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ANALYSIS

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Life-cycle energy and climate benefits of energy recovery from wastes and biomass residues in the United States

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Agricultural and forestry residues, animal manure and municipal solid waste are replenishable and widely available. However, harnessing these heterogeneous and diffuse resources for energy requires a holistic assessment of alternative conversion pathways, taking into account spatial factors. Here, we analyse, from a life-cycle assessment perspective, the potential renewable energy production, net energy gain and greenhouse gas (GHG) emission reduction for each distinct type of waste feedstock under different conversion technology pathways. The utilization of all available wastes and residues in the contiguous United States 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 tonnes of CO_2-equivalent 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.

At the beginning of 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 60 countries worldwide[1]. As a consequence, global production of ethanol and biodiesel combined almost quadrupled (from about 35 billion litres to 135 billion litres) in the short span from 2005 to 2016 (ref. [2]). However, these policies had two major flaws. First, 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 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]. Second, 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 tonnes (Mt) of dry waste[16]. To put this in perspective, the approximately 60 billion litres of corn ethanol produced in the United States in 2017 required about 150 Mt of corn (assuming a yield of 402 l ethanol per Mt). 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 mitigation of 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, that is, towards becoming a circular economy[23,24]. However, 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 waste and the local conditions under which the wastes will be processed. The majority of previous life-cycle assessment (LCA) studies have focused on either a smaller number of waste types[14,27–35], certain types of bioenergy product[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 waste from a systems perspective is necessary for policies that address the best use of wastes and biomass residues.

Here, we determine the net energy gain and the global warming potential (GWP) of energy recovery from waste; which pathways simultaneously maximize renewable energy production, net energy gain and climate benefits for each type of waste and how this varies given the spatial distribution of their availability (specifically, in the contiguous United States); and what are the aggregate energy and climate benefits when all available wastes and biomass residues across the contiguous United States 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 United States. To this end, we quantify life-cycle GHG emissions and net energy gain for 15 conversion pathways (detailed

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Table 1 | Description and attributes of conversion pathways

Conversion pathway	Label	Description	Feedstock feasibility	Energy input	Energy output (main)	Energy output (coproducts)	Displaced products	Refs.
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 through 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	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 through anaerobic digestion and is then combusted in gas engines to produce electricity and heat	Animal manure, MSW (except plastics, rubber and leather, and textiles)	Natural gas, diesel	Electricity	Heat	State power grids, natural-gas-based heat	28, 29, 40, 43–50
Gasification	M1	Syngas is produced through 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 through anaerobic digestion and is then upgraded and compressed for pipeline transmission	Animal manure, MSW (except plastics, rubber and leather, and textiles)	Electricity, heat, diesel	Methane	N/A	Natural gas	28, 40, 43–50
Enzymatic hydrolysis + fermentation	Eth1	Ethanol production through pretreatment, enzymatic hydrolysis and fermentation	Ag. and forest residues, construction and demolition (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; 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 fuel 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 at high temperature (above 500 °C). The conversion is continued by hydrodeoxygenating the bio-oil with hydrogen, which is produced through steam methane reforming (SMR) of process off-gases	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
Pyrolysis ex situ	Bj4	Same process as Bj3 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
HTL in situ	Bj5	Wet feedstock is converted into biocrude at a temperature of 250–550 °C (with water as a medium), and is then hydrodeoxygenated with hydrogen, which is produced through 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 Bj5 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

