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Graphical Break-Even Based Decision-Making Tool (BBDM) to Minimise GHG Footprint of Biomass Utilisation: Biochar by Pyrolysis

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This study develops a graphical decision-making tool inspired by the break-even concept. It facilitates the selection of biomass utilisation where the highest possible profit and lowest GHG emissions indicate the optimal choice. The GHG intensity (kg CO_2eq/MWh) and GHG price (USD/kg CO_2eq) comprise the y-axis and x-axis of the Break-even Based Decision Making (BBDM) tool. The applicability of the tool is demonstrated by a case study where the biomass (switchgrass and wheat straw) is treated with slow pyrolysis for energy generation and/or biochar production. Burning for electricity is generally a preferable option, especially for countries with high GHG intensity. Biochar application as a form of carbon sequestration is suggested at low GHG intensity. This application becomes the preferred option when the GHG price is higher than 0.03 USD/kg CO_2eq for switchgrass and higher than 0.01 USD/kg CO_2eq for wheat straw. Wheat straw, as agricultural waste, has the advantage of lower GHG footprint while switchgrass offers a higher energy output. In general, the choice of the best use of biomass can be different under different circumstances. The developed tool is able to provide a rigorous basis for decision support when the GHG intensity and GHG price are defined.

1. Introduction

The energy sector is one of the main contributors to GHG and air pollutants footprints. Various measures have been proposed or implemented to tackle this environmentally sustainable issues. The energy transition is one of the pathways toward emission mitigation by minimising the dependency on fossil energy. IRENA (2019) suggests the increased use of renewable energy combined with intensified electrification are decisive for the world to meet key climate goals by 2050. Energy from biomass (bioenergy) is one of the most investigated options. However, there is still an ongoing debate (Sterman et al., 2018) on carbon neutrality or renewable characteristics. Mitigation alone is deemed insufficient to achieve the Paris Agreement target in addressing the global warming/climate change issues (Haszeldine et al., 2018). Negative emission technologies (NETs) have to be deployed within physical and economic limits (Smith et al., 2016). Negative emissions can also be achieved by implementation biochar-based carbon management networks (Tan, 2019), besides the various emissions capture technologies, which have a relatively lower risk and investment cost. Pyrolysis is one of the notable pathways for biomass utilisation as the outputs are bioenergy and biochar with sequestration function.
The economic and emission accounting for a sustainable biomass utilisation remains a challenge in decision making due to its dynamic nature (the selection highly depends on the baseline scenario) and still subject to uncertainty (biochar application, biogenic carbon of biomass). Kulas et al. (2018) conducted the techno-economic analysis and life cycle assessment (LCA) of biochar as a soil amendment, as feedstock to produce activated carbon, and as fuel to displaced coal. Activated carbon is identified as the biochar utilisation that provides the highest mitigation benefits than as an energy source. Brown et al. (2011) assess the profitability of two biochar production, the value of biochar as a carbon offset plays a significant role; slow pyrolysis with the substrate cost of 83 USD/t is identified as not profitable. Yang et al. (2016) assessed the GHG emission of biomass-based pyrolysis in China and suggested the GHG intensity as 1.55 x10^{-2} kg CO_2 eq./MJ. It is

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recommended that returning 41 % of biochar to the field would contribute to close to zero net GHG emissions. Fidel et al. (2019) studied GHG emissions when biochar ended on the soil. The differences in the results from laboratory incubation experiment and the impact of biochar at the field scale were highlighted as a pitfall. A meta-analysis by He et al. (2017) suggests biochar application significantly increased soil CO_2 fluxes by 22 % but decrease N_2O fluxes by 31 %. The selection of the baseline scenario, the definition of displaced energy (avoided emissions) and the current understanding of biochar effectiveness and scalability needs to be further assessed for a consensus. The energy displacement is always done in reference to a baseline that needs to be clearly defined as the avoided emissions can change with the energy transition. There is an underlying assumption that the energy is being displaced (by energy with lower intensity). However, in some cases, the generated energy is fulfilling incremental energy demand. The complexity of the bioenergy system and its indirect effect, the selection of the system function and system boundaries that directly affect the results obtained have been highlighted by Lijó et al. (2019). Despite the inconsistent results, data that are changing from time to time according to the technology development, GHG intensity as well as the carbon tax (in this study, termed GHG price), a systematic methodology is a key to facilitate the decision making.

