## Title

# Life cycle energy and climate benefits of energy recovery from wastes and biomass residues in the US

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## Abstract

Agricultural and forestry residues, animal manure and municipal solid waste are replenishable and widely available. But harnessing these heterogeneous and diffuse resources for energy and the environment requires a holistic assessment of alternative conversion pathways taking into account spatial factors. Here, we analyze, from a life cycle assessment (LCA) perspective, the potential renewable energy production, net energy gain and greenhouse gas (GHG) emissions reduction for each distinct type of waste feedstocks under different conversion technology pathways. The utilization of all available wastes and residues in the contiguous US can generate 3.1-3.8 exajoules (EJ) of renewable energy but only deliver 2.4-3.2 EJ of net energy gain, and displace 103-178 million metric ton $CO_2$ equivalent of GHG emissions. For any given waste

feedstock, looking across all US counties where it is available, except in rare instances, no single conversion pathway simultaneously maximizes renewable energy production, net energy gain and GHG mitigation. Maximizing the benefits of waste conversion requires attention to: first, the life cycle implications of different technology pathways; second, the spatial distribution of waste feedstocks; and third, the local conditions under which waste feedstocks will be processed.

## Main

In the new millennium, energy insecurity, global climate change, and stagnant rural economies led to policies supporting domestic biofuels as a renewable alternative fuel in more than sixty countries worldwide[1]. As a consequence, global production of ethanol and biodiesel combined almost quadrupled (from about 35 billion liters to 135 billion liters) in the short span from 2005 to 2016[2]. But these policies had two major flaws. Firstly, appropriation of edible crops for biofuel (mainly, corn and sugarcane for ethanol, and soybean, canola and palm for biodiesel) was an important factor responsible for food price inflation alongside other factors such as rising income that drove to rapid growth in food demand (especially meat demand), rising energy prices, adverse weather shocks, currency fluctuations, and trade policies[1, 3-6],the consequences of which were particularly severe for poorer households in developing countries[7]. Secondly, these crops required intensive use of land, water, nitrogen, and other farm chemicals, which meant low, and in the worst case, uncertain net environmental benefits[8-12].

Being widely available and replenishable, wastes and biomass residues from agricultural, dairy, forestry and household activities seem to contain the basic attributes of a sustainable energy resource in stark contrast to bioenergy from food crops[13-15]. The US Department of Energy 2016 Billion Ton Study estimates an annual availability of 233 million metric tons (MMT) of dry waste[16]. To put this in perspective, the approximately 60 billion liters of corn ethanol produced in the US in 2017 required about 150 MMT of corn (assuming a yield of 402 liters of ethanol per MMT). Furthermore, wastes and biomass residues can be used to derive a number of alternative energy products including electricity along with heat, biomethane (or renewable natural gas), ethanol, renewable diesel, or bio jet fuel, each through various conversion pathways, which currently are at different stages of technical and economic maturity[14, 15, 17-21]. Beyond energy production and mitigating climate change, efficient use of wastes and residues is integral to the achievement of sustainable development[22], and to redesigning our economies to minimize material and energy throughput, i.e., towards becoming a circular economy[23, 24]. But at the same time, sustainable use of this resource hinges on overcoming some challenges. The collection, transport and storage of biomass feedstocks are costly and could account for over 50% of total cost in the supply chain of bioenergy products[25]. The composition of wastes also varies from one location to another, and their processing requires substantial energy inputs. In addition, national-scale policies tend to ignore local trade-offs leading to suboptimal use of scarce resources[26]. Harnessing the full energetic and environmental potential of this resource, therefore, requires a holistic assessment of alternative competing pathways to their utilization taking into account the spatial distribution of each specific type of wastes and the local conditions under which they will be processed. The majority of previous LCA studies have either focused on a smaller number of waste types[14, 27-35], certain types of bioenergy products[15, 19, 20, 36-38], or certain conversion technologies[29, 31, 37, 39-45]. Comparing the effectiveness and environmental impacts of all feasible conversion pathways for all types of wastes from a systems perspective is necessary for policies that address the best use of wastes and biomass residues.

Given this context, the questions motivating this study are the following: first, what factors determine the net energy gain and the global warming potential (GWP) of energy recovery from waste; second, which pathways simultaneously maximize renewable energy production, net energy gain and climate benefits for each type of wastes and how this varies given the spatial distribution of their availability (specifically, in the contiguous US); third, what are the aggregate energy and climate benefits when all available wastes and biomass residues across the contiguous US are dedicated for a specific policy objective such as maximizing renewable energy production, maximizing net energy gain, or maximizing climate benefits? These questions are aimed at deriving both general insights on the optimal use of wastes and biomass residues, and also illustrating their overall climate change mitigation potential in the context of a large country, specifically the US. To this end, we quantify life cycle GHG emissions and net energy gain for fifteen conversion pathways (detailed description in Table 1) and twenty-nine waste feedstocks with spatially explicit estimates of waste potential for the US. We find that the source of electricity consumed during processing and the environmental footprint of the displaced products are key in determining the best use of wastes and biomass residues. The utilization of all available wastes and residues in the contiguous US can generate 3.1-3.8 EJ of renewable energy but deliver only 2.4-3.2 EJ of net energy gain, and displace 103-178 million metric ton $CO_2e$ of GHG emissions. For any given waste feedstock, looking across all US counties where it is available, except in rare instances, no single conversion pathway simultaneously maximizes renewable energy production, net energy gain and GHG mitigation.