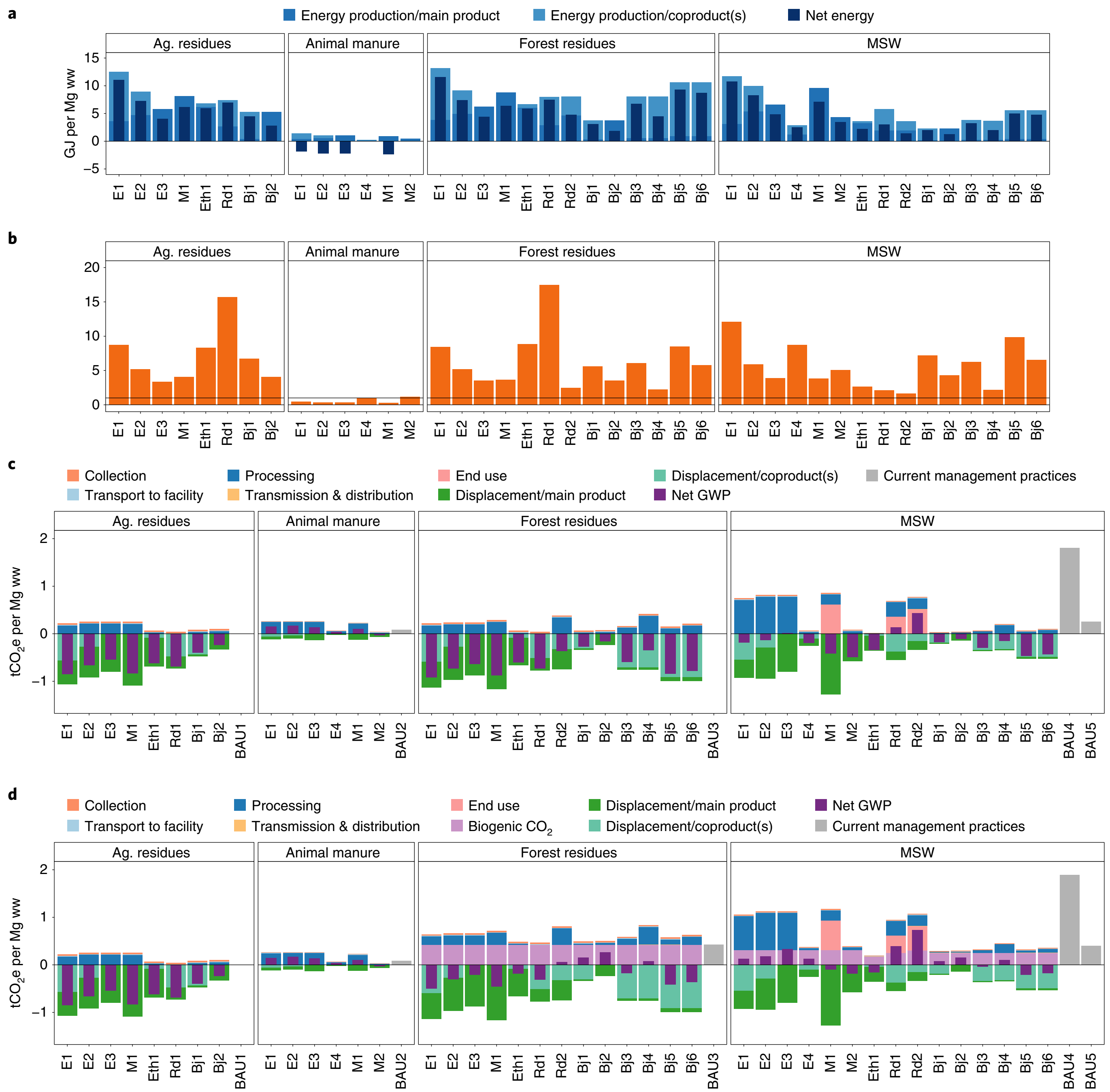

Fig. 1 | Energy, net energy and emissions from waste biomass utilization in the United States. **a**, Energy production and net energy by waste type and conversion pathway. **b**, Energy return on investment by waste type and conversion pathway (the horizontal line refers to an energy return on investment of 1). **c**, Life-cycle emissions when biogenic CO_2 is excluded. **d**, Life-cycle emissions when biogenic CO_2 is included. ww, wet weight. Electricity pathways: E1—CHP, E2—gasification + CHP, E3—integrated gasification combined cycle, 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—alcohol-to-jet (ethanol), Bj2—sugar-to-jet (fermentation), Bj3—pyrolysis (in situ), Bj4—pyrolysis (ex situ), Bj5—HTL (in situ), Bj6—HTL (ex situ). Business-as-usual (BAU) 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 of conversion pathways.

description in Table 1) and 29 waste feedstocks with spatially explicit estimates of waste potential for the United States. 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 United States 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 Mt of CO_2-equivalent ($MtCO_2e$) 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.

