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National and regional generation of municipal residue biomass and the future potential for waste-to-energy implementation

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ABSTRACT

Municipal residue biomass (MRB) in the municipal solid waste (MSW) stream is a potential year-round bioenergy feedstock. A method is developed to estimate the amount of residue biomass generated by the end-user at the scale of a country using a throughput approach. Given the trade balance of food and forestry products, the amount of MRB generated is calculated by estimating product lifetimes, discard rates, rates of access to MSW collection services, and biomass recovery rates. A wet tonne of MRB could be converted into about 8 GJ of energy and 640 kg of carbon dioxide (CO_2) emissions, or buried in a landfill where it would decompose into 1800 kg of CO_2 equivalent (in terms of global warming potential) methane (CH_4) and CO_2 emissions. It is estimated that approximately 1.5 Gt y^{-1} of MRB are currently collected worldwide. The energy content of this biomass is approximately 12 EJ, but only a fraction is currently utilized. An integrated assessment model is used to project future MRB generation and its utilization for energy, with and without a hypothetical climate policy to stabilize atmospheric CO_2 concentrations. Given an anticipated price for biomass energy (and carbon under a policy scenario), by the end of the century, it is projected that nearly 60% of global MRB would be converted to about 8 EJ y^{-1} of energy in a reference scenario, and nearly all of global MRB would be converted into 16 EJ y^{-1} of energy by the end of the century under a climate policy scenario.

1. Introduction

Nearly all the products we create are eventually discarded. Human-appropriated global biomass, estimated to be about a fifth of total global primary productivity [1,2], eventually returns to the global ecosystem as the municipal residue biomass (MRB) component of municipal solid waste (MSW). The majority of MRB is collected and aggregated at population centers where energy demands are high, making it a potential non-seasonal bioenergy feedstock, either through incineration or conversion to a liquid fuel (provided cellulosic ethanol technology becomes economically feasible). Other technologies for thermal disposal, such as pyrolysis and gasification, make MRB a potential environmentally sound source of low-carbon energy, chemical feedstocks, and other value-added products [3]. The availability of this resource increases with increasing population and per capita energy consumption [4], and using MRB for energy reduces land demands for waste disposal sites near urban areas where land pressures are high [5]. Though waste-to-energy facilities currently require large

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capital expenditures [6], the economics of energy from MRB would be dramatically improved under a carbon market where energy from MRB displaces fossil energy [7], and where combusted MRB prevents the formation of methane from anaerobic decomposition of landfilled waste.

To determine precisely the potential for energy from MRB, it is necessary to know the quantity of biomass generated by end-users annually, its composition and energy content, the rate at which it is collected, the rate at which it can be recycled, composted, or otherwise recovered, and the economic incentives involved in its disposal (i.e., converting it to energy versus burying it in a landfill). Estimating the potential for MRB energy on national, regional and global scales is challenging because detailed historical data on MSW on the country level are not well archived [4,8]. The majority of studies on waste generation rates and its composition are local, focusing on a set of individuals or households [9], an local area [10], or an individual country [11,12]. Results of studies conducted on different geographical scales are often difficult to reconcile due to differing definitions, methodologies, and the challenges associated with spatial extrapolation.

To analyze MSW trends at national and global scales, it would be desirable to have a national annual database of MSW statistics. Unfortunately, such a database does not yet exist. However, the United Nations (UN) Statistics Division [13] does maintain a limited dataset on MSW aggregated at the country level for a select countries, based on data from the Organisation for Economic Cooperation and Development (OECD). These data include the rate at which MSW is incinerated, recycled, composted, and buried. Within some countries, the UN Statistics Division also keeps data on the proportion of the population with access to MSW collection services. While the UN Statistics Division give some picture of MSW generation around the world, unfortunately the data are incomplete, are updated infrequently, and have varying degrees of reliability. Also, the UN Statistics Division does not maintain data on the composition of this waste (e.g. proportion of biomass), and thus it is difficult to estimate the energy and carbon content of MSW. The Intergovernmental Panel on Climate Change (IPCC) has produced estimates of waste and its composition by world region for use as default values in a national emissions worksheet [14], but the data are aggregated into a small number of large world regions, and it is not clear what proportion of the population in each region has access to MSW collection service. Perhaps because of this lack of data, there is a dearth of detailed studies investigating the energy potential from MRB on a global scale.

Therefore, large-scale studies must rely on statistical proxies to estimate the amount of MSW generated in each country. For example, in a study of the technical feasibility of waste-to-energy, Consonni, Giugliano, and Grosso [15] resorted to an ‘‘educated guess’’ about the composition of MSW based on data collected in Italy during the 1990s and professional experience of the authors. In another study that aimed to quantify global methane (CH_4) emissions from landfills, Bogner and Matthews [4] noted the lack of reliable MSW data from developing countries had lead to shortcomings in the IPCC approach, and therefore adopted per capita energy consumption as a proxy for per capita MSW generation. Global methane emissions databases must resort to the similar strategies; lacking specific annual data on MSW generation, the Carbon Dioxide Information Analysis Center (CDIAC) uses an extrapolation based on GDP growth, with rough adjustments in the slope to account for waste-to-energy in the developed world [16].

Efforts involving integrated assessment models to project future global potential of energy from MRB often assume a growth curve based on Gross Domestic Product (GDP) [17] or assume per capita MSW generation asymptotically approaches some specific annual rate (e.g., 2.5 Mg person^{-1} y^{-1}) as per capita GDP increases [18]. Further assumptions are made concerning the composition of MSW in order to estimate an appropriate energy conversion factor [17,18]. GDP makes a convenient explanatory variable because statistics are readily available for all countries of the world and are derived in part from the consumption of goods. While using GDP in a simple regression model to estimate MSW generation can provide a first order approximation, it can also lead to unrealistic results when projected into the future. Across the world, the distribution of GDP is highly skewed and the statistical fit is heavily influenced by developed countries such as the US. Thus, using GDP as a explanatory variable for total MSW generation tends to assume that all countries will eventually have throughputs that resemble the US, and furthermore, the trend will continue on that trajectory into the future. This can result in enormous future estimates for MSW generation in countries with large populations and high future labor productivity projections, such as China. Moreover, a GDP regression on MSW is non-processed based, in that it is disconnected from an analysis based on material throughput of the global economy. Studies have suggested that many of these relationships are non-linear (see, for example, [19]), and a simple GDP regression approach is also unable to capture changes in composition of MSW. The GDP proxy approach neglects the dynamics of product demand, end-user disposal rates, access to MSW service, and development of recycling and composting techniques that increase as economies develop. While overall MSW generation tends to increase with GDP, projecting these patterns into the future requires a more detailed parameterization of the generation and composition of discarded materials, the development of MSW collection service and recovery strategies, and the market potential for energy from MRB.

The purpose of this paper is threefold. First, a throughput approach is used to develop a set of functions that refine the current estimates for the amount of MRB based on domestic consumption of agricultural and forestry products, population, and per capita wealth. From this, estimates of the collected biomass are calculated for nearly all countries and regions of the world. Second, these statistical relationships are used to project future MRB generation based on projections from an integrated assessment model. Finally, third, this paper examines the effect that a hypothetical climate policy would have on the future proportion of MRB converted to energy and the resulting carbon emissions with respect to waste-to-energy implementation. Modeling the life cycle of bio-resources leads to better quantification of how economic and policy decisions affect the global flows of mass, energy, and carbon.