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THE USE OF WOOD FROM DEGRADED LAND FOR CARBON SEQUESTRATION

Wood and other biomass have the great potential of decreasing carbon dioxide emissions to the atmosphere, or at least mitigating the speed of the increase in the concentration of carbon dioxide. This paper presents an analysis of the possible use of degraded land – thermal power plant ash ponds – for the growth of fast-growing trees for fuel wood and the subsequent utilization of this fuel wood by means of a verified technique – co-combustion with coal, or a proposed technique – pyrolysis. Pyrolysis of wood with the combustion of pyrolysis gases and carbon sequestration would provide approximately 26% more favorable effects on climate change than the co-combustion of wood in a coal-fired boiler.

Keywords: wood, degraded land, co-combustion, pyrolysis, carbon dioxide

Introduction

In the context of climate change, developed countries are beginning to invest a great deal of effort in the research, development and realization of carbon sequestration techniques. All the techniques thus far implemented are energetically and economically demanding. However, the CO_2 concentration in the atmosphere is constantly rising.

Theoretical consideration leads to the conclusion, that biomass has a great potential to decrease carbon dioxide emissions to the atmosphere, or at least to mitigate the speed of the increase in the concentration of carbon dioxide. According to the Intergovernmental Panel on Climate Change (IPCC), between 1970 and 2004, global emissions of CO_2, CH_4, N_2O, HFCs, PFCs and SF_6, weighted by their global warming potential (GWP), increased by 70%, from 28.7 to 49 Gigatonnes of carbon dioxide

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equivalents ($GtCO_{2-eq}$). The emissions of these gases increased at different rates. CO_2 emissions grew by about 80% between 1970 and 2004 and represented 77% of the total anthropogenic GHG emissions in 2004 [IPCC 2007; Moss et al. 2007].

Various scenarios concerning the development of greenhouse gas concentrations in the atmosphere have been created [IPCC 2007]:
– “near-term” scenarios that cover the period up to 2035
– “long-term” scenarios that cover the period up to 2100 and
– “extended-term” up to 2300.

The largest growth in global GHG emissions between 1970 and 2004 came from the energy supply sector (an increase of 145%) [IPCC 2007; Moss et al. 2007]. Energy from biomass has a hugely positive impact on the fulfillment of positive global warming scenarios, because it can be carbon-neutral, or even carbon-negative. At present, a bioenergy supply of 270 EJ, possible on a sustainable basis, can cover almost 50% of the world’s total primary energy demand. Moreover, one hectare of energy willow plantation on polluted lands and lands that are low-yield absorbs up to 200 tons of CO_2 from the air over 3 years. An annual bioenergy supply covering the global energy demand in 2050, superseding 1,000 EJ, should be possible with sufficient political support [Ladanai, Vinterbäck 2009]. All sorts of waste wood and biomass can be used as an energy source [Ladomerský 2000; Ladomerský et al. 2003; Hroncová, Ladomerský 2008; Ladomerský, Hroncová 2009; Chrebet et al. 2013].

Research methodology

The objective of the research was the analysis of the possible use of degraded land – thermal power plant ash ponds – for the growth of fast-growing trees for fuel wood with the utilization of this wood for electric power generation. Two techniques of energy utilization are compared according to their CO_2 abatement; a verified technique – co-combustion with coal, and a proposed technique – pyrolysis, with the combustion of pyrolysis gases and pyrolysis oil. The results of the analysis may be used in strategic decision-making within power plant management, in order to effectively utilize degraded land and decrease GHG emissions as much as possible.

The research methodology was based on the carbon and energy balances of the compared techniques. Data used as a basis for the analysis consisted of the preliminary results from the authors’ 2 m^3 volume experimental retort, results from the latest pyrolysis technique in the Czech Republic (2013 confidential information) and published data.