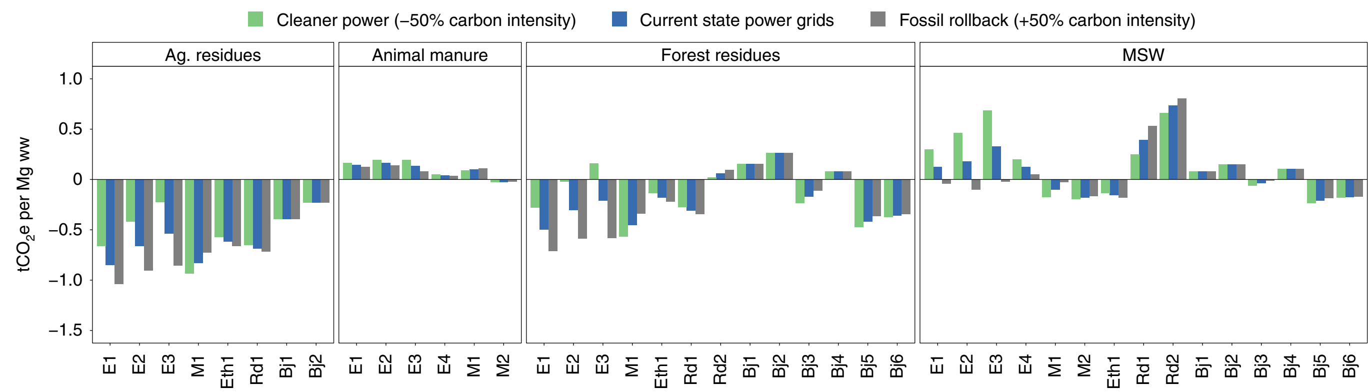

Fig. 2 | Sensitivity analysis of emission estimates. Electricity pathways: E1—CHP, E2—gasification + CHP, E3—integrated gasification combined cycle, E4—anaerobic digestion + CHP. Methane pathways: M1—gasification, M2—anaerobic digestion. Ethanol pathway: Eth1—enzymatic hydrolysis + fermentation. Renewable diesel pathways: Rd1—gasification + FT synthesis, Rd2—pyrolysis + hydroprocessing. Bio jet fuel pathways: Bj1—alcohol-to-jet (ethanol), Bj2—sugar-to-jet (fermentation), Bj3—pyrolysis (in situ), Bj4—pyrolysis (ex situ), Bj5—HTL (in situ), Bj6—HTL (ex situ).

Technical comparison of conversion pathways. We first estimate the renewable energy production, net energy gain and GHG footprint of different conversion pathways on a per unit wet weight basis for various types of waste. Feedstock-level results are depicted in Supplementary Figs. 5–7. Methods 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 $GJ\,Mg^{-1}$ (Fig. 1a,b). It is clear that the energy value of coproducts 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. For animal manure, only anaerobic digestion (M2) yields positive net energy, and its energy return on investment is only slightly greater than 1. The net GWP across the pathways ranges from −0.9 to 0.7 $tCO_2e\,Mg^{-1}$ (Fig. 1d). As with the importance of coproducts in net energy gain, emissions avoided by the resulting coproduct(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 the greatest climate benefits. For municipal solid waste (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. For animal manure, only anaerobic digestion producing either methane (M2) or electricity and heat (E4) yields climate benefits. This corresponds to 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 (that is, result in positive net GWP), all conversion pathways for forest residues yield smaller net GWP relative to burning them on site. When compared with landfilling without any methane flaring or capture, all conversion pathways for MSW result in smaller negative effects on the climate. However, landfilling with methane capture and on-site CHP would greatly reduce the GHG emissions of landfilling and become more attractive than renewable-diesel-related conversion pathways (Fig. 1c,d).