## Technical comparison of conversion pathways

We first estimate renewable energy production, net energy gain and GHG footprint of different conversion pathways on a per unit wet weight basis for various types of wastes. Feedstock-level results are depicted in Supplementary Figures 5-7. The methods section explains how we first calculate these for each distinct waste biomass source at the US county-level, and subsequently, compute a mass weighted-average for each of the four broad categories of wastes at the national level. The renewable energy yield across conversion pathways ranges from 0.2 to 13.1 gigajoules

(GJ) per megagram (Mg) of waste while net energy gain ranges from -2.4 to 11.6 GJ per Mg (Figure 1a and Figure 1b). It is clear that the energy value of co-products is critical to achieving positive net energy for a number of conversion pathways and waste feedstocks. Except for animal manure related pathways, all conversion pathways result in positive net energy gains and considerable energy return on investment (EROI). For animal manure, only anaerobic digestion (M2) yields positive net energy and its EROI is only slightly greater than 1. The net GWP across the pathways ranges from -0.9 to 0.7 metric ton (Mt) $CO_2e$ per Mg (Figure 1d). As with the importance of co-products in net energy gain, emissions avoided by the resulting co-product(s) displacing a substitute accounts for a substantial portion of the climate benefits for most pathways.

Looking into each broad waste category, for agricultural and forest residues, combined heat and power generation (CHP) offers both the greatest net energy gain and climate benefits. For MSW, CHP offers the highest net energy gain while anaerobic digestion returns more climate benefits than other pathways. When compared with current management practices, all conversion pathways result in climate benefits for agricultural residues. As for animal manure, only anaerobic digestion producing either methane (M2) or electricity and heat (E4) yields climate benefits. This corresponds with previous studies which indicate that anaerobic digestion is the optimal conversion pathway for animal manure[15, 27, 28]. Although some pathways appear not to contribute to climate change mitigation (i.e., result in positive net GWP), all conversion pathways for forest residues yield smaller net GWP relative to burning them on-site. When compared to landfilling without any methane flaring or capturing, all conversion pathways for MSW result in smaller negative effects to the climate. However, landfilling with methane capture and onsite CHP would greatly reduce the GHG emissions of landfilling and become more attractive than renewable diesel related conversion pathways (Figure 1c and Figure 1d).

## Break-down of GHG emission sources

Disaggregating the contribution to total GHG emissions from the different stages in the production chain shows that emissions during the processing stage, which requires electricity and heat input, and credits for avoided emissions attributable to displaced products are key determinants of GHG emissions for most conversion pathways (Figure 1). This is generally in line with results from a number of recent studies, such as de Jong et al. (2017), Pressley et al. (2014), and Tonini et al. (2016). For agricultural residues, current management practice (i.e., left and decayed on field) entail no GWP due to the fact that the $GWP_{bio}$ index for annual crops is zero. While the same $GWP_{bio}$ index applies to animal feed, methane and $N_2O$ emissions from animal farm operations contribute to total emissions from direct land application of manure. For MSW, the major sources of non-biogenic carbon are contained in plastics, rubber and leather, and textiles. For non-electricity pathways, non-biogenic carbon in MSW feedstocks would be transferred into energy products and eventually be emitted into the atmosphere as $CO_2$ during end use. This explains a large amount of emissions during the end-use stage for these pathways. For electricity-related pathways (E1-E4), non-biogenic carbon would be emitted as $CO_2$ during the processing phase. For other types of MSW feedstocks, biogenic carbon would be emitted as biogenic $CO_2$ at various phases. Thus, we treated biogenic $CO_2$ as a separate source of GHG emissions.

## Sensitivity analysis of emission estimates

Given that electricity consumption during biomass processing is the major source of energy inputs and emissions across most conversion pathways, a sensitivity analysis on the emissions intensities of state power grids was conducted. Note that even though biomass processing requires significant heat energy, it is typically derived from natural gas, whose emissions intensity is much less variable across regions relative to the emissions intensity of electricity. Results show that cleaner power grids in general would yield less climate benefits for electricity pathways and more climate benefits for non-electricity pathways (Figure 2). For cleaner power grids, electricity-related pathways would on one hand result in less emissions during the processing stage, but on the other hand lead to less climate benefits from the displacement of grid electricity. For the majority of non-electricity pathways, electricity is only an input so that cleaner power grids would result in less emissions during the processing stage and the overall life cycle. For instance, whereas converting agricultural and forest residues into electricity through CHP (E1) and biomethane through gasification (M1) appear equally beneficial under current conditions, M1 becomes more beneficial when power grids are cleaner. Another sensitivity analysis on transportation distance was also conducted (Supplementary Figure 8). However, a distance ranging from 25 to 150 km negligibly affects results on GHG emissions. Thus, we assumed 150 km as the transportation distance in order to provide conservative estimates for net energy gain as well as GHG emissions.

## Maximizing aggregate energy and climate benefits

We next describe the maximum energy and climate benefits achievable at a national scale through optimal utilization of waste biomass generated in each county within the US taking into account spatial variation in the electricity mix. As noted earlier, about 233 MMT of dry waste resources is available annually in the contiguous US[16]. The spatial distribution of this total resource base is depicted in Supplementary Figures 1 and 2. Approximately 25% of this total is concentrated in 115 counties, 50% are in 374 counties, and 75% are in 884 counties (Supplementary Figures 1-2 and Supplementary Note 1). Agricultural states in the Pacific West, the Midwest and the South in general stand out with more agricultural residues than other regions. Counties in the Mountain West and the South are endowed with substantial forest residues. The availability of animal manure corresponds with livestock and poultry production, which is concentrated in California and the Midwest. The availability of MSW is concentrated in densely-populated regions such as Southern California, Florida and parts of the Northeast. Overall, however, some of the largest metropolitan areas stand out in terms of the availability of total waste resources.

Searching for the conversion pathway that is optimal with respect to all three criteria - renewable energy, net energy and GWP, we find that, except in rare instances, no single pathway exists for any given type of waste across all US counties and states (Table 2). Across different types of agricultural residues, combined heat and power generation (E1) consistently stands out with respect to all three objectives for a substantial fraction of counties and states. As for animal manure, no single pathway satisfies all three objects. For forest residues and municipal wastes, optimal conversion pathways that satisfy all three objectives vary by specific waste feedstocks. The percentage of locations where there is a single optimal pathway varies substantially.

