Energy Policy 123 (2018) 503–513

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Hydrothermal carbonization (HTC) of green waste: Mitigation potentials, costs, and policy implications of HTC coal in the metropolitan region of Berlin, Germany

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ARTICLE INFO

JEL classification:
Q42
Q51
Q54

Keywords:
Hydrothermal carbonization
Char
Biocoal
Bioenergy
Climate change
Life cycle

ABSTRACT

We quantify the greenhouse-gas mitigation potential and carbon abatement costs if green waste in the metropolitan region of Berlin, Germany, is diverted from composting into the production of hydrothermally carbonized coal (HTC coal) that is used to substitute for hard coal in electricity and heat generation. Depending on the origin of the green waste, we specify an urban, a rural-urban, and a rural scenario. All scenarios combined can mitigate 70,511 metric tons (t) of carbon-dioxide equivalents (CO_2e) per year. The carbon abatement costs reach 163 €/t CO_2e in the urban scenario, 76 €/t CO_2e in the rural-urban scenario, and 77 €/t CO_2e in the rural scenario. The lower abatement costs in the latter two scenarios are mainly due to HTC-coal co-firing in an existing power plant rather than constructing a new biomass power plant for HTC-coal mono-firing as in the urban scenario. While the abatement costs exceed the current carbon prices, they compare more favorably with commonly assumed damage costs of unmitigated climate change. Thus, the public support of HTC coal could be considered, with the primary policy focus on HTC-coal co-firing. HTC-coal co-firing could also lower the emissions of existing power plants during the fossil-fuel phase-out.

1. Introduction

Biomass is a controversial source of renewable energy. On the one hand, energy crops are highly debated for their role in food security and greenhouse-gas (GHG) emissions from land-use change (e.g., Rosegrant and Msangi, 2014; Searchinger et al., 2009). For electricity generation, on the other hand, biomass has the advantage of being dispatchable (e.g., Neuhoff et al., 2016). Thus, it can contribute to reduced power storage and system costs in an electricity-generation system that is dominated by fluctuating renewables, such as solar and wind energy (Schill and Zerrahn, 2018).

In addition to biomass residues, these considerations have strengthened the focus on biogenic waste, such as municipal green waste (e.g., leaves and grass cuttings), for electricity generation. However, there are limits to the potentials of biogenic waste (see, e.g., Brosowski et al., 2016 for Germany). Moreover, such feedstocks are often characterized by high water contents, low heating values, and heterogeneous quality (e.g., Libra et al., 2011), which renders them unsuitable for direct biomass combustion and possibly even anaerobic digestion. Thus, the use of biogenic waste for electricity generation relies on efficient conversion technologies. One such promising technology is hydrothermal carbonization (HTC) (e.g., Titirici et al., 2007; Funke and Ziegler, 2010; Libra et al., 2011).

HTC is a thermochemical conversion process that transforms biomass into a carbon-rich, coal-like product – HTC coal (or biocoal, hydrochar) – and some gaseous – mainly carbon dioxide (CO_2) – and liquid by-products (for more details, see Section S.1 in the Supplementary material).[2] HTC coal can be co-fired in conventional coal power plants or mono-fired in combined-heat-and-power (CHP) biomass plants. Since HTC typically requires biomass with a water content of 75–90% (Libra et al., 2011: 98), it can transform wet feedstocks into solid fuels without energy-intensive pre-drying.[3] Compared

Abbreviations: a, year; CH_4, methane; CHP, combined heat and power; CO_2, carbon dioxide; CO_2e, carbon-dioxide equivalent; FM, fresh matter; FM_{prep}, prepared fresh matter; GHG, greenhouse gas; HTC, hydrothermal carbonization; LCA, life-cycle assessment; N_2O, nitrous oxide

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[2] All sections, tables, and figures with the leading ‘S.’ can be found in the Supplementary material online.
[3] HTC coal can be mechanically dewatered relatively easily before it is further dried (e.g., Ramke et al., 2012).