Breakdown 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 (Fig. 1). This is generally in line with results from a number of recent studies, such as refs. [15,20,34]. For agricultural residues, current management practice (that is, 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 feedstock, biogenic carbon would be emitted as biogenic CO_2 in 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 emission intensities of state power grids was conducted. Note that, even though biomass processing requires a substantial amount of heat energy, it is typically derived from natural gas, whose emission intensity is much less variable across regions relative to the emission intensity of electricity. Results show that cleaner power grids in general would yield less climate benefit for electricity pathways and more climate benefit for non-electricity pathways (Fig. 2). For cleaner power grids, electricity-related pathways would on one hand result in lower emissions during the processing stage, but on the other hand lead to less climate benefit from the displacement of grid electricity. For the majority of non-electricity pathways, electricity is only an input, so cleaner power grids would result in lower emissions during the processing stage and the overall life cycle. For instance, whereas converting agricultural and forest residues into electricity through CHP (E1) and into 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 Fig. 8). However, a distance ranging from 25 to 150 km negligibly affects results on GHG emissions. Thus, we

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	Percentage (%)		Number of states	Percentage (%)	
Ag. residues	Barley straw	136	52	38	14	5	36	E1
	Citrus residues	118	53	45	9	3	33	E1
	Corn stover	1,276	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
	Non-citrus residues	1,686	795	47	48	20	42	E1
	Oat 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, 1,000+ 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	2,418	590	24	49	11	22	E1
	Other forest residues	1,256	588	47	35	15	43	E1
	Other forest thinnings	304	96	32	11	5	45	E1
MSW	CD waste	3,109	0	0	49	0	0	—
	Food waste	2,792	0	0	48	0	0	—
	MSW wood	3,109	2,487	80	49	39	80	Bj5
	Paper and paperboard	3,109	0	0	49	0	0	—
	Plastics	3,109	0	0	49	0	0	—
	Rubber and leather	3,109	0	0	49	0	0	—
	Textiles	3,109	0	0	49	0	0	—
	Yard trimmings	3,066	0	0	49	0	0	—
	Other MSW	3,109	0	0	49	0	0	—

Note: E1—CHP; Bj5—HTL (in situ).

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 United States taking into account spatial variation in the electricity mix. As noted earlier, about 233 Mt of dry waste resources is available annually in the contiguous United States[16]. The spatial distribution of this total resource base is depicted in Supplementary Figs. 1 and 2. Approximately 25% of this total is concentrated in 115 counties, 50% is in 374 counties and 75% is in 884 counties (Supplementary Figs. 1 and 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 to 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 residue, CHP (E1) consistently stands out with respect to all three objectives for a substantial fraction of counties and states. For animal manure, no single pathway satisfies all three objectives. 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 a single pathway that achieves all three objectives for any given waste feedstock across locations is lacking, 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 emission reduction (MER). For each county in the United States, we first select the conversion pathway for each type