To summarise, there has been plenty of economic and environmental assessments on the pyrolysis processes of different biomass types and the biochar utilisation. The consistency of the decision-making methodology needs improvement, and it is generally based on scenario analysis. A systematic decision-making tool which considers the impacts under different circumstances, preferably in graphical form, with the capability of identifying the optimal biomass utilisation deserves further development.

This study aims to propose a graphical decision-making tool in facilitating the selection of biomass treatment or utilisation. The novel contributions of this work include:

(i) A set of generic equations that form the basis for the decision-making tool, considering both the economic and life-cycle environmental footprint (in this case study GHG).

(ii) A novel graphical Break-even Based Decision-Making (BBDM) tool, where the environmental price (GHG) and the GHG intensity of energy are chosen to determine the suitable biomass utilisation. It is efficient in identifying the alternatives with the highest possible profit and lowest GHG emissions.

(iii) A pyrolysis case study of biomass, where two types of substrates (a) energy crop and (b) agricultural residue for energy and biochar production, are assessed to demonstrate the applicability of BBDM. BBDM is designed to be feasible in capturing the optimal utilisation under the dynamic change of GHG price and GHG intensity of energy.

The developed BBDM tool is not limited to the presented case study, but for a broader range of decision making. A similar concept can be applied to the selection of environmentally sustainable transportation modes. The extended application is further discussed in conclusion.

2. Methodology

This section presents the break-even relations that underpin the graphical decision-making tool as well as the algorithms for the construction. The break-even point in this context defines when two pyrolysis/biomass treatment processes (*i and j*) would generate equivalent profit, see Eq(1). GHG price is applied in order to identify a compromise solution for an economic-environmental decision as well as to reduce the multi-objective problem into a single objective. The total profit is defined as in Eq(2), $Profit_{economic}$ considers the earning from the selling of recovered products (energy and biochar) deducted by the operating cost of the entire life cycle, Eq(3). $Profit_{environment}$, defined in Eq(4), considers the GHG credit from recovering the energy and applying the biochar to the soil (sequestration) deducted by the emission released along with the processes which incur a penalty cost of GHG. Eqs(5) - Eq(7) show the estimation of GHG credit and GHG penalty incurred by the process. The independent variable is the “break-even” GHG price. Eq(8) shows the estimation of GHG price when the total profit of two pyrolysis processes are equal.

$$Profit_{total\,(i)} = Profit_{total\,(j)} \tag{1}$$

$$Profit_{total} = Profit_{economic} + Profit_{environment} \tag{2}$$

$$Profit_{economic} = Eenergy + Ebiochar - OC \tag{3}$$

Where $Eenergy$ are the earnings from recovered energy, $Ebiochar$ are the earnings from biochar, and OC is the operating cost

$$Profit_{environment} = Cenergy + Cbiochar - P_{op} \tag{4}$$

$$Cenergy = AmountRE \times CI \times GHG_{price} \quad (5)$$

$$Cbiochar = AmountB \times SF \times GHG_{price} \quad (6)$$

$$P_{op} = A_s \times O_{ef} \times GHG_{price} \quad (7)$$

Where $Cenergy$ is the GHG credit from the recovered energy, $Cbiochar$ is the GHG credit from the application of biochar, P_{op} is the GHG penalty by the operating process, $AmountRE$ is the amount of recovered or generated energy (syngas, bio-oil and or biochar) by the pyrolysis process of agricultural waste or energy crops, CI is the GHG intensity of energy (e.g. electricity power) where the emission is associated with electricity generation from identified regions based on the energy mix, GHG_{price}= is the cost coefficient (e.g. carbon emission tax, environmental price), $AmountB$ is the amount of biochar produced, SF is the carbon emission sequestration factor of biochar, A_s is the amount of substrate, O_{ef} is the emission factor of pyrolysis processes.
Eq(8) is applied to identify the break-even point/ boundary, where $Profit_{total\,(i)} = Profit_{total\,(j)}$. GHG_{price} is identified by varying the CI.

$$GHG_{price} = \frac{Eenergy_j + Ebiochar_j - OC_j - Eenergy_i - Ebiochar_i + OC_i}{AmountRE_i \times CI - P_{op,i} + AmountB_i \times SF - AmountRE_j \times CI - P_{op,j} + AmountB_j \times SF} \quad (8)$$

The generic steps to construct the graphical decision tool BBDM are as follows:

(i) Define the functional unit (can be based on carbon content, amount, e.g. 1 t or 1 ha of the substrate)

(ii) Define the assessed scenarios (e.g. different pyrolysis setting, type of substrate, the ratio of recovered products), system boundary and assumptions.