Since there lacks a single pathway that achieves all three objectives for any given waste feedstock across locations, there is a need to consider three distinct scenarios of optimal use of biomass wastes – maximum energy production (MEP), maximum net energy (MNE), and maximum emissions reduction (MER). For each county in the US, we first select the conversion pathway for each type of wastes under each of the three scenarios. The national results are the aggregation of county-level results. The calculations are described in the methods section and results are depicted in Table 3 and Figure 3. Scenario results suggest that there is substantial benefit from utilizing wastes and biomass residues to either displace energy production or reduce GHG emissions or both. As one would expect, MEP results in the highest potential of renewable energy production which totals 3.8 exajoules (EJ) – 3.7% of total US energy demand in 2016[46], and MER results in the highest potential of emissions reduction that is 178 MMT $CO_2e$ – 2.7% of total US GHG emissions in 2016[47]. The MNE scenario indicates the highest potential of net energy as well as a moderate amount of emissions reduction (75% of MER). A break-down of scenario results by waste feedstock reveals the preferred conversion pathways under each of the three scenarios (Supplementary Table 4). CHP (E1) is the preferred option for agricultural resides under both the MEP and MNE scenarios, while either CHP(E1) or gasification (M1) may maximize GHG emissions reduction depending on specific feedstock. For dairy manure, CHP (E1) is the preferred option that maximizes renewable energy production but anaerobic digestion to biomethane (M2) maximizes both the net energy gains and climate benefits. For forest residues, CHP (E1) results in largest amount of renewable energy and net energy gain, while either HTL with in-situ hydrogen production (Bj5) or gasification (M1) maximizes GHG emissions reduction. Different from other categories of wastes, optimal use of MSW feedstocks would require a greater number of conversion technology pathways depending on specific feedstock. Non-biogenic carbon in MSW is concentrated in three feedstocks - plastics, rubber and leather, and textiles. Thus, the non-biogenic carbon is immediately emitted into the atmosphere when processing those feedstocks instead of being stored in landfills. While the inclusion of biogenic $CO_2$ reduces net GWP for forest residues and MSW (Figure 1c and Figure 1d), it does not change the ranking of conversion pathways under the three scenarios.

The county-level distribution of renewable energy production, net energy gain and its associated climate benefits also indicates that most counties would lose a relatively small amount of energy production potential from MEP to MER while most counties would see a greater increase in terms of emissions reduction (Figure 3). Maximizing energy production would result in negative net energy in 125 counties and emissions increase in 532 counties (Figure 3b and 3c). Therefore, maximizing either net energy or emissions reduction would lead to better utilization of wastes and residues relative to maximizing renewable energy. Given that the terms renewable energy and clean energy tend to often be used interchangeably by policy makers, this analysis shows that there exist potential tradeoffs between different criteria relevant to sustainable development.

## Conclusions

Maximizing the benefits of waste conversion requires attention to: first, the life cycle implications of different technology pathways; second, the spatial distribution of waste feedstocks; and third, the local conditions under which waste feedstocks will be processed. The policy insight that emerges from this analysis is that national mandates such as the US Renewable fuel standard (RFS) might not maximize even renewable energy production let alone maximize environmental benefits. Likewise, renewable portfolio standards, a widely employed policy in the electricity sector, could lead to sub-optimal use of waste biomass. In the literature, bioenergy and biofuel policies have been analyzed mainly from the perspective of climate change mitigation, food security or cost, but this analysis shows they also do not optimize energy production. From a methodological perspective, this analysis illustrates the value of combining LCA with spatial analytical techniques for multi-criteria assessment of alternative conversion pathways and the identification of hot spots for the refinement of existing energy policies. Indexing volumetric targets and mandates as well as financial subsidies for renewable energy to life cycle emissions-based performance measures will lead to more sustainable use of wastes and biomass residues.

This study is a first step towards using a common system boundary for a consistent comparison of a large variety of waste conversion technologies from the twin perspectives of net energy gain and climate benefits. Incorporating non-GHG environmental considerations including air quality impacts and fresh water use and water quality impacts, as well as an assessment of the levelized life cycle cost of energy for the different pathways are two important directions for future research.

## Methods

**An overview of conversion technology pathways.** The fifteen conversion technology pathways included in this study can be categorized into five groups: electricity pathways (E1-E4), methane pathways(M1-M2), ethanol pathway (Eth1), renewable diesel pathways (Rd1-Rd2), and bio jet fuel pathways (Bj1-Bj6). Details about the conversion pathways including process description, feedstock feasibility, energy inputs and outputs, the co-products, the displaced products, and the references are presented in Table 1.

**Approach to energy and emissions accounting.** We conducted a life cycle analysis (LCA) to estimate the energy balances and GHG emissions associated with the conversion of a given feedstock to the final energy product(s) in each county. The different phases of the life cycle that are accounted for include collection of waste, transport to the conversion facility, processing (including pre-treatment), transmission and distribution, and end use (Supplementary Note 2 and Supplementary Figure 3). Thornley et al. (2015) showed that different functional units would result in varying outcomes when comparing alternative uses of biomass and the function unit should correspond with “the actual nature of the research questions” [48]. Since this study mainly focus on the optimal use of wastes, the functional unit of this LCA is thus one megagram (Mg) of wet waste.

Energy and emissions from collection and transport of feedstock are estimated based on this activity requiring heavy-duty diesel trucks. Feedstock-specific technology data (including lower heating values, moisture content, non-biogenic carbon content, energy inputs and outputs by conversion pathway) were collected from the literature to calculate energy and emissions flows in each phase as well as the overall net energy gains[15, 39, 42, 49-52]. Table 1 shows additional data sources. Losses during transmission and distribution were taken into account.[50] Emissions associated with the provision of energy inputs were based on life cycle emissions intensities of electricity generation and other fossil-based fuel production (heat, natural gas, diesel, hydrogen) [53-55]. Emissions intensities of the production of electricity and fossil-based fuels vary geographically, and variation across states in such emissions intensities were taken into account (Supplementary Note 3 and Supplementary Table 1). Life cycle GHG emissions intensities of state power grids were estimated by multiplying a state’s generation mix from the Emissions & Generation Resource Integrated Database (eGRID2016) with life cycle GHG emissions intensities of respective electricity generation technologies from the LCA Harmonization project[56, 57]. The GWP for non-$CO_2$ GHG is based on IPCC AR5 100-year conversion factors[58].