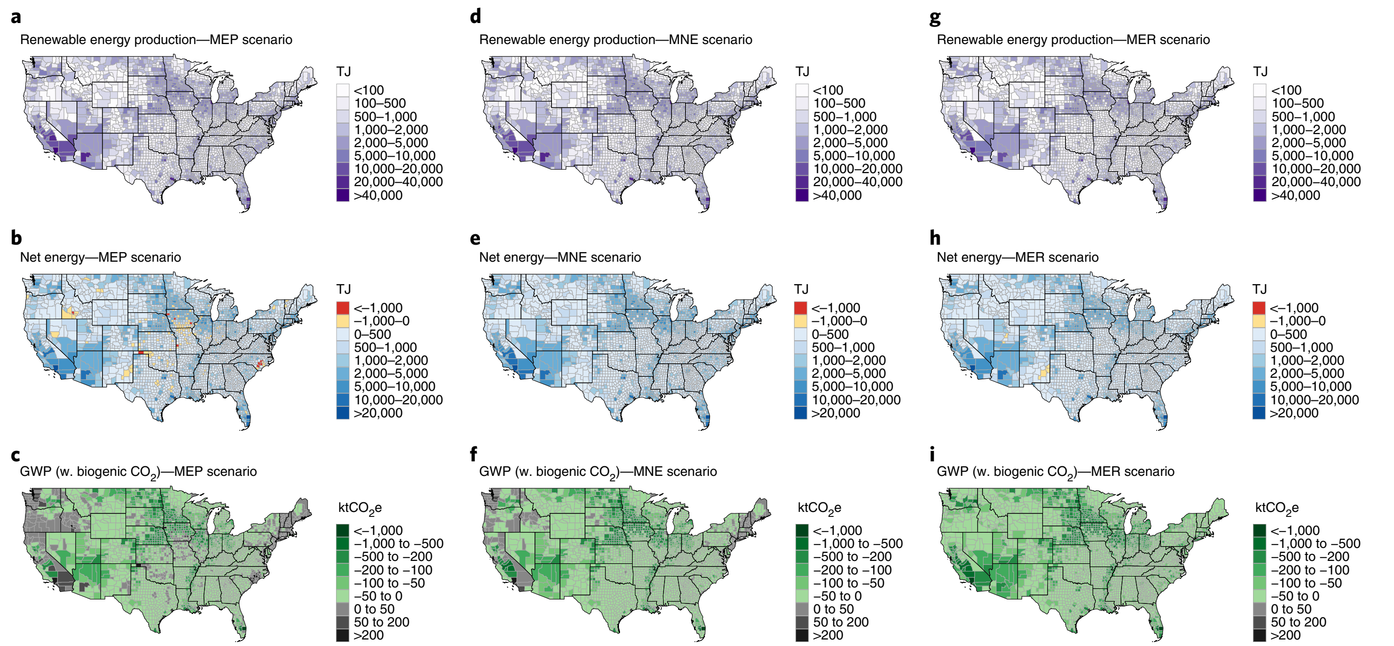

Fig. 3 | County-level renewable energy production, net energy and emissions. **a–c**, The MEP scenario. **d–f**, The MNE scenario. **g–i**, The MER scenario.

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 (%)	$MtCO_2e$	Index (%)
MEP	3.8	100	2.9	89	−103	58
MNE	3.7	96	3.2	100	−133	75
MER	3.1	81	2.4	76	−178	100

of waste under each of the three scenarios. The national results are the aggregation of county-level results. The calculations are described in Methods and results are depicted in Table 3 and Fig. 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 EJ—3.7% of total US energy demand in 2016 (ref. [46]), and MER results in the highest potential of emissions reduction, 178 $MtCO_2e$—2.7% of total US GHG emissions in 2016 (ref. [47]). The MNE scenario indicates the highest potential of net energy as well as a moderate amount of emissions reduction (75% of MER). A breakdown 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 emission 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 the largest amount of renewable energy and net energy gain, while either hydrothermal liquefaction (HTL) with in situ hydrogen production (Bj5) or gasification (M1) maximizes GHG emission reduction. In contrast to 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 these feedstocks instead of being stored in landfills. While the inclusion of biogenic CO_2 reduces net GWP for forest residues and MSW (Fig. 1c,d), 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 emission reduction (Fig. 3). Maximizing energy production would result in negative net energy in 125 counties and emission increase in 532 counties (Fig. 3b,c). Therefore, maximizing either net energy or emission 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 trade-offs 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 might not maximize even renewable energy production let alone environmental benefits. Likewise, renewable portfolio standards, a widely employed policy in the electricity sector, could lead to suboptimal use of waste biomass. In the literature, bioenergy and biofuel policies have been analysed mainly from the perspective of climate-change mitigation, food security or cost, but this analysis shows that they also do not optimize energy production. From a methodological perspective, this analysis illustrates the value of combining LCA with spatial analytical techniques for multicriterion assessment of alternative conversion pathways and the identification of hotspots for the refinement of existing energy policies. Indexing volumetric targets and mandates as well as financial subsidies for renewable energy to life-cycle emission-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 freshwater 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 15 conversion technology pathways included in this study can be categorized into five groups: electricity pathways (E1–E4), methane pathways (M1, M2), an ethanol pathway (Eth1), renewable diesel pathways (Rd1, Rd2) and bio jet fuel pathways (Bj1–Bj6). Details of the conversion pathways including process description, feedstock feasibility, energy inputs and outputs, coproducts, displaced products and references are presented in Table 1.