In terms of CO_2 abatement, when comparing the differences between the two techniques for the energy utilization of fast-grown fuel wood, complete life cycle analysis is not necessary for the strategic management of the power plant. Regarding the given techniques and feedstock, emissions of other GHG N_2O a CH_4 are negligible:

- The highest industrial emissions of N_2O are from municipal waste incineration plants. IPCC 2006 set emission factors for N_2O from municipal waste incineration plants within the range 8 – 20 $g.t^{-1}$ MSW. Combustion of pyrolysis gas from biomass pyrolysis will produce much fewer emissions, therefore we can expect an emission factor as low as $1g.t^{-1}$, e.g. 0.310 kg $CO_{2\text{-eq}}.\ t^{-1}$, practically a negligible amount [IPCC 2006; Bailis 2009].
- Emissions of CH_4 are not produced during the combustion of biomass or pyrolysis gas using the best available technique.
- The positive effect of biochar on N_2O emission abatement from the soil is not accounted for, because clear quantitative data is not available [Lehmann 2009]. For example, for every ton of biochar applied, 0.394 kg of N_2O emissions ($CO_{2\text{-eq}}$ = 298 x 0.394 = 117 $kg.t^{-1}$) to the air will be avoided. Another estimate says that a N_2O emission reduction from soil (expressed as CO_{2eq}) contributes to total CO_{2eq} abatement by 4% [Roberts 2010]. This secondary effect slightly improves the impact of pyrolysis on GHG mitigation.

For the above-mentioned reasons, this analysis is therefore only focused on CO_2 emissions.

Assumption and balances

A simplified scheme to calculate the substitution of carbon from fossil fuel with biocarbon for the generation of the same amount of electricity: 1 kg C of wood = 1 kg C of coal. In classic power plants, the excess heat is wasted. In new pyrolysis devices, the excess heat is utilized for feedstock drying. Self-usage of electricity and fossil fuels for the process do not directly account for the CO_2 balance, but subtracted in energy efficiency. The basic parameters of feedstock and the compared techniques are given in table 1. All the data is given for the dry mass of feedstock.

Table 1. Basic parameters for 1 t wood (dry mass) and compared techniques
Tabela 1. Podstawowe parametry dla 1 t drewna (sucha masa) i porównywalnych technik

Process / *Proces* Parameter / *Parametr* [kg]	Co-combustion of wood in coal fired boiler *Współspalanie drewna w kotle opalanym węglem*	Pyrolysis with combustion of pyrolysis gas and oil *Piroliza ze spalaniem gazu i oleju pirolitycznego*
C_{input}	490	490
BY	0	175*

* Pyrolysis variant with maximum electricity production, but with the lowest CO_2 abatement
** Wariant pirolizy z maksymalnym wytwarzaniem energii elektrycznej, ale z najmniejszym umniejszeniem CO_2*
C_{input} – carbon input [kg] in 1 t feedstock (dry mass) to co-combustion and pyrolysis
C_{input} – węgiel wprowadzony [kg] w 1 t wsadu surowcowego (sucha masa) do współspalania i pirolizy
BY – biochar yield [kg], the mass of biochar produced from 1 t feedstock
BY – wydajność biowęgla [kg], masa biowęgla produkowanego z 1 t wsadu

Carbon yield $C_{biochar}$ [kg] is defined as the ratio between the mass of carbon in the biochar and the input carbon in the 1 t wood (dry mass).

$C_{biochar} = 0{,}8 \times BY$

Carbon in biochar for long-term sequestration C_{lts} [kg] is defined as the mass of carbon in the biochar, which remains stable in the soil for hundreds of years.

$C_{lts} = 0.8 \times C_{biochar}$

In the pyrolysis with a low biochar yield, which is on the other hand favorable for electricity generation, the C content in the biochar is a minimum of 80%. The carbon content in the biochar for long-term sequestration can be as high as 80%, which confirms other published data [Lehmann 2009].

The substitution of fossil fuel carbon with biocarbon for the generation of the same amount of electricity from biomass carbon:

– Co-combustion of wood in coal-fired boiler

  $C_{fosilco} = C_{input} \times \eta_{Co}$

– Pyrolysis of wood with pyrolysis gas combustion

  $C_{fosilpy} = (C_{input} - C_{biochar}) \times \eta_{py}$

  where: η_{Co} – electric energy efficiency of co-combustion (38%)

  η_{py} – electric energy efficiency of the combustion of pyrolysis gas and pyrolysis oil (35%)

CO_2 emission reduction by substituting fossil fuels with biofuel in the generation of electricity:

– Co-combustion of wood in a coal-fired boiler $CO_2\,(co) = 3.667 \times C_{fosilco}$

– Pyrolysis of wood with pyrolysis gas combustion

  $CO_2\,(py) = 3.667 \times C_{fosilpy}$

  3.667 is transformation coefficient CO_2/C

  CO_2 emission reduction by sequestration:

  $CO_2\,(s) = 3.667 \times C_{lts}$

  CO_2 abatement ($\sum$reduction):