Comparing the burdens associated with converting a given feedstock to different end products does not, however, paint a complete picture of the benefits of choosing one conversion pathway over another. The ultimate environmental benefit of any given pathway is also a function of the process(es) or product(s) that it displaces. For instance, if conversion of manure to renewable natural gas for pipeline injection entails more GHG emissions relative to conversion to biogas for onsite power generation, it is plausible that the former is more beneficial if electricity from biogas displaces were to clean electricity while renewable natural gas displaces diesel used in trucks or displaces fossil natural gas. Supplementary Figure 4 illustrates a simple schematic representation of this concept. Posen et al. (2014) illustrate this idea in the context of converting cellulosic biomass to ethanol and displacing gasoline vis-à-vis producing bioethylene and displacing fossil-fuel derived ethylene[59]. For the handling of co-products, we chose the displacement method over allocation methods based on energy or economics for the following reasons: First, the International Standards Organization (ISO) advocates the use of the displacement method[60] and it has been adopted as the default method in many LCA models and biofuel regulation development in the US. Second, many pathways yield a number of different types of energy products – electricity, heat, methane, and/or liquid fuels. The conventional products to be displaced can easily be defined. Third, the distinguishment of main-product and co-products in this study is mainly for categorizing the pathways into five groups. We intended to examine the conversion pathways from a systems perspective, that is, all types of energy products via each conversion pathway instead of the main products only. The displacement method represents the idea of system expansion and is more suitable for our analysis. Fourth, the characteristics (utility, energy form, etc.) of electricity are different from those of other types of energy products. So is each other type of energy products. Allocation simply based on energy content may result in distorted results. In addition, the price ratios for an economic allocation may be challenging as some of the energy products from waste conversion may be non-commoditized and the prices may fluctuate and vary greatly by geographic location. Net GHG emissions were calculated by subtracting displaced emissions from the life cycle emissions of each conversion pathway. Biogenic $CO_2$ emissions are included throughout life cycles. The GWP of biogenic $CO_2$ emissions was estimated by multiplying the $GWP_{bio}$ indices with biogenic $CO_2$ emissions. Additional details on the method and data sources for biogenic $CO_2$ emissions are listed in Supplementary Note 4 and Supplementary Table 2. Thus, net GWP of a given feedstock converted through a given pathway is equivalent to the sum of net GHG emissions and the GWP of biogenic emissions. Emissions and energy related to material use (such as enzymes and catalysts) are not included in the analysis.

The basic county-level calculations we performed in order to assess the potentials of energy production and life cycle GWP are the following:

$$EP_{i,j,c} = WW_{i,c} \times \sum_k (EO_{i,j,k} \times (1 - TD_k)) \qquad \dots (1)$$

$$NE_{i,j,c} = EP_{i,j,c} - WW_{i,c} \times (\sum_l EI_{i,j,l} + E_{collection,i} + E_{transport} \times D1) \qquad \dots (2)$$

$$\begin{aligned} GWP_{i,j,c} = {} & WW_{i,e} \times (E_{collection,i} + E_{transport} \times D1) \times EmissI_{diesel,c} + \sum_l (EI_{i,j,l} \times \\ & EmissI_{l,c})) + Emiss_{process} + W_{i,j,k} \times EmissI_{diesel,c} \times D2 + \\ & Emiss_{enduse} + GWP_i^{bioCO2} - EP_{i,j,k} \times EmissI_{m,c} \qquad \dots (3) \end{aligned}$$

$$GWP_i^{bioCO2} = GWP_{bio,i} \times Emiss_{bioCO2,i} \qquad \dots (4)$$

where,

$EP_{i,j,c}$ - Renewable energy production (MJ) of feedstock *i* via conversion pathway *j* in county *c*;

$WW_{i,c}$ - wet weight (kg) of feedstock *i* in county *c*;

$EO_{i,j,k}$ - energy output *k* (MJ/kg) of feedstock *i* via conversion pathway *j*;

$TD_k$ – transmission and distribution loss of energy output k, 6.5% assumed for electricity, 20% for heat, and 2% for methane;

$NE_{i,j,c}$ - net energy (MJ) of feedstock $i$ via conversion pathway $j$ in county $c$;

$EI_{i,j,l}$ - energy input $l$ (MJ/kg) of feedstock $i$ via conversion pathway $j$;

$GWP_{i,j,c}$ - net GWP ($gCO_2e$) of feedstock $i$ via conversion pathway $j$ in county $c$;

$E_{collection,i}$ - Energy consumption rate (MJ/kg) of collecting feedstock $i$;

$E_{transport}$ - Energy consumption rate (MJ/kg-km) of transporting feedstock $i$ to conversion facility;

$D1$ - Transport distance (km) from temporary storage or collection site to conversion facility, 150 km assumed;

$EmissI_{diesel,c}$ - life cycle GHG emissions intensity ($gCO_2e$/MJ) of petroleum-based diesel in county $c$;

$EmissI_{l,c}$ - life cycle GHG emissions intensity ($gCO_2e$/MJ) of energy input $l$ in county $c$;

$Emiss_{process}$ – direct GHG emissions (excluding biogenic $CO_2$) during processing;

$W_{i,j,k}$ - physical weight (kg) of energy output $k$ of feedstock $i$ via conversion pathway $j$;

$D2$ - Transport distance (km) for distribution, 150 km assumed;

$Emiss_{enduse}$ – direct GHG emissions (excluding biogenic $CO_2$) during end use;

$GWP_i^{bioCO2}$ – GWP ($gCO_2e$) of biogenic carbon in feedstock $i$

$EP_{i,j,k}$ - energy production (MJ) of output k of feedstock $i$ via conversion pathway $j$;

$EmissI_{m,c}$ - life cycle GHG emissions intensity ($gCO_2e$/MJ) of energy product m (which output k can substitute) in county $c$;

$GWP_{bio,i}$ - biogenic $CO_2$ global warming index with full impulse response functions for feedstock $i$;

$Emiss_{bioco2,i}$ - biogenic CO2 emissions of feedstock $i$.