Approach to energy and emission accounting. We conducted an 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 pretreatment), transmission and distribution, and end use (Supplementary Note 2 and Supplementary Fig. 3). Thornley et al. showed that different functional units would result in varying outcomes when comparing alternative uses of biomass, and the functional unit should correspond to "the actual nature of the research questions"[48]. Since this study mainly focuses on the optimal use of wastes, the functional unit of this LCA is thus 1 Mg of wet waste.

Energy and emissions from collection and transport of feedstock are estimated on the basis of 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 the conversion pathway) were collected from the literature to calculate energy and emission 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 emission intensities of electricity generation and other fossil-based fuel production (heat, natural gas, diesel, hydrogen)[53–55]. Emission intensities of the production of electricity and fossil-based fuels vary geographically, and variation across states in such emission intensities was taken into account (Supplementary Note 3 and Supplementary Table 1). Life-cycle GHG emission intensities of state power grids were estimated by multiplying a state's generation mix from the Emissions & Generation Resource Integrated Database with life-cycle GHG emission intensities of respective electricity generation technologies from the LCA Harmonization project[56,57]. The GWP for non-CO_2 GHG is based on IPCC Fifth Assessment Report 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 on-site power generation, it is plausible that the former is more beneficial if electricity from biogas displaces clean electricity while renewable natural gas displaces diesel used in trucks or displaces fossil natural gas. Supplementary Fig. 4 illustrates a simple schematic representation of this concept. Posen et al. 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 coproducts, we chose the displacement method over allocation methods based on energy or economics for the following reasons. First, the International Standards Organization advocates the use of the displacement method[60] and it has been adopted as the default method in many LCA models and in biofuel regulation development in the United States. Second, many pathways yield a number of different types of energy product—electricity, heat, methane and/or liquid fuels. The conventional products to be displaced can easily be defined. Third, the distinction between main product and coproducts in this study is mainly to categorize the pathways into five groups. We intended to examine the conversion pathways from a systems perspective, that is, all types of energy product through 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 and so on) of electricity are different from those of other types of energy product, and so are those of each other type of energy product. 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 by 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, the 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:

$$\mathrm{EP}_{i,j,c} = \mathrm{WW}_{i,c} \sum\nolimits_k \left(\mathrm{EO}_{i,j,k}(1-\mathrm{TD}_k)\right) \tag{1}$$

$$\mathrm{NE}_{i,j,c} = \mathrm{EP}_{i,j,c} - \mathrm{WW}_{i,c}\left(\sum\nolimits_l \mathrm{EI}_{i,j,l} + E_{\mathrm{collection},i} + E_{\mathrm{transport}} D_1\right) \tag{2}$$

$$\begin{aligned} \mathrm{GWP}_{i,j,c} = \mathrm{WW}_{i,c}(&E_{\mathrm{collection},i} + E_{\mathrm{transport}} D_1) \\ &\mathrm{EmissI}_{\mathrm{diesel},c} + \sum\nolimits_l \left(\mathrm{EI}_{i,j,l}\mathrm{EmissI}_{l,c}\right)) + \mathrm{Emiss}_{\mathrm{process}} \\ &+ W_{i,j,k}\mathrm{EmissI}_{\mathrm{diesel},c} D_2 + \mathrm{Emiss}_{\mathrm{enduse}} + \mathrm{GWP}_i^{\mathrm{bioCO2}} - \mathrm{EP}_{i,j,k}\mathrm{EmissI}_{m,c} \end{aligned} \tag{3}$$

$$\mathrm{GWP}_i^{\mathrm{bioCO2}} = \mathrm{GWP}_{\mathrm{bio},i}\mathrm{Emiss}_{\mathrm{bioCO2},i} \tag{4}$$