https://doi.org/10.1016/j.enpol.2018.08.033
Received 22 February 2018; Received in revised form 31 July 2018; Accepted 18 August 2018
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to direct biomass combustion, HTC coal is associated with reduced slagging and fouling (Reza et al., 2014) as well as increased maximum weight loss rates, higher ignition temperatures, and elevated combustion temperature regions (e.g., Liu et al., 2013). As a more homogenous fuel with a higher energy density, HTC coal is also easier to handle than the original biomass during transport, storage, and combustion. For certain types of biogenic waste, HTC can be even more suitable for energy recovery than anaerobic digestion. Leaves, for example, yield only a very low amount of methane (CH_4), 15–25 m^3 per metric ton (t) of fresh-matter (FM) input (ICU, 2011: 14). While associated with higher yields of 90 m^3 CH_4/t FM input (ICU, 2011: 14), the utilization of grass cuttings for anaerobic digestion might involve technical difficulties, such as increased abrasion, increased stirring requirements, and frequent removals of sediment (Prochnow et al., 2009).

For all these favorable technical aspects, the use of HTC coal as a source of renewable energy from biogenic waste may represent an innovative GHG mitigation measure. However, before its large-scale implementation or even public support, a thorough assessment of the GHG mitigation potential and costs of HTC coal is needed. For this purpose, we provide a case study for the metropolitan region of Berlin, Germany, in which we focus on leaves and grass cuttings as inputs for the HTC process. The metropolitan region of Berlin is chosen as an example of a densely populated and, thus, emission-intensive area. The green waste from this region may become available for HTC since it is planned to recover its energy value; currently, it is usually composted (Schwilling et al., 2011). Our evaluation of HTC coal is based on its annual GHG mitigation potential, obtained from a life-cycle assessment (LCA), and its carbon abatement costs, i.e. the costs to mitigate a unit of CO_2 equivalents (CO_2e).

We present three scenarios that are not mutually exclusive. They are differentiated by the geographical origin of the green waste (urban, rural-urban, and rural). Consequently, they also differ by other parameters, such as the location of the HTC plant or the site and mode of HTC-coal combustion. The green waste for HTC is diverted from composting and the subsequent soil application of the compost to replace mineral fertilizers. The HTC coal, in pulverized form, substitutes for hard coal in electricity and heat generation.[4]

While we provide a case study for a relatively narrow region, our approach serves to embed the HTC scenarios in a realistic setting. In particular, the HTC scenarios are tailored to existing actors in the region's waste-management and energy sectors. For the location of the HTC plants and the logistics concepts for biomass transportation, preparation, and storage, we further take account of current infrastructure that can be utilized under the HTC system. Our data for the HTC process refer to an industrial-scale demonstration plant developed by *SunCoal Industries GmbH* (*SunCoal*), a manufacturer of HTC systems in Ludwigsfelde, Brandenburg.

We obtain the greatest GHG mitigation potentials per year (a) and the lowest abatement costs in the rural-urban (22,532 t CO_2e/a, 76.1 €/t CO_2e) and rural (25,749 t CO_2e/a, 77.2 €/t CO_2e) scenarios; the urban scenario has the lowest GHG mitigation potential (22,230 t CO_2e/a) and highest abatement costs (162.7 €/t CO_2e). With positive GHG mitigation potentials in all scenarios, our results indicate, first, that the substitution of fossil coal by HTC coal derived from green waste is an effective GHG mitigation measure. Second, while all scenarios' abatement costs exceed the current CO_2 prices in the European Union Emissions Trading System, below 17 €/t CO_2 (EEX, 2018), they compare more favorably with the damage costs of unmitigated climate change, which are not fully internalized in the CO_2 prices. Third, it is more efficient to substitute for fossil coal by co-firing the HTC coal in an existing coal-fired CHP plant (rural-urban and rural scenarios) than to invest in a new biomass CHP plant for HTC-coal mono-firing (urban scenario). Fourth, the green waste we consider has to be collected and disposed of in any case. Thus, abatement costs of more than 76 €/t CO_2e at zero feedstock costs show that HTC can play a role as a GHG mitigation measure particularly if it is co-used as a waste-management technology.