– Co-combustion of wood in a coal-fired boiler = $- CO_2\,(co)$

– Slow pyrolysis of wood with pyrolysis gas and oil combustion and biochar sequestration = $- CO_2\,(py) - CO_2\,(s)$

Results and discussion

The use of degraded land for growing biomass

Although worldwide there is still a large unused surface available for growing energy biomass, for example savannas, in developed countries there could arise a problem with the availability of free land for growing energy crops. Farming, transportation and other costs involved in obtaining energy from biomass have to be taken into account. According to Heller, Keoleian and Volk [2003], assuming reasonable biomass transportation distance and energy conversion efficiencies, generating electricity from willow biomass crops could produce 11 units of electricity per unit of fossil energy consumed.

A so far unexploited potential for the growth of biomass for energy are various degraded areas, especially around large industrial sites, such as heaps after raw material mining, and sludge beds. Sludge beds contain various types of waste, mainly fly-ash and slag from thermal power plants and heating plants. Some sludge beds are already recultivated, others operate and some are still intensively used. Good examples are sludge beds of large thermal power plants combusting brown or black coal. If a proper care is taken of these sludge beds during their operation, they are sufficiently stable and, after biological recultivation, they are potentially suitable for growing energy crops. The trial growth of energy crops on such sludge beds has started in Slovakia [Tkáč et al. 2011; Majerník et al. 2013]. Short rotation woody crops such as willow, grown in close proximity to a power plant can become a favorable source of energy biomass for co-combustion. In addition, short rotation woody crops also provide other, mostly environmental, benefits including reduced net greenhouse gas. Crops, besides stabilizing the sludge bed by their roots, also take up large amounts of rain water, hence providing sludge bed dewatering. Of course, the use of degraded land around power plants would decrease the biomass transportation distance. In Poland, in most cases, wood biomass is supplied to consumers within 70 to 300 km [Ratajczak et al. 2012].

Degraded land also provides a large space for the disposal of anaerobic digested sewage sludge, which would at the same time serve as fertilizer for short-rotation woody crops.

The alkaline environment of a black and brown coal fly-ash sludge bed is a good barrier for the eventual leaching of metals from anaerobic digested sewage sludge to the environment.

Bioenergy production on degraded land, such as for example a recultivated slag – fly-ash mixture pond, can even sequester carbon, reduce leaching and increase its stability. From this, it is obvious that the biological recultivation of ash ponds should have a very positive environmental impact on the vicinity of thermal power plants. Willow is a very valuable wood species for this purpose [Walkowiak, Bartkowiak 2012]. The biological recultivation of slag – fly-ash mixture ponds as a complex issue is an unresearched topic thus far.

Analysis of biological and thermal processes of wood utilization with respect to CO_2 abatement

Greenhouse gases originate from organic matter in various biological and thermal processes. The bBasic conversion of biomass in biological and thermal processes can be expressed by these equations:

$$C(org) \xrightarrow{\text{aerobic}} CO_2 \quad (1)$$

$$C(org) \xrightarrow{\text{anaerobic}} CH_4 + CO_2 \quad (2)$$

$$C(org) \xrightarrow{\text{thermooxidation}} CO_2 \quad (3)$$

$$C(org) \xrightarrow{\text{pyrolysis}} C + CO_2 + CH_4 + C_xH_y + H_2 \quad (4)$$

$$C(org) \xrightarrow{N_2,\, O_2,\, H_2O,\, \text{gasification}} C + CO_2 + CH_4 + C_xH_y + H_2 \quad (5)$$

From these equations, basic options for CO_2 mitigation using biomass can be determined:

