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Maximizing social benefit from finite energy resource allocation

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Abstract

Background: Since the industrial revolution, human population and fossil energy consumption have steadily increased. With concerns over fossil energy impact on air quality and global climate, there is increasing interest in collection and conversion of non-fossil energy feedstocks. These finite renewable feedstocks (biomass, solar, wind) provide a challenge based on their land-limited supply and temporal availability. Consequently, society needs methodologies to increase end-user efficiency to maximize the energetic utility and sociological benefit from the finite land base.

Methods: This paper presents a methodology for evaluating whole system effectiveness from a finite unit of biomass feedstock. By analyzing conversion of raw energy inputs into final energy services (FES) delivered in the form of transport or heat to society, we assess the FES returned on energy investment ($\mathrm{ERoEI}_{\mathrm{fes}}$). Comparison of $\mathrm{ERoEI}_{\mathrm{fes}}$ across 11 different conversion pathways illustrates the relative delivered social benefit of each pathway derived from the same finite feedstock.

Results: We found previously that New York (NY) could sustainably produce 14.2 Tg/y of biomass feedstocks from agriculture and forestry (equivalent to 7% of NY's primary energy consumption of 3.9 EJ). We found that high value FES as a percentage of energy in the biomass feedstock ranged from 5 to 15% for transport and 12 to 71% for heat (residential or commercial). However, the FES provided for six pathways was more than 2-fold higher if co-products were used. This method (1) internalizes energetic processing and use losses (2) to compare pathways and systems (3) that maximize services and value derived from land-limited sustainably harvested resources (4) thus providing a holistic approach increasing the value of a unit of land to generate primary energy resources, sustainably.

Conclusion: This case study provides a framework to assess a range of conversion pathways for any finite energy feedstock for society. Across all biomass types and conversion processes, the replicable $\mathrm{ERoEI}_{\mathrm{fes}}$ methodology provides a foundation for decision-makers to compare FES delivered and then develop policies that reap the most benefit per unit of finite feedstock, thus assisting in more effective transition away from fossil-based feedstocks.

Keywords: Biomass, energy conversion, Efficiency, Energy return-on-energy-investment (ERoEI), Transportation, Heat, Land-use, New York (NY), Final energy (FE), Final energy services (FES), Grass, Forest

Highlights

- Comparing $\mathrm{ERoEI}_{\mathrm{fes}}$ from different energy pathways can inform maximization of societal benefit from finite energy resources.
- The most efficient bioenergy pathways are cost-competitive with fossil fuels.
- Using co-products more than doubles the energy service benefits of several energy pathways.
- Our applied methodology and results can improve decision-making for efficient use of finite energy resources for society, using bioenergy as an example.

Background

As concern over climate change grows with increased weather variability impacting crop yields and as population and demand for products and energy increases, material production on our finite land base will be under a variety of new pressures. Society must increase whole-system efficiency to better meet human needs for food,

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feed, fiber, and fuel. One response to limited land availability is increased crop productivity on existing cropped area (intensification). For example, farm and forest owners have been integrating different strategies to create more products per hectare of land (e.g., maize and soybean [1], milk production [2]). Another approach is converting non-agricultural land into agricultural land (extensification [3]). However, extensification raises concerns such as release of CO_2 from land conversion [3, 4] and loss of wildlife habitat [5]. A third response would be to improve end-use of agricultural products. For example, the 2013 Food and Agricultural Organization (FAO) report indicated "produced but uneaten food… occupies almost 1.4 billion hectares of land; this represents close to 30 percent of the world's agricultural land area" [6]. Thus, improving end-use of food and other products may be an effective way to increase innovation and sustainable production from our finite land area.

In addition to intensification, extensification, and improved end-use of agricultural resources, modern societies use large amounts of energy per capita [7, 8]. As such, there is also interest in diversifying the products derived from the land to include bioenergy for energy security, improving the local economy and providing alternatives to non-renewable energy sources [9]. NY has 1.3% of US land area [10], but houses 6% of the US population [11], uses 4% of US energy [12], and emits 3% of the national energy-based greenhouse gases (GHG) [13]. Similar to countries like Poland, Spain, and Netherlands [14], energy consumption in NY is 3,932,829 TJ [15] and roughly split between three sectors: transportation, electricity, and heating. These categories do not indicate end-use efficiency by sector, merely the amount of primary fuel consumed by each sector. With these realities, NY Governor Andrew Cuomo announced several initiatives connected to NY land resources, including doubling land-based wind and solar and maximizing contributions from renewable resources as part of a suite of activities to achieve 100% clean power by 2040.

