces an energy accumulation in agricultural products—Eb in the main product and Ebr in the waste biomass [7].

The efficiency of agricultural production is determined by the ratio of energy at exit Eb and that of input Econs. 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:

\[
\text{CFP}_{\text{atm}} = \frac{1}{EFEN} \times \frac{\text{CFP}_f}{\eta_f} = 0.0944 \quad (2)
\]

Since for the production of Econs fossil fuels are consumed in the atmosphere, a quantity of \( C_{\text{f0}} = E_{\text{cons}} \cdot \text{CFP}_f \) 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.](image-url)
Table 1  Energies produced, consumed and energy efficiency for the main agricultural crops.

| Crops      | $E_{total}$ | $E_{bal}$ | $E_{br}$ | $E_{cons}$ | 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 | CFPpr | kg·C/KWh | 0.0082 |          |
| Syngas foot print [CFPsg] |         | kg·C/kWh | 0.1059 | From gasifier |
| Conversion yield for diesel burning | Kconv-f | adim | 0.864 |          |
| Conversion yield for BM burning | Kconv-bm | adim | 0.786 |          |
| Conversion yield for syngas burning | Kconv-g | adim | 0.746 |          |
| Global BM footprint      | CFPbm   | kg·C/KWhu | 0.112  |          |
| Global diesel footprint  | CFPfu   | kg·C/KWhu | 0.095  |          |
| Global syngas footprint  | CFPgu   | kg·C/KWhu | 0.142  |          |

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 pelleted 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 Ecs.c part can be consumed directly for the production of the vegetal agricultural production and another Ecs.u that feeds the energy consumers external to the analyzed system. Part of the input energy, which represents the losses of Ecs.ev, is...
evacuated in the case of Cbre. Also comes the ASH without energy and carbon, which is incorporated into the soil.

The energy balance is:

\[ \Delta E_{bes} = E_{cs}^{inp} - E_{cs}^{out} = 0 \]  \hspace{1cm} (3)

Input energy is:

\[ E_{cs}^{inp} = E_{bre} + E_{cs}^{act} \]  \hspace{1cm} (4)

Energy for system consumption is:

\[ E_{cs}^{act} = E_{cs}^{pr} + E_{cs}^{ard} + E_{cs}^{he} = K_{act} \cdot (K_{be} \cdot E_{bre}) \]  \hspace{1cm} (5)

where in the analyzed case, \( K_{act} \approx 0.17 \), resulting for \( E_{cs}^{inp} \) the relation:

\[ E_{cs}^{inp} = K_{be} \cdot E_{bre} + K_{act}(K_{be} \cdot E_{bre}) = (1 + K_{act})(K_{be} \cdot E_{bre}) \]  \hspace{1cm} (6)

The output energies are: \( E_{cs}^{ev} \)—exhaust gas energy from the heat exchanger; \( E_{cs}^{u} \)—energy usable in external applications to the system; \( E_{cs}^{c} \)—energy consumed for the system by energy consumption. The energy relationship at the output is:

\[ E_{cs}^{out} = E_{cs}^{ev} + (E_{cs}^{u} + E_{cs}^{c}) = (1 - \eta_{cs})E_{cs}^{out} + (E_{cs}^{u} + E_{cs}^{c}) \]  \hspace{1cm} (7)

where \( \eta_{cs} = \eta_{pr} \cdot \eta_{ard} \cdot \eta_{he} = (1/1.1) \cdot 0.96 \cdot 0.9 = 0.7855 \approx 0.78 \)  \hspace{1cm} (8)

The energy \( E_{cs}^{c} \) consumed in the system is determined by the take-off \( K_{bc} \) in the useful energy at the exit:

\[ E_{cs}^{c} = K_{bc}(E_{cs}^{out} - E_{cs}^{ev}) = K_{bc} \cdot \eta_{sc} \cdot E_{cs}^{inp} = K_{bc} \cdot \eta_{sc} \cdot (1 + K_{act})E_{bre} = K_{bc} \cdot K_{conv} \cdot (K_{be} \cdot E_{bre}) \]  \hspace{1cm} (9)

where \( K_{conv} = \eta_{sc} \cdot (1 + K_{act}) \)  \hspace{1cm} (10)

The carbon balance shows that since the carbon footprint for \( E_{cs}^{c} + E_{cs}^{u} \) is incorporated into the exhaust outlet, it follows that:
\[ \Delta Cbes = Cbre - Csc.ev = 0 \]  

(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 Ecs.u and Ecs.c is zero.

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

\[ \Delta Eec = (Ecf + Ecs.c) - (Econs + Ecs.act) = 0 \]  

(12)

Ecf energy from fossil fuels produces a positive carbon footprint.

\[ Ecf = (Econs + Ecs.act) - Ecs.c \]

where \[ Econs = \frac{E_{total}}{EFEN} \approx \frac{Ebr}{EFENs} \]  

The carbon balance is:

\[ \Delta C_{ec} = Cf - Ccons = Ecf \cdot CFpf - Ccons = 0 \]

\[ and \quad Ccons = Cf \]  

(14)

For atmosphere carbon balance is:

\[ \Delta C_{atm} = (Ccons + Cb) - Cb = Ccons \]  

(15)

Carbon footprint in atmosphere is:

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

\[ \frac{Cf}{Ebr / EFENs + Ecs.c} = Ecf \cdot CFpf \frac{1}{Ebr / EFENs + Ecs.c} \]

(16)

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

\[ Ecs.c = Econs + Ecs.act = \]

\[ Ebr / EFENs + Kact \cdot (Kbe \cdot Ebr) = \]

\[ Ebr \left( \frac{1}{EFENs} + Kact \cdot Kbe \right) \]  

(17)