For the comparison of conversion pathways, county-level results were first aggregated to the national level and by feedstock. Weighted average (by weight) of results by feedstock in each of the four broader category of waste resources were calculated for the comparison by waste type (as shown in Figure 1). For the current management practices for wastes and residues, we used the same emissions accounting method and life cycle framework to estimate the GWP (Supplementary Note 5 and Supplementary Table 3).

**Sensitivity analysis.** A sensitivity analysis of net GHG emissions was conducted to explore the impacts of emissions intensity of current state power grids and transportation distance. For the sensitivity analysis on electricity, two additional electricity generation scenarios were constructed: "cleaner power" - assuming a 50% reduction in emissions intensity of power grids in all states; and "fossil rollback" - assuming a 50% increase in emissions intensity of power grids in all states. In addition, a range of 25 - 150 km were examined to test the sensitivity of transportation distance.

**Technical availability of waste resources.** County-level waste availability data were obtained from the base-year estimates under the reference scenario in the US DOE's BT16. BT16 estimates the biophysical potential, the spatial distribution, economic constraints, as well as environmental impacts associated with existing and potential biomass resources[16]. Waste resources included in this study comprise of four types of wastes: agricultural residues (14 feedstocks, including both primary and secondary agricultural residues as defined in BT16), animal manure (2 feedstocks), forest residues (4 feedstocks), and municipal solid waste (9 feedstocks). Technical availability was defined as the maximum potential of waste resources without taking into account feedstock costs. BT16 reports dry weight of waste feedstocks, and wet weight was calculated with moisture content to account for collection and transport emissions.

**Scenario analysis.** To explore the optimal utilization of waste biomass resources, we developed three alternative scenarios: maximum renewable energy production (MEP), maximum net energy

(MNE), and maximum GHG emissions reduction (MER). For all scenarios, the optimal conversion pathway for each feedstock was selected based on the maximum value of energy or emissions reduction. Under each scenario, the county-level results were then added up to get the potentials of total renewable energy production, net energy, and emissions reduction at the national level.

### Data availability

The data that support the findings of this study are available .via: https://github.com/labyseson/Waste-LCA.

### Code availability

Codes for energy and emissions accounting as well as data visualization are available via: https://github.com/labyseson/Waste-LCA.

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## Contributions

R.D. designed and directed the study, guided data collection, modeling and analysis, and co-wrote the manuscript. B.L. contributed to the study design, collected the data, conducted the modeling and analysis, and co-wrote the manuscript.

## Competing interests

The authors declare no competing interests.

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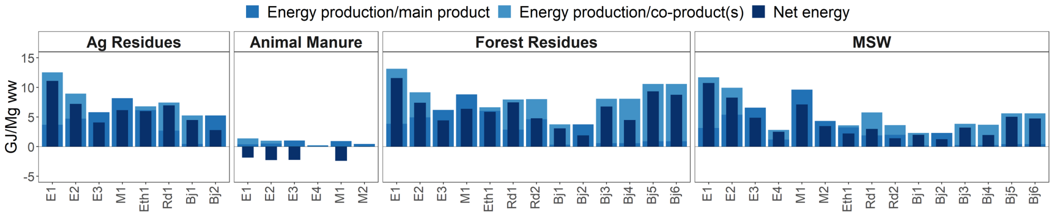
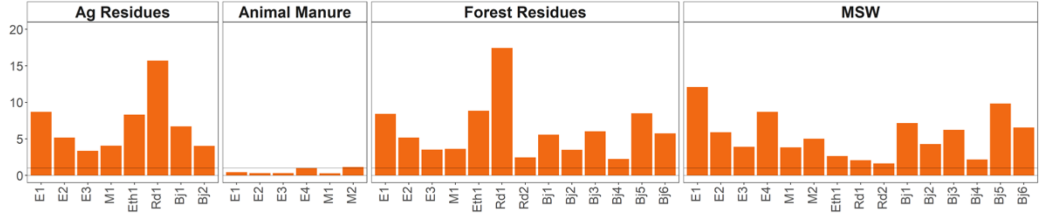
# Figures