Societies depend on land to produce multiple products to meet society's needs, but it is likely that increased extreme precipitation, drought, and heat events from climate change [16] may undermine both the intensification and extensification strategies for both food and bioenergy production. Additionally, 2/3 of US energy resources are wasted from inefficient end-use [17, 18]. Improving whole-system energy efficiency can reduce associated environmental impacts on air, water, and climate [19].

The most common model for assessing the availability and accessibility of energy products to drive the economy is return on investment (RoI). RoI is a simple calculation: what is returned is divided by what is invested [20]. RoI analysis can be performed in monetary terms, energy terms (energy returned on energy invested, ERoEI), or another resource such as water (energy returned on water invested, ERoWI; [21]). The utility of these ratios is based on the denominator—the evaluation of the inputs invested. These ratios are intended to support decision-making for identifying the most cost-effective sources for *acquiring* primary energy from different *energy resource* pools (e.g., oil well, wind); the greater the energy return, the greater the positive impact on stimulating the economy [22]. Typically, ERoEI reflects the conversion efficiency of energy resources (e.g., maize) into *energy carriers* (e.g., ethanol), and the analysis ends at *final energy* (FE) or *useful energy* (e.g., liters of ethanol at a station pump); availability of high NE resources drives prosperity with little concern for system inefficiency with higher ERoEI indicating inexpensive energy production. With relatively cheap fossil energy resources and no regulatory instruments for reducing greenhouse gases or other environmental externalities, there is little impetus to improve system-wide efficiency. As we move away from non-renewable resources and toward more sustainable energy systems, we must evaluate the whole-system efficiency in order to maximize social benefit from either finite fuel resources (coal, nuclear) or the finite land base (with a limited surface area for annual solar energy capture by biomass, solar, etc).

Using NY as a case study, we modify the beginning and end of typical ERoEI analysis. First, we limit the upstream resource base to the sustainably harvested biomass from the available land in NY. Second, through a variety of conversion pathways, we compare the relative *final energy services* (FES, specifically distance traveled or space heated) achieved from the biomass harvested from the finite land base. As society moves to more sustainable energy systems, this new $\mathrm{ERoEI}_{\mathrm{fes}}$ can help determine the maximum social benefit as a function of real resource limits (yield from the available land) and current technologies (energy conversion and end-use efficiencies).

There are many forms of energy, but the efficiency of their transformation into end-use is not adequately evaluated. We previously determined that a total of 14.2 Tg/y of biomass feedstock could be sustainably produced in NY [2]. Converted to cellulosic ethanol, this feedstock would displace 16% of the 2015 state motor fuel [15, 23]. However, this saleable retail product does not represent FES delivered to society because the ethanol must undergo another conversion process to provide transportation in an internal combustion engine (ICE) while dispersing waste heat on the highway. Meanwhile, it is widely agreed that electric cars are significantly more efficient at traveling distance than ICE [24]. However, it is also recognized that conversion of biomass to electricity can be low compared to natural gas because of moisture content in the biomass. Additionally, both fuel sources are inefficient if waste heat from electricity generation is not used. Importantly, a power plant concentrates this wasted heat on site as compared to dispersed heat loss by individual ICEs. We developed $\text{ERoEI}_{\text{fes}}$ to compare conversion pathways from the same biomass feedstock, for example, comparing the low ERoEI bioelectricity coupled to highly efficient EV with the high ERoEI bioethanol coupled to relatively inefficient ICE to travel distance.

In the context of seemingly infinite supplies of fossil energy, identifying and accessing fuel was subsidized by the raw fuel itself. However, needs of the growing population with increasingly more energy intensive methods of extraction [20, 25], concerns about climate change, and the needs of future generations demand that we assess and improve the energy system efficiency. That is, we need to improve the energy returned as FES for society from the total energy invested [26]. This will require innovation throughout the energy system.

Of the primary energy use in the USA, only 40% becomes energy services [17]. We chose NY for our case study because it similar to the entire USA in terms of energy use inefficiency (38% becomes energy services) [18] and because it has substantial available land for bioenergy production. Here, we leverage our previous analysis of sustainable biomass production (identifying the sustainable increase in productivity by intensification and extensification) [2] to identify end-use effectiveness by comparing a variety of bioenergy conversion and FES pathways. Specifically, we compare FES delivered to society using 11 different pathways derived from the same potential sustainable biomass harvest in 2020 [2, 27]. To identify opportunities for improving energy self-sufficiency, we assess the FES achieved per unit of biomass. Our methodology can be applied to other feedstocks and fuels, locations, and production and conversion systems. However, our objective is to assess the societal benefit (distance traveled or space heated) per unit of energy feedstock (biomass) or land area across different pathways.