1. Aerobic treatment – the composting of wood biomass together with other biomass. The compost produced can be utilized in two ways, either applied to the soil, or combusted to produce energy.
   The first variant of compost utilization would contribute to soil quality, but only temporary carbon sequestration would be achieved – only a few years until the full oxidation of CO_2.
   The second variant – composting and compost combustion, does not make sense at first glance. Its purpose is achieved when some other high water content organic matter is co-composted with the wood. Composting can provide intense dewatering, at low cost compared with drying. This way a fuel can be produced with a significantly higher heat content than the heat content of the original materials. The use of energy from this renewable source would eliminate CO_2 emissions from coal combustion, thus the contribution of biomass to greenhouse gas emission mitigation can be calculated.
   For both variants, fast-growing woody crops are suitable, deciduous species being more suitable than coniferous species.
2. Preventing the decomposition of fallen trees in the forest and simply burying wood biomass under a thicker layer of ground [Zeng 2008]. Carbon dioxide bound in wood biomass remains stable in the ground for many centuries. Fast-growing trees could also be used for this purpose.
   A real economic analysis of this technique has not yet been carried out. Financial benefits could be calculated from the selling of CO_2 emissions, or eventually from some kind of subvention for greenhouse gas emission reduction. Technically it is the simplest method of carbon sequestration, but it does not appear to be a competitive way of using fast-growing biomass in comparison with wood utilization in wood industry technology.
3. Anaerobic digestion of wet biomass (but not wood) for biogas generation (CH_4 + CO_2). The combustion of biogas, mostly in gas Otto engines, generates electricity and the generated heat could possibly be used. The use of energy from this renewable source would eliminate CO_2 emissions from coal combu-

stion, thus the contribution of biomass to greenhouse gas emission mitigation can be calculated.

4. Economically advantageous, highly effective and technically reliable is the combustion or co-combustion of biomass for heat generation, with the advantage of possible electricity generation. The substitution of fossil fuels with bio fuels contributes to CO_2 abatement.
5. The production of biochar by pyrolysis and its application to the soil, with the combustion of volatile substances from pyrolysis for pyrolysis reactor heating. Excess heat should be used to generate electricity and as a heat source. CO_2 abatement is achieved by the sequestration of biochar and by the substitution of fossil fuels with bio fuel.

The CO_2 balance of the energy utilization of fast-growing biomass in power plants

For a sustainable climate on Earth, the concentration of atmospheric CO_2 will need to be reduced from the current 385 ppm to 350 ppm. Carbon sequestration in agricultural and forestry practices is gaining a lot of attention [Hansen et al. 2008].

Energy utilization of biomass grown on fly-ash ponds is possible in two basic ways:

– the co-combustion of biomass with coal,
– charcoal production by the slow pyrolysis of biomass with the combustion of the gaseous and liquid products of pyrolysis in a cogeneration unit with an internal combustion engine.

In the nearest future, it will be interesting to follow the development of new techniques for thermal treatment and the energy utilization of wood, such as flash pyrolysis and torrefaction [Hafsi, Benbouzid 2007; Kuppens et al. 2010; Voets et al. 2011; Witczak et al. 2011; Bridgwater 2012].

The co-combustion of biomass with coal is now becoming relatively common in electricity generation. For electric power producers biochar production and its deposition in the soil is a new method, besides developing CCS methods, for carbon dioxide mitigation.

In combined electricity and heat generation with a steam turbine, the overall energy efficiency could be considered as 80%. In combined electricity and heat generation with a cogeneration unit, an overall efficiency of 75% could be achieved. Considering the large amounts of heat generated by coal-fired power plants, it is not possible to effectively utilize heat from biomass. Therefore, only electricity generation will be accounted for. The efficiency of electric energy generation is taken as 38% using a gas turbine and 35% using a cogeneration unit. The results of CO_2 balance, reduction and abatement calculated according to the equations given above are in table 2.

Table 2. CO_2 emission from electricity generation in power plant with co-combustion of coal with biomass in comparison with slow pyrolysis of biomass with combustion of gaseous and oil pyrolysis products in cogeneration unit with internal combustion engine and produced biochar for sequestration. Values are calculated for 1 t of dry wood

Tabela 2. Emisja CO_2 w procesie wytwarzania energii elektrycznej w elektrowni wykorzystującej współspalanie węgla z biomasą w porównaniu z wolną pirolizą biomasy ze spalaniem gazowych i olejowych produktów pirolizy w urządzeniu do współspalania z wewnętrznym silnikiem spalającym i wyprodukowanym biowęglem do sekwestracji; wartości obliczono dla 1 t suchego drewna

Process* / *Proces* — Parameter / *Parametr* [kg]	Co-combustion wood in coal-fired boiler / *Współspalanie drewna w kotle opalanym węglem*	Pyrolysis with combustion of pyrolysis gas and oil / *Piroliza ze spalaniem gazu i oleju pirolitycznego*
C_{lts}	0	112
$C_{fosilco}$; $C_{fosilpy}$	186	122
CO_2 (s)	0	411
CO_2 (co); CO_2 (py)	683	450
CO_2 abatement / *Zmniejszenie CO_2*	−683	−861

*Self usage of electricity and fuels in the process not accounted for

**Nierozliczone zachodzące w trakcie procesu zużycie energii elektrycznej i paliw na potrzeby własne*

Summary comparison of co-combustion and pyrolysis of biomass

Pyrolysis of biomass grown on a fly-ash pond near a power plant with electricity generation using a cogeneration unit and with carbon sequestration would yield at least a 26% higher CO_2 abatement in comparison with the co-combustion of biomass. Biochar production and its application to the soil has several other positive effects. For example, the gradual improvement of the quality and fertility of the pond soil cover, fertilization, and N fixation, which are not evaluated in this paper.