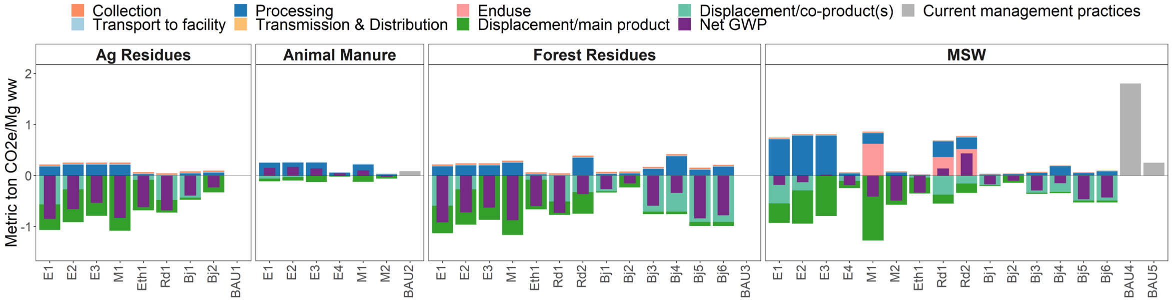
**(a) Energy**



**(b) Energy return on investment**



**(c) GWP - excluding biogenic CO2**



**(d) GWP - including biogenic CO2**

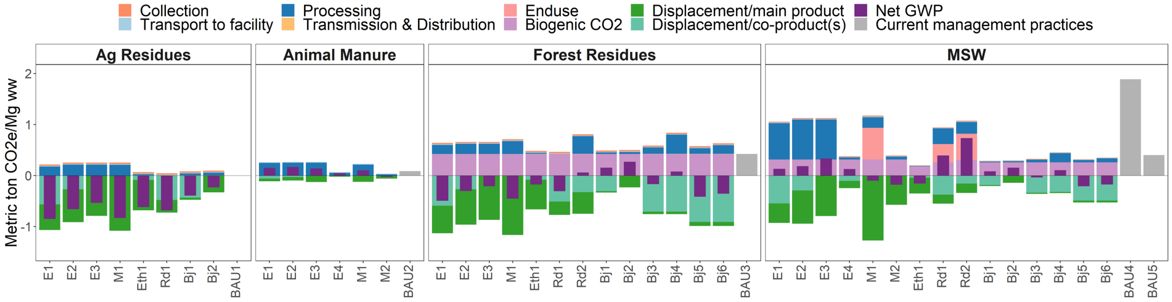


**Figure 1. Energy, net energy and emissions from waste biomass utilization in the US.** (a) Energy production and net energy by waste type and conversion pathway. (b) Energy return on investment by waste type and conversion pathway (the horizontal line refers to an EROI of 1). (c) Life cycle emissions when biogenic $CO_2$ is excluded. (d) Life cycle emissions when biogenic $CO_2$ is included. Electricity pathways: E1 – CHP, E2 - Gasification + CHP, E3 - IGCC, E4 - anaerobic digestion + CHP; Methane pathways: M1 – gasification, M2 - anaerobic digestion;

Ethanol pathway: Eth1 - enzymatic hydrolysis + fermentation; Renewable diesel pathways: Rd1 - gasification + FT synthesis, Rd2 - pyrolysis + hydroprocessing; Bio jet fuel pathways: Bj1 - ATJ (ethanol), Bj2 - STJ (fermentation), Bj3 - pyrolysis (in situ), Bj4 - pyrolysis (ex situ), Bj5 - HTL (in situ), Bj6 - HTL (ex situ). Business-as-usual practices: BAU1 - left on field (agricultural residues), BAU2 - direct land application (animal manure), BAU3 – burning on-site (forest residues), BAU4 – landfilling without methane flaring or capture (MSW), BAU5 - landfilling with 75% of methane capture and use for on-site CHP (MSW). See Table 1 for additional details on conversion pathways.

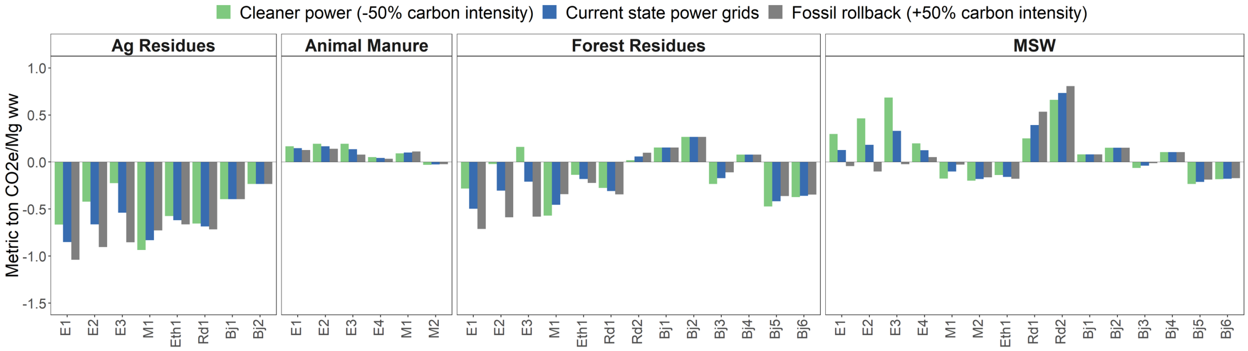


**Figure 2. Sensitivity analysis of emission estimates**. Electricity pathways: E1 – CHP, E2 - Gasification + CHP, E3 - IGCC, E4 - anaerobic digestion + CHP; Methane pathways: M1 – gasification, M2 - anaerobic digestion; Ethanol pathway: Eth1 - enzymatic hydrolysis + fermentation; Renewable diesel pathways: Rd1 - gasification + FT synthesis, Rd2 - pyrolysis + hydroprocessing; Bio jet fuel pathways: Bj1 - ATJ (ethanol), Bj2 - STJ (fermentation), Bj3 - pyrolysis (in situ), Bj4 - pyrolysis (ex situ), Bj5 - HTL (in situ), Bj6 - HTL (ex situ).