Materials and methods

Our analysis using $\text{ERoEI}_{\text{fes}}$ differs from previous ERoEI assessments in two important ways. Firstly, $\text{ERoEI}_{\text{fes}}$ compares FES from the same energy feedstock. To do this, we analyze energy use through the energy production system deducting any energy expenditure by harvesting, processing, or conversion of the raw resource from the final energy (FE) product before converting the remaining FE into two different FES: (1) transportation (distance traveled in a passenger vehicle) and (2) heating (space heating for buildings). While structurally similar to traditional ERoEI, this analysis expands the boundary to include FES, helping to assure that the FES delivered is both a quantitative and qualitative gain. Secondly, we contextualize this $\text{ERoEI}_{\text{fes}}$ by applying it to a finite but sustainable renewable energy supply to compare the effectiveness of current technologies to convert energy feedstock (sustainably produced NY biomass) into FES (transport or heat) for society from its available land base. That is, our land-limited $\text{ERoEI}_{\text{fes}}$ quantifies an “effective societal productivity” from finite sustainable biomass production while promoting system-wide efficiency.

To do this, we analyzed biomass by type, including physical characteristics (e.g., moisture content (MC), land productivity, energy content using lower heating value—LHV), energy inputs (planting, harvesting, transporting), processing (e.g., pelleting, ethanol conversion, electric generation), and end-use (e.g., internal combustion engines (ICE) v. electric vehicles (EV)) to assess the difference in final energy service (FES) accomplished for society from the same limited renewable feedstock. All types of energy were converted to joules (J). We do not account for embodied energy of labor, infrastructure such as grid/gas stations and roads/train tracks. For other processes, we chose representative values of current technologically available systems.

Scenarios

We cast five scenarios where the final energy service (FES) was transportation and six scenarios where the FES was space heating. Each scenario had one or more conversion process derived from harvested biomass. As a baseline, we included a wood chip power plant and maize grain ethanol plants currently operating in the state. Cellulose refers to a mix of cellulose feedstocks sustainably harvested: hardwood, softwood, short rotation woody crops, and grasses [2, 27].

FES scenarios for transport:

T1: Maize grain converted to ethanol in two existing plants for use in an internal combustion engine (ICE)

T2: Cellulose converted to ethanol for use in an ICE

T3: Cellulose converted to ethanol then converted to electricity for use in an electric vehicle (EV)

T4: Pelleted cellulose converted to electricity for use in an EV

T5: Green wood chips converted to electricity for use in an EV

FES scenarios for heat:

H1: Cellulose converted to ethanol then converted to electricity for electric heat (EH)

H2: Pelleted cellulose converted to electricity for EH

H3: Green wood chips converted to electricity for EH

H4: Cellulose converted to ethanol for use in a boiler for heat

H5: Pelleted cellulose used in a pellet stove for heat

H6: Maize grain used in a grain stove for heat

Harvest

Sustainability factors from biomass harvest

Constraints on agricultural harvest included the following: maintain current agricultural production, use perennials instead of annuals, use no-till or conservation tillage, use improved fertilizer management, and maintain profitability. Constraints on forest harvest included the following: maintain current production, harvest only timberlands, harvest less than net growth, focus on pre-commercial thinning and non-commercial species, leave standing dead trees and portion of tops, and provide adequate profitability (see Additional file 1: Table S1). These represent ambitious but achievable goals for continued rural innovation that increases productivity while reduces use of imported fuels and fertilizers [2].

Energy for growing and harvesting biomass, energy in biomass

For agricultural products, energy inputs were calculated for field preparation, field inputs (e.g., embodied energy of equipment, fertilizer), harvest energy (see Additional file 1: Tables S2 and S3), and transport to roadside [2, 27]. For forest products, energy use was calculated from forest harvest (e.g., felling, de-limbing), chipping, and transport to roadside [2, 27]. We do not include infrastructure such as creating logging roads. This analysis does not include energy loss during storage, assumes field-dried moisture content, and resulted in an average of 19 GJ per dry Mg of the combined sustainable harvest of cellulose (summarized in Table 1, for assumptions, values, and sources [2, 27]).