Open questions, however, remain to be addressed in separate research projects:

- The impact of sludge bed subsoil on the chemical composition of biomass from contaminated areas [Masu et al. 2012].
- The chemical composition of biochar from biomass grown on contaminated areas.
- The leachability of eventual problematic substances from biochar in comparison with the leachability of fly-ash from biomass grown on contaminated areas. It is however known that nutrients bound in biochar are released very slowly.

Conclusions

Great potential to decrease carbon dioxide emissions to the atmosphere, or at least to mitigate the speed of the increase in the concentration of carbon dioxide, is in the biomass, which should be grown on degraded, low quality land.

Bioenergy production on degraded land, for example a recultivated slag – fly-ash mixture pond, can in addition sequester carbon, reduce leaching and increase the stability of the pond.

The theoretical analysis of CO_2 emissions was performed on two techniques – electricity generation in a power plant with the co-combustion of biomass compared with the pyrolysis of biomass with the combustion of gaseous and oil pyrolysis products in a cogeneration unit and biochar for sequestration.

The co-combustion of wood in a coal-fired boiler would provide approximately −683 CO_2 kg abatement from 1 t of dry wood.

Pyrolysis (an emerging technique) of wood with pyrolysis gas combustion and carbon sequestration would provide in the worst case −861 CO_2 kg abatement from 1 t of dry wood.

This technique would provide at least a 26% more favorable effect on climate change than the co-combustion of wood in a coal-fired boiler.

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WYKORZYSTANIE DREWNA Z TERENÓW ZDEGRADOWANYCH DO SEKWESTRACJI WĘGLA

Streszczenie

Zdegradowane tereny stanowią niewykorzystany potencjał, jeżeli idzie o uprawę biomasy do celów energetycznych. Zaliczają się do nich zwłaszcza obszary znajdujące się na obrzeżach terenów przemysłowych, tj. hałdy pozostałe po wydobyciu surowców czy składowiska szlamów. W przypadku gdy tereny te są wystarczająco stabilne, to po biologicznej rekultywacji potencjalnie będą nadawały się pod uprawę roślin energetycznych. Lesiste uprawy o krótkiej rotacji, takie jak wierzba, uprawiane na wspomnianych składowiskach szlamów w pobliżu elektrowni mogą stać się korzystnym źródłem biomasy przeznaczonej do współspalania. Celem badań była analiza możliwego wykorzystanie terenów zdegradowanych, tj. składowisk popiołu z elektrociepłowni, pod uprawy drzew szybkorosnących, których drewno zostanie przeznaczone do produkcji energii elektrycznej. Porównano dwie techniki wykorzystania do celów energetycznych pod względem zmniejszania przez nie ilości CO2. Pierwszą z nich jest sprawdzona technika współspalania z węglem, natomiast proponowana technika to piroliza ze spalaniem gazów i oleju pirolitycznego. Metodologia badań opiera się na bilansie węgla i energii w porównywanych technikach, który ma strategiczne znaczenie dla zarządzania elektrownią. Do obliczenia substytucji węgla z paliw kopalnych przez biowęgiel koniecznej do wytworzenia tej samej ilości energii elektrycznej użyto uproszczonego schematu: 1 kg C drewna = 1 kg C węgla. Z punktu widzenia wytwarzania energii elektrycznej współspalanie drewna w kotle węglowym jest bardziej pożądane niż piroliza ze spalaniem gazów i oleju pirolitycznego. Z kolei piroliza (rozwijająca się technika) drewna ze spalaniem gazów z pirolizy oraz sekwestracją węgla przyniosłaby przynajmniej o 26% lepsze efekty, jeżeli idzie o zmiany klimatyczne niż współspalanie drewna w kotle opalanym węglem.

Słowa kluczowe: drewno, tereny zdegradowane, współspalanie, piroliza, dwutlenek węgla

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