(iii) Collect the required data.

(iv) Define replaceable energy (Optional). $AmountRE$ in Eq(5) is equal to the replaceable energy if the recovered/generated energy from pyrolysis are all to displace the current energy generation practice. In some cases, the recovered energy is used to fulfil the increasing energy demand where the current energy generation practice (e.g. fossil fuel) is not being replaced. In this case, there is none or only a partial avoidance/unburdening emission ($AmountRE \times CI$).

(v) Apply the data to the Eq(8) to identify the GHG price.

(vi) GHG price is plotted on the y-axis, and GHG intensity of electricity serves as the x-axis. A graph of the reciprocal function ($y = \frac{1}{x}$ or $y = -\frac{1}{x}$) is obtained, see Figure 1.

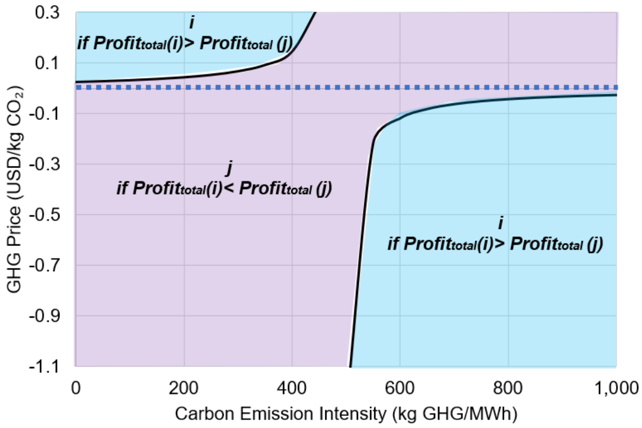

Figure 1: Generic example of the decision-making tool BBDM

(vii) Assign the area (label and colour). The identified border/line divides the space and suggests that under a given GHG intensity and the known GHG price, which accessed scenarios would the highest total profit (economic and environmentally). Figure 1 shows a generic example of the decision-making tool. The blue area is assigned to Case *i*, suggests Case *i* provided a high profit and lower emission than Case *j* in the blue area. The presented scale is adjusted by removing the area where GHG price < 0 (below the blue dotted line in Figure 1) as the GHG price is always ≥0.

3. Case study

The type of substrates/biomass, accessed in this study, are energy crops and agricultural residues. The selected treatment option is pyrolysis, specifically slow pyrolysis system. Figure 2 shows the overall framework of the case study. The emission released during the field operation, including the use of fertiliser for energy crops are considered in this case study.

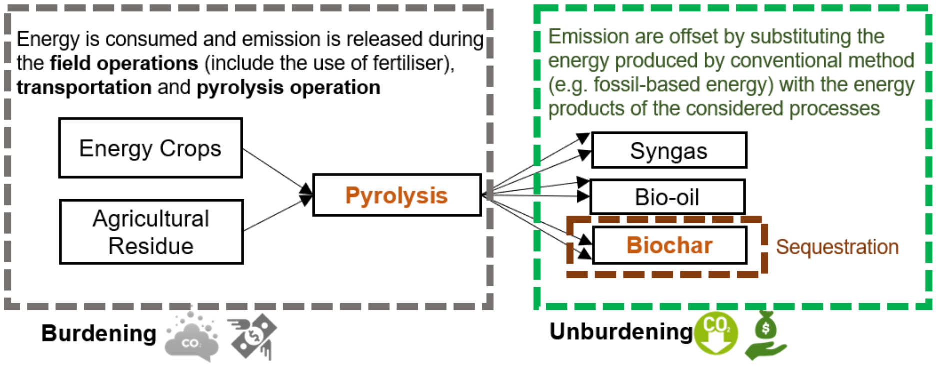

Figure 2: The overall assessment framework of the case study

Table 1 presents the assessed scenarios. The functional unit applied in this case study is 1 ha of the substrate (switchgrass or wheat straw). Table 2 shows the applied data. This study assumes all the recovered energy is qualified to replace the conventional energy generation rather than use to fulfil the increasing demand which is not eligible for avoided/unburdening emission accounting, see Section 2 Step iv. The second assumption is that there is available land which is suitable for biochar application. It should be noted that the graphical tool of this case study is based on the specification inputs reported by Gaunt and Lehmann (2008). In practice, localised data inputs are required to feed into the proposed methodology for a customised graphical tool and solutions.