Transport

Transport 1—energy for moving raw biomass to a processing plant

Harvested cellulose was transported by truck, rail, or barge (> 95% travel by truck) with an average of 45 km to 24 sites for cellulosic ethanol production ([23], Appendix F). Results for "wet" biomass transport (at feedstock-specific moisture content) were applied to other uses of the same biomass, assuming similar transport distances regardless of processing type. For the two maize grain ethanol plants in NY, average grain transport distance was 197 km ([23], Appendix F).

Transport 2—energy for moving processed fuel to a retail site

Processed ethanol fuel was moved to a retail station (e.g., "gas" station) by truck with an average distance of 39 km ([23], Appendix F); we applied this value for all other processed fuels except electricity. For transmission and distribution (T&D) losses from electrical grid transportation, we followed the US EIA methodology [28, 29] where loss is the result of total disposition minus direct use. The NY specific value for T&D loss was 5.3% [29].

Primary product conversion

Moisture content of feedstock and product

Harvested maize grain was the feedstock for the two existing maize grain ethanol plants. For comparison, unprocessed maize grain (15.5% MC) was considered a product for use in a pellet stove. Chipped green wood (45% MC) was the feedstock for an existing biomass electric power plant in in Lyons Falls, NY (Lyonsdale). Cellulosic biomass (37% MC) was the feedstock for cellulosic ethanol or pelleted cellulose (5% MC).

Energy for cellulosic ethanol processing

Cellulosic ethanol production using all of NY biomass was assessed in Wojnar et al. ([23], Executive Summary). Specifically, the distributed system (24 plants across the state producing 230 million liter/year, MLY) estimates 5 billion liters of ethanol can be produced annually. In this

Table 1 Inputs and products

Feedstock/conversion	Inputs		Products				ERoEI*
	Feedstock energy content	Other energy inputs	Primary product		Secondary product		
	GJ/Mg	GJ/Mg[!]	GJ/Mg[!]	Form	GJ/Mg[!]	Type	1°P/other inputs
Green wood chips/existing 22% CHP	20.0	0.4	4.4	Electricity	9.6	Plant heat	9.9
Maize/existing ethanol plants	19.2	5.9	10.4	ETOH	2.5	DGS[^] for heat	1.8
Maize/n/a	19.2	1.1	19.2	Grain	0.0	n/a	17.8
Cellulose/pelleted	19.3	0.8	16.1	Pellets	0.0	n/a	19.9
Cellulose[#]/pelleted/30% CHP	19.3	1.1	4.8	Electricity	8.1	Plant heat	4.6
Cellulose/cellulosic ethanol	19.3	0.2	7.9	ETOH	0.6	Electricity	43.5
Cellulose/ethanol/35% CHP	19.3	0.3	2.7	Electricity	4.1	Electricity (ETOH) + plant heat (CHP)	8.5

[#] Pelleted cellulose available to generate electricity in a 30% efficient CHP is based on the net 1° product of pellets (16.1 GJ/Mg) to generate 4.8 GJ of electricity as primary product per Mg of feedstock

[^] DGS is for distillers grains that when pelleted can be used for heat (or for feed with a higher MC)

*Energy return on energy invested does not include feedstock energy content (ERoEI = 1°P/other energy inputs)

[!] GJ per Mg of original feedstock

system, all process energy is derived directly from the biomass. We did not account for materials, labor, or energy to construct or maintain cellulosic ethanol plants.

Energy for maize ethanol processing

Grain ethanol production is from two existing ethanol plants and their maximum production capacity. Grain ethanol requires 10 MJ/l of energy inputs for processing ([23], Appendix F). We did not account for materials, labor, or energy to construct or maintain maize ethanol plants.

Energy for drying biomass

Moisture content for maize grain used in pellet stoves was assumed to be 15.5%. Distillers Grains with Solubles (DGS) from existing grain ethanol plants are reduced to 50% MC and account for some of the process losses on site. Dryers cannot reduce moisture of DGS adequately by themselves, so dry biomass is added to it to achieve 30–40% overall MC and then dried to 15% for pelleting. Nonetheless, the same quantity of moisture must be removed from the original mass. We assumed a dryer used 1.18 MJ to remove 0.45 kg of water. For pelleting cellulose, we deducted 15% of initial feedstock to dry biomass to 15% [30, 31]. The process of pelleting brings the pellets down to 5% MC.