where $\mathrm{EP}_{i,j,c}$ is the renewable energy production (MJ) of feedstock i through conversion pathway j in county c; $\mathrm{WW}_{i,c}$ the wet weight (kg) of feedstock i in county c; $\mathrm{EO}_{i,j,k}$ energy output k (MJ kg^{-1}) of feedstock i through conversion pathway j; TD_k the transmission and distribution loss of energy output k (6.5% assumed for electricity, 20% for heat and 2% for methane), $\mathrm{NE}_{i,j,c}$ the net energy (MJ) of feedstock i through conversion pathway j in county c; $\mathrm{EI}_{i,j,l}$ energy input l (MJ kg^{-1}) of feedstock i through conversion pathway j; $\mathrm{GWP}_{i,j,c}$ the net GWP (gCO_2e) of feedstock i through conversion pathway j in county c; $E_{\mathrm{collection},i}$ the energy consumption rate (MJ kg^{-1}) of collecting feedstock i; $E_{\mathrm{transport}}$ the energy consumption rate (MJ kg^{-1} km^{-1}) of transporting feedstock i to the conversion facility, D_1 the transport distance (km) from the temporary storage or collection site to the conversion facility (150 km assumed), $\mathrm{EmissI}_{\mathrm{diesel},c}$ the life-cycle GHG emission intensity (gCO_2e MJ^{-1}) of petroleum-based diesel in county c, $\mathrm{EmissI}_{l,c}$ the life-cycle GHG emission intensity (gCO_2e MJ^{-1}) of energy input l in county c, $\mathrm{Emiss}_{\mathrm{process}}$ the direct GHG emissions (excluding biogenic CO_2) during processing, $W_{i,j,k}$ the physical weight (kg) of energy output k of feedstock i through conversion pathway j; D_2 the transport distance (km) for distribution (150 km assumed), $\mathrm{Emiss}_{\mathrm{enduse}}$ the direct GHG emissions (excluding biogenic CO_2) during end use, $\mathrm{GWP}_i^{\mathrm{bioCO2}}$ the GWP (gCO_2e) of biogenic carbon in feedstock i, $\mathrm{EP}_{i,j,k}$ the energy production (MJ) of output k of feedstock i through conversion pathway j; $\mathrm{EmissI}_{m,c}$ the life-cycle GHG emission intensity (gCO_2e MJ^{-1}) of energy product m (which output k can substitute) in county c, $\mathrm{GWP}_{\mathrm{bio},i}$ the biogenic CO_2 global warming index with full impulse response functions for feedstock i and $\mathrm{Emiss}_{\mathrm{bioco2},i}$ the biogenic CO_2 emissions of feedstock i.

For the comparison of conversion pathways, county-level results were first aggregated to the national level and by feedstock. Weighted averages (by weight) of results by feedstock in each of the four broader categories of waste resources were calculated for the comparison by waste type (as shown in Fig. 1). For the current management of wastes and residues (that is, BAU practices in Fig. 1), we used the same emission 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 the emission 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 emission intensity of power grids in all states; and 'fossil rollback'—assuming a 50% increase in emission intensity of power grids in all states. In addition, a range of 25–150 km was examined to test the sensitivity to 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 Department of Energy's BT16. BT16 estimates the biophysical potential, spatial distribution, economic constraints and environmental impacts associated with existing and potential biomass resources[16]. Waste resources included in this study comprise four types of waste: agricultural residues (14 feedstocks, including both primary and secondary agricultural residues as defined in BT16), animal manure (2 feedstocks), forest residues (4 feedstocks) and MSW (9 feedstocks, including food waste). 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 for a more precise estimation of energy consumption and emissions during the collection and transport stages.

Scenario analysis. To explore the optimal utilization of waste biomass resources, we developed three alternative scenarios: MEP, MNE and MER. For all scenarios, the optimal conversion pathway for each feedstock was selected on the basis of the maximum value of energy or emission reduction. Under each scenario, the county-level results were then added up to obtain the potentials for total renewable energy production, net energy and emission reduction at the national level.

Data availability

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

Code availability

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

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Author contributions
D.R. conceived and designed the study, guided data collection, modelling and analysis and co-wrote the manuscript. B.L. contributed to the study design, collected the data, conducted the modelling and analysis and co-wrote the manuscript.

Competing interests
The authors declare no competing interests.

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