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

\[ Ecs.u = (1 - Kbe) \cdot Kconv \cdot (Kbe \cdot Ebr) \]

from where \[ Kbe = 1 - \frac{Esc.u}{Kconv \cdot (Kbe \cdot Ebr)} \]  

(18)

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

\[ Kconv \cdot (Kbe \cdot Ebr) - Escu \]  

(19)

And using Eq. (9) results:

\[ Ecs.c = Kconv \cdot (Kbe \cdot Ebr) - Escu = \]

\[ Ebr \left( \frac{1}{EFENs} + Kact \cdot Kbe \right) \]  

(20)

It is shared with Ebr and it follows:

\[ Kconv \cdot Kbe - Escu / Ebr = \]

\[ 1 / EFENs + Kact \cdot Kbe \]  

(21)

In order to ensure the Ecs.u value required for the Kbe harvested waste biomass, it must be greater than:

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

where \[ Kbu = \frac{Esc.u}{Ebr} \]  

(22)

Table 3 shows the values of the Kbe coefficient according to the Kbu of the energy demand.

| Kbu  | 0.100 | 0.200 | 0.300 | 0.400 | 0.512 |
|------|-------|-------|-------|-------|-------|
| Kbe  | 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\textsubscript{bch} carbon content and contains an E\textsubscript{bch} energy.

For energy from biomass CHAB system energy balance is:

\[
\Delta E_{bes} = E_{cs.inp} - E_{cs.out} = 0 \tag{23}
\]

Input energy is:

\[
E_{cs.inp} = E_{br} + E_{cs.act} \tag{24}
\]

\[
E_{cs.inp} = K_{be} \cdot E_{br} + K_{act}(K_{be} \cdot E_{br}) = (1 + K_{act})(K_{be} \cdot E_{br}) \tag{25}
\]

The relationship for the output energy is:

\[
E_{cs.out} = E_{cs.ev} + (E_{cs.u} + E_{cs.e}) + E_{bch} = (1 - \eta_{es})(E_{cs.out} - E_{bch}) + (E_{cs.u} + E_{cs.e}) + E_{bch} \tag{26}
\]

Because at the carbon balance the carbon footprint for E\textsubscript{cs.e} + E\textsubscript{cs.u} is included in the exhaust outlet it results that:

\[
\Delta C_{bes} = C_{br} - (C_{cs.ev} + C_{bch}) = C_{br} - (C_{cs.ev} + K_{be} \cdot C_{br}) = 0 \tag{27}
\]

\[
C_{cs.ev} = C_{br}(1 - K_{be}) \tag{28}
\]

In this case for atmosphere carbon balance is:

\[
\Delta C_{atm} = (C_{cons} + C_{b} - C_{bch}) - C_{b} = C_{cons} - C_{bch} \tag{29}
\]

| 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\textsubscript{2} footprint | kg\cdot CO\textsubscript{2}/kWh | 0.357 | 0.375 | 0.345 |
| Carbon footprint | kg\cdot 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 | 0.10 | 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\textsubscript{2} footprint | kg\cdot CO\textsubscript{2}/kWh | 0.357 | 0.413 | 0.342 |
| Carbon footprint | kg\cdot C/kWh | 0.097 | 0.113 | 0.093 |
Carbon footprint in atmosphere is:

\[ CFP_{atm} = \frac{C_{cons} - C_{bch}}{E_{cf} + E_{cs.c}} = \frac{C_f - K_{bch} \cdot C_{bre}}{E_{cf} + E_{cs.c}} \]

Two situations are analyzed: \( CFP_{atm} = 0 \) or, for \( E_{cf} = 0 \), is obtained \( CFP_{atm} < 0 \).

For condition \( CFP_{atm} = 0 \):

\[ E_{cf} \cdot CFP_f - K_{bch} \cdot (K_{be} \cdot E_{br}) \cdot CFP_{bm} = 0 \]

If \( E_{cs.c} = 0 \) of the balance results \( E_{cons} = E_{cf} \).

\[ (E_{br} / EFENs) \cdot CFP_f - K_{be} \cdot (K_{bch} \cdot CFP_{bm}) \cdot E_{br} = 0 \]

To meet this condition, you must:

\[ K_{be} = \frac{CFP_f}{CFP_{bm}} \cdot \frac{1}{K_{bch} \cdot EFENs} \]

For gasification results \( K_{be_g} \geq 0.44 \), and for pyrolysis \( K_{be_p} \geq 0.23 \). When using gasification, more energy is available for external applications.

If the system energy \( E_{cs.c} \approx E_{br} / EFENs \) covers the energy requirement it results that \( E_{cf} = 0 \) and the carbon footprint is negative:

\[ CFP_{atm} = -\frac{K_{bch} \cdot (K_{be} \cdot E_{br}) \cdot CFP_{bm}}{(E_{br} / EFENs)} = -K_{bch} \cdot K_{be} \cdot CFP_{bm} \cdot EFENs \]

For \( K_{be} = 0.67 \) with gasification \( CFP_{atm_g} = -0.124 \), and with pyrolysis \( CFP_{atm_p} = -0.814 \). 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
conception 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 \( EFEN_s = 9.68 \). An energy use factor \( K_{be} \in (0, 1) \) 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 necessary \( K_{be_g} \geq 0.44 \), and for a
\( K_{be_g} = 0.67 \) is a negative footprint \( CFPatm_g = -0.124 \)
kg C/kWh, relatively small, less biochar is obtained but
available more power for other applications.

(6) In system with pyrolysis process for zero carbon
footprint is necessary \( K_{be_p} \geq 0.44 \), and for a \( K_{be_p} = 0.67 \)
is a negative footprint \( CFPatm_p = -0.814 \) 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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