Energy for pelleting biomass

Energy inputs for pelleting (except for drying as described above) were estimated using a modification of Haase [30]. This estimate was used for pelleting of both the cellulose mix and the DGS co-product from maize ethanol production. We did not account for materials, labor, or energy to construct or maintain pelleting plants.

Energy efficiency of cellulose conversion to electricity

We identified three pathways for converting cellulose into electricity. The first pathway is based on an existing green wood (45% MC) electric power plant with a 22% conversion efficiency, where 22% of the energy in green wood chips becomes electricity. The second pathway is based on an existing Canadian coal plant retrofit to run on pelleted biomass (5% MC) where 30% of the energy in wood pellets becomes electricity in a combined heat and power (CHP) plant (Atikokan Station, Personal Communication, Brent Boyko, January 6, 2016). The third pathway converts the cellulosic ethanol to electricity in a 35% efficient electric power plant. In all cases, we assumed that required energy inputs parasitized the resultant fuel and are internalized in the conversion efficiency. We did not account for materials, labor, or energy to construct or maintain electric generating plants.

Primary energy service provided

Bioenergy to direct heat conversion

For conversion of biomass products to heat, we assumed an 80% efficient boiler for pellets (5% MC), a 75% efficient pellet stove for maize grain (15.5% MC), and a 99% efficient electric heating system. The proportion of energy that NY biomass could replace in the form of residential heat and hot water was derived from the most recent Residential Energy Consumption Survey [32]. We did not account for materials, energy, or labor involved in production or maintenance of pellet stoves, boilers, or electric heat systems.

Efficiency of existing vehicles for transport

We assumed that ICE vehicles convert 20% of fuel for transport (ICEs range from 14 to 30% efficient, [33, 34]) and EVs convert 75% of fuel for transport (EVs are 74–94% efficient, [34, 35]). The proportion of energy that NY biomass could replace motor gasoline transportation in the form of cellulosic ethanol (in ICE) or bio-electricity (in EV) was calculated using statewide primary energy consumption values by fuel type [15]. We did not account for materials, energy, or labor involved in production or maintenance of ICE/EV, grid/gas stations, or road/train infrastructure.

Potential secondary products (co-products)

Electricity from cellulosic ethanol production

Potential cellulosic ethanol production for 2020 will generate a co-product of 0.46 kWh/liter of ethanol produced ([23], Appendix G). We did not deduct T&D loss as we assumed this small amount of electricity would not travel far before use.

Distillers grains from grain ethanol production

Wet Distillers Grains (WDG) are 70% MC with a shelf life of 4–5 days. Dried Distillers Grains with Solubles (DDGS) are 10–12% MC with an indefinite shelf life. Distillers grains have high energy and protein content and are more suitable and valuable for animal feed than as a direct energy source as a fuel. However, in order to enable comparison with other pathways, we convert them to pellets for heat (assuming 0.91 Mg of maize = 378 L of ethanol + 479 kg of WDG or 309 kg of DDGS and deducting cost of drying and pelleting as described above). Because of the high nitrogen content, combustion of DDGS would require additional treatment of exhaust gases to remove nitrous oxides (NOx) if such technology was not already in place, but we did not include the energy requirement of any such infrastructure. We did not deduct any value for transporting this biomass to a consumer for either heat or animal feed.

Waste heat from biomass electric power generation

While in the past, the Lyonsdale plant sold its waste heat to a nearby paper plant, it no longer does so. However, with better planning, these systems can be designed to utilize the waste heat. For the current Lyonsdale system, we assumed an overall system efficiency of 70% if plant heat was utilized (22% of energy converted to electricity and 48% converted to useable heat). For a 2020 pellet-CHP and ethanol CHP scenarios, we assumed an 80% overall system efficiency. We did not account for the construction or maintenance of any infrastructure needed to properly utilize this potential co-product.

Existing energy product price

NY residential electric price averaged 18.4 cents/kWh including taxes (2008–2018, [36]). Ethanol price was estimated to be $0.79/l ($3/gal) [23]. Gasoline was $0.81/l ($3.08/gal, average of 2008–2018 values [37]).

Note: final energy vs. final energy services

We distinguish between final energy (FE) product defined as saleable retail energy products (conversion technology intended to produce saleable units of energy, e.g., liters of ethanol or kWh) from final energy services (FES) which are the actual services provided to society (e.g., vehicle transport or space heating). For products, we define the primary product (1°P) as the desired retail product from a processing plant and the secondary product (2°P) as a potentially saleable co-product. For FES, we distinguish between services accomplished by the 1°P from the potential services accomplished by the 2°