Table 1: Scenarios description

Scenario	Description
1	Switchgrass (energy crop) + Pyrolysis optimised for energy (burn)
2	Switchgrass (energy crop) + Pyrolysis optimised for biochar (bury)
3	Wheat straw (agricultural residue) + Pyrolysis optimised for energy (burn)
4	Wheat straw (agricultural residue) + Pyrolysis optimised for biochar (bury)

Table 2: Data to construct a graphical decision-making tool. Extracted from Gaunt and Lehmann (2008)

	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Amount of electricity	MWh ha^{-1} y^{-1}	17.98	13.67	11.22	8.52
Operating cost	USD ha^{-1} y^{-1}	205.90	205.90	27.81	27.81
Emission from operating process	kg ha^{-1} y^{-1}	6.62	11.41	8.20	14.20
Sequestrated emission	kg ha^{-1} y^{-1}	-	3,768	-	2,119

Price of electricity = 22.4 USD MWh^{-1} and Price of biochar = 0.047 USD kg^{-1}

4. Results and discussions

Figure 3 shows the developed BBDM tool to compare (a) Scenario 1 and 2 as well as (b) Scenario 3 and 4. When there is no GHG charge (GHG price = 0), all the circumstances (energy crop or agricultural residue; small or large GHG intensity) suggest pyrolysis optimised for energy production. Burning the recovered products for energy provides a higher profit.

The selection shift to pyrolysis optimised for biochar production with the increase of GHG price (> 0.03 USD/kg CO_2eq for switchgrass, >0.01 USD/kg CO_2eq for wheat straw), where the biochar is applied to the soil (bury). The GHG price is essential to encourage the application of biochar for GHG footprint reduction. However, burning is preferable with increasing GHG intensity. This is due to the higher footprints offset by displacing the dirty electricity grid mix (higher GHG intensity) with energy generated from pyrolysis. The applicability of the developed tool for decision-making can be demonstrated by using Country A (200 g CO_2eq/kWh) and Country B (1,000 g CO_2eq/kWh) as an example, at GHG price of 0.025 USD/kg (Plumper and Popovich, 2019). Figure 3a suggests the switchgrass in Country A and B is more suitable for energy production (burn) in order to have a higher total profit (earnings from selling the energy and the GHG credit). Figure 3b suggests the wheat straw in Country A should be utilised for biochar production but energy generation for Country B. To encourage the production of biochar (bury) in Country B, as illustrated in Figure 3b, the GHG price have to be increased, e.g. to 0.04 USD/kg.

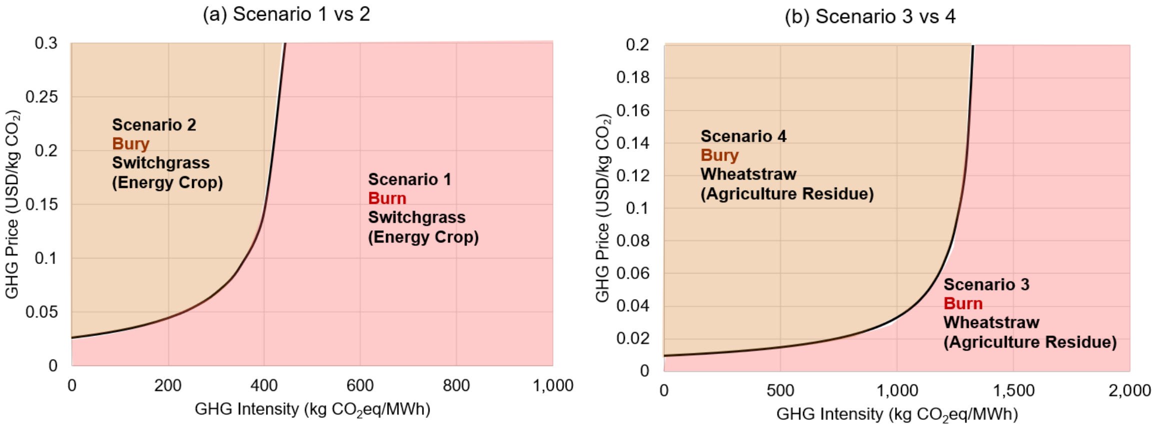

Figure 3: Graphical decision-making tool (burn or bury) for (a) Scenario 1 vs 2 and (b) Scenario 3 vs 4