Our analysis contributes to the environmental, economic, and policy literature on HTC coal for energy generation. In particular, economic and policy-relevant studies for HTC coal are still rare and largely rely on simulations of industrial-scale HTC plants derived from laboratory-scale data (e.g., Eberhardt et al., 2011; Erlach et al., 2011; Wirth et al., 2012; Stemann et al., 2013a). Similar to our analysis, Eberhardt et al. (2011), Erlach et al. (2011), as well as Stemann et al. (2013a) find that HTC coal cannot compete with fossil coal at market-based CO_2 prices. The literature further finds that the production costs of HTC coal tend to depend strongly on feedstock costs, with shares of up to 50% (Erlach et al., 2011; Eberhardt et al., 2011). However, these results are not directly comparable to our study, where the green waste is available at zero cost. According to Erlach et al. (2011), the production costs of HTC coal derived from poplar wood chips can be reduced slightly if the HTP plant is integrated with a wood-fired CHP plant. Our urban and rural-urban HTC scenarios incorporate similar synergy effects with a waste-incineration plant and a CHP plant, respectively.

2. Methodology

Based on an LCA, we provide the GHG mitigation potential and carbon abatement costs of HTC coal under three scenarios in the metropolitan region of Berlin, Germany. The metropolitan region of Berlin, as defined in our study, comprises all Berlin city districts plus the adjacent rural counties of Brandenburg/Havel, Havelland, Potsdam, Potsdam-Mittelmark, and Teltow-Fläming, located in the federal state of Brandenburg, southwest of Berlin. As input material into the HTC process, we focus on leaves and grass cuttings.

2.1. Scenarios

Differentiated by the geographical origin of the feedstocks, we design an urban, a rural-urban, and a rural HTC scenario. The urban HTC scenario draws on leaves and grass cuttings from the Berlin city districts that are collected by the public waste-management company *Berliner Stadtreinigung* (*BSR*) and by parks departments (Table 1). The rural-urban HTC scenario, in turn, uses leaves and grass cuttings collected by private gardening and landscaping firms in the Berlin city districts and grass cuttings from three counties in Brandenburg, while the rural HTC scenario relies exclusively on grass cuttings from two counties in Brandenburg. Since the three HTC scenarios use different biomass resources, they can be realized simultaneously.

In each scenario, we assume that the HTC plant has an annual throughput of 55,000 t prepared and purified FM input (FM_{prep}). This corresponds to the approximate capacity of the HTC demonstration plant developed by *SunCoal* (SunCoal, unpublished data). Since leaves and grass cuttings contain different proportions of inorganic material, such as stones, plastics, glass, and sand (Table S.1), the scenarios require different amounts of initial FM inputs to obtain 55,000 t FM_{prep}/a. In particular, the urban scenario uses 73,701 t FM/a, the rural-urban scenario 75,621 t FM/a, and the rural scenario 81,361 t FM/a (Table 1). These FM inputs are all covered by the available biomass potentials (Medick et al., 2017: Table 1).

In addition to the biomass sources, the three scenarios make different assumptions for the site and operator of the HTC plant, the site and mode of HTC-coal firing, the site for biomass preparation and storage, as well as the corresponding transport stages (Table 1). A detailed description of the logistics concepts can be found in Section S.2.

Managing most of the urban feedstocks, the assumed operator of the HTC plant in the urban HTC scenario is *BSR*. The HTC plant is located at

[4] In 2013, 50.5% of Berlin's electricity was provided by hard coal, and 7.5% by lignite; the respective numbers for district heat were 23.6% and 16.7% (Amt für Statistik Berlin-Brandenburg, 2016: Tables 3.6 and 3.9).

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