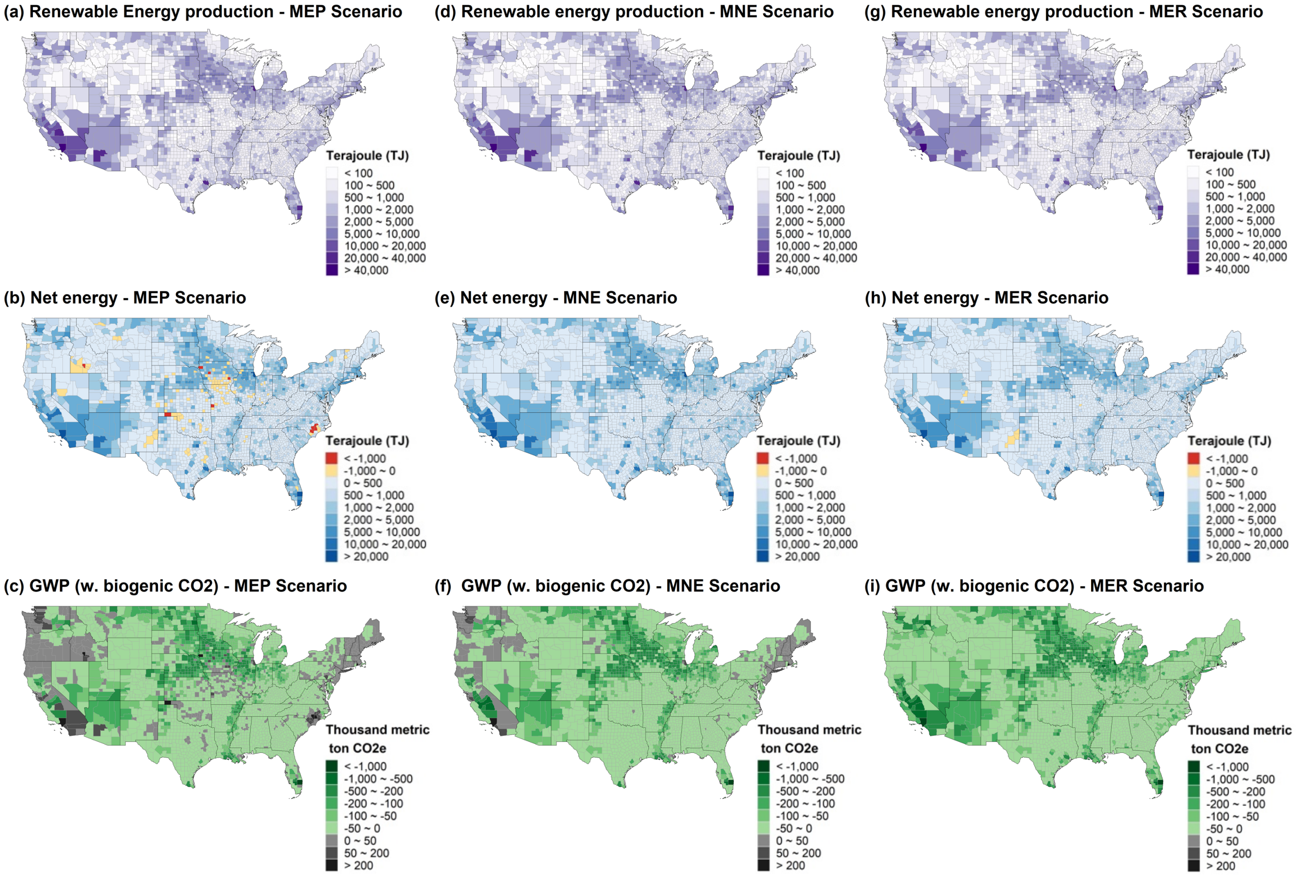


**Figure 3. County-level renewable energy production, net energy and emissions**. (a, b, c) The maximum renewable energy production (MEP) scenario. (d, e, f) The maximum net energy (MNE) scenario. (g, h, i) The maximum GHG emissions reduction (MER) scenario.

# Tables

**Table 1**. Description and attributes of conversion pathways

| Conversion pathway | Abb. name | Description | Feedstock feasibility | Energy input | Energy output (main) | Energy output (co-products) | Displaced products | References |
|---|---|---|---|---|---|---|---|---|
| Combined heat and power (CHP) | E1 | Thermal combustion through biomass CHP plants | All | Electricity, heat, diesel | Electricity | Heat | State power grids, natural gas-based heat | 15, 39, 40 |
| Gasification + CHP | E2 | Syngas is produced via gasification and is then combusted in gas engines to produce electricity and heat | All | Electricity, heat | Electricity | Heat | State power grids, natural gas based heat | 15, 33, 61 |
| Integrated gasification combined cycle (IGCC) | E3 | Electricity generation through combined gas and steam turbines with no heat recovery | All | Electricity, heat | Electricity | N/A | State power grids | 15, 33, 50 |
| Anaerobic digestion + CHP | E4 | Biogas is produced via anaerobic digestion and is then combusted in gas engines to produce electricity and heat | Animal manure, MSW | Natural gas, diesel | Electricity | Heat | State power grids, natural gas based heat | 28, 29, 40, 43, 50 |
| Gasification | M1 | Syngas is produced via gasification and is then upgraded and purified to produce methane. | All | Electricity, heat | Methane | N/A | Natural gas | 15, 61 |
| Anaerobic digestion | M2 | Biogas is produced via anaerobic digestion and is then upgraded and compressed for pipeline transmission | Animal manure, MSW | Electricity, heat, diesel | Methane | N/A | Natural gas | 28, 40, 43, 50 |
| Enzymatic hydrolysis + fermentation | Eth1 | Ethanol production via pretreatment, enzymatic hydrolysis, and fermentation | Ag and forest residues, CD waste, MSW wood, paper, yard trimmings | Natural gas, diesel | Ethanol | Electricity | Petroleum based gasoline, state power grids | 36, 50, 62 |
| Gasification + Fischer-Tropsch (FT) synthesis | Rd1 | Gasification to decompose biomass into syngas, and FT synthesis to convert syngas into liquid fuels with the presence of catalysts; excess steam is used for electricity generation | Ag and forest residues, CD waste, MSW wood, paper, plastics, yard trimmings | Electricity | Renewable diesel | Renewable gasoline, bio jet fuel, methane, electricity | Petroleum based diesel, gasoline and jet fuel, natural gas, state power grids | 20, 34, 44, 50 |
| Pyrolysis + hydroprocessing | Rd2 | Thermochemical conversion of a feedstock into bio-oil, bio-char, and pyrolysis gas; and integrated with hydrocracking and hydrotreatment processes for liquid fuel production | Ag and forest residues, CD waste, food waste, MSW wood, paper, plastics, yard trimmings | Electricity, natural gas | Renewable diesel | Renewable gasoline | Petroleum based diesel and gasoline | 35, 37 |
| Alcohol-to-Jet (ethanol) | Bj1 | Bio jet production with ethanol as the intermediate product | Ag and forest residues, CD waste, MSW wood, paper, yard trimmings | Hydrogen, electricity | Bio jet fuel | Renewable diesel, renewable gasoline | Petroleum based diesel, gasoline and jet fuel | 50 |
| Sugar-to-Jet (fermentation) | Bj2 | Sugar is separated from waste feedstock and is then converted into hydrocarbon or hydrocarbon intermediates through fermentation | Ag and forest residues, CD waste, MSW wood, paper, yard trimmings | Hydrogen | Bio jet fuel | N/A | Petroleum based jet fuel | 50 |
| Pyrolysis-in situ | Bj3 | Feedstock is dried, ground, and then converted to a mixture of bio-oil, gas, and char with high temperature (above 500 ℃). The | Forest residues, CD waste, MSW wood, | Electricity | Bio jet fuel | Renewable diesel, renewable gasoline | Petroleum based diesel, gasoline and jet fuel | 19, 20, 45 |

| Conversion pathway | Abb. name | Description | Feedstock feasibility | Energy input | Energy output (main) | Energy output (co-products) | Displaced products | References |
|---|---|---|---|---|---|---|---|---|
| | | conversion is continued by hydro-deoxygenating the bio-oil with hydrogen, which is produced through SMR of process off-gases | paper, yard trimmings | | | | | |
| Pyrolysis-ex situ | Bj4 | Same process as Bj5 except that hydrogen is produced from SMR of natural gas | Forest residues, CD waste, MSW wood, paper, yard trimmings | Hydrogen | Bio jet fuel | Renewable diesel, renewable gasoline | Petroleum based diesel, gasoline and jet fuel | 19, 20, 45 |
| Hydrothermal liquefaction (HTL)-in situ | Bj5 | Wet feedstock is converted into biocrude under temperature of 250-550 ℃ (with water as a medium), and is then hydro-deoxygenated with hydrogen, which is produced through steam methane reforming (SMR) of process off-gases and also anaerobic digestion of wastewater | Forest residues, CD waste, MSW wood paper, yard trimmings | Electricity | Bio jet fuel | Renewable diesel, renewable gasoline | Petroleum based diesel, gasoline and jet fuel | 19, 20, 45 |
| HTL-ex situ | Bj6 | Same process as Bj3 except that hydrogen is produced from SMR of natural gas | Forest residues, CD waste, MSW wood paper, yard trimmings | Electricity, hydrogen | Bio jet fuel | Renewable diesel, renewable gasoline | Petroleum based diesel, gasoline and jet fuel | 19, 20, 45 |

**Table 2.** Synergies between renewable energy, net energy and GWP at the county and state levels

| **Waste type** | **Feedstock** | **Total number of counties with feedstock available** | **All three criteria aligned** | | **Total number of states with feedstock available** | **All three criteria aligned** | | **Optimal pathway** |
|---|---|---|---|---|---|---|---|---|
| | | | Number of counties | Percent (%) | | Number of states | Percent (%) | |
| Ag. Residues | Barley straw | 136 | 52 | 38 | 14 | 5 | 36 | E1 |
| | Citrus residues | 118 | 53 | 45 | 9 | 3 | 33 | E1 |
| | Corn stover | 1276 | 793 | 62 | 36 | 22 | 61 | E1 |
| | Cotton gin trash | 815 | 329 | 40 | 17 | 6 | 35 | E1 |
| | Cotton residues | 796 | 305 | 38 | 17 | 6 | 35 | E1 |
| | Noncitrus residues | 1686 | 795 | 47 | 48 | 20 | 42 | E1 |
| | Oats straw | 12 | 4 | 33 | 2 | 1 | 50 | E1 |
| | Rice hulls | 144 | 77 | 53 | 6 | 3 | 50 | E1 |
| | Rice straw | 148 | 80 | 54 | 6 | 3 | 50 | E1 |
| | Sorghum stubble | 191 | 161 | 84 | 9 | 6 | 67 | E1 |
| | Sugarcane bagasse | 29 | 11 | 38 | 3 | 2 | 67 | E1 |
| | Sugarcane trash | 29 | 11 | 38 | 3 | 2 | 67 | E1 |
| | Tree nut residues | 620 | 234 | 38 | 40 | 14 | 35 | E1 |
| | Wheat straw | 696 | 207 | 30 | 32 | 11 | 34 | E1 |
| Animal Manure | Hogs, 1000+ head | 934 | 0 | 0 | 37 | 0 | 0 | - |
| | Milk cows, 500+ head | 639 | 0 | 0 | 44 | 0 | 0 | - |
| Forest Residues | Primary mill residues | 488 | 178 | 36 | 44 | 12 | 27 | E1 |
| | Secondary mill residues | 2418 | 590 | 24 | 49 | 11 | 22 | E1 |
| | Other forest residues | 1256 | 588 | 47 | 35 | 15 | 43 | - |
| | Other forest thinnings | 304 | 96 | 32 | 11 | 5 | 45 | E1 |
| MSW | CD waste | 3109 | 0 | 0 | 49 | 0 | 0 | - |
| | Food waste | 2792 | 0 | 0 | 48 | 0 | 0 | - |
| | MSW wood | 3109 | 2487 | 80 | 49 | 39 | 80 | Bj5 |
| | Paper and paperboard | 3109 | 0 | 0 | 49 | 0 | 0 | - |
| | Plastics | 3109 | 0 | 0 | 49 | 0 | 0 | - |
| | Rubber and leather | 3109 | 0 | 0 | 49 | 0 | 0 | - |
| | Textiles | 3109 | 0 | 0 | 49 | 0 | 0 | - |
| | Yard trimmings | 3066 | 0 | 0 | 49 | 0 | 0 | - |
| | Other MSW | 3109 | 0 | 0 | 49 | 0 | 0 | - |

**Note:** E1 - CHP; Bj5 - HTL (in situ).

**Table 3.** Total renewable energy production, net energy gain and GWP across scenarios

| **Policy scenarios** | **Renewable energy production** | | **Net energy gain** | | **GWP** | |
|---|---|---|---|---|---|---|
| | EJ | Index | EJ | Index | MMT $CO_2e$ | Index |
| MEP[1] | 3.8 | 100% | 2.9 | 89% | -103 | 58% |
| MNE[2] | 3.7 | 96% | 3.2 | 100% | -133 | 75% |
| MER[3] | 3.1 | 81% | 2.4 | 76% | -178 | 100% |

**Note:** [1] MEP: Maximum renewable energy production scenario.

[2] MNE: Maximum net energy gain scenario.

[3] MER: Maximum GHG emissions reduction scenario.