Figure 4 shows the impact of substrate types to the break-even based decision-making tool. At 200 g CO_2eq/kWh (Country A), wheat straw is a better substrate for pyrolysis unless the GHG price is set to be higher than 0.02 USD/kg CO_2eq, see Figure 4a. Switchgrass, the dedicated biomass, has a higher net GHG footprint compared to wheat straw (agricultural residue) due to the burdening effect of field production in growing the switchgrass. However, switchgrass has a higher net GHG footprint with increasing GHG intensity, as reflected in Figure 4a (preferable options than wheat straw), due to the higher amount of energy from pyrolysis to displace the high GHG intensity energy mix.

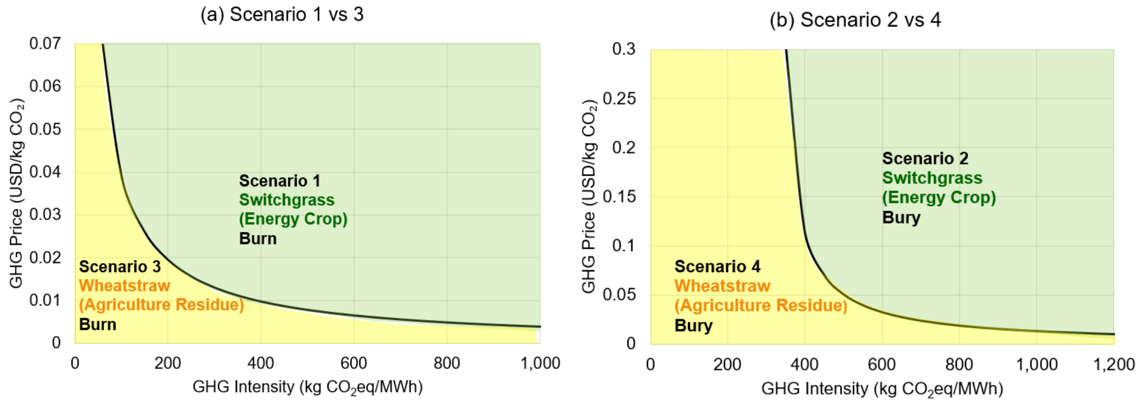

Figure 4: Graphical decision-making tool (types of substrate) for (a) Scenario 1 vs 3 and (b) Scenario 2 vs 4

5. Conclusions

The BBDM tool has been proposed as a means to determine the suitable biomass utilisation with highest possible profit and lowest GHG emission for a particular context with known GHG intensity and a defined GHG price. The tool provides rapid and effective decision support capability via an intuitive graphical display, in contrast to mathematical programming models. It is feasible for the comparison of different treatment options (e.g. gasification, pyrolysis and other waste to energy), technologies (pyrolysis in different setting e.g. temperature), utilisation (energy, soil amendment, activated carbon), types of substrate and useful to capture the impacts contributed by the changes of GHG intensity and GHG price. The results of the pyrolysis case study show that burn is generally a preferable decision (at GHG price = 0) especially with the increase of GHG intensity, for both switchgrass and wheat straw. At GHG intensity = 200 g CO_2eq/kWh and GHG price = 0.025 USD/kg, pyrolysis of wheat straw is suggested to be optimised for biochar production and application to the soil (bury). However, at GHG intensity = 1,000 g CO_2eq/kWh, pyrolysis of wheat straw is suggested to be optimised for energy generation unless the GHG price is increased, e.g. to 0.04 USD/kg. Future studies should consider (i) a better accounting framework of biogenic and non-biogenic carbon as carbon neutrality cannot be assumed for all biomass energy a priori (ii) additional footprints (e.g. NO_x, SO_2, particulate matter) (iii) land availability and suitability for biochar application to improve the fidelity of the decision tools. The BBDM tool has a broader potential and flexibility for an extended application in decision-making. The presented case study shows one of the applications (biomass utilisation/treatment) however the similar concept/foundation can be applied to the different field; for example, transportation modes and fuel selection by using load and distance as the axes. The BBDM tool transforms the treatment/utilisation selection problem into an easily understandable format from which arises sound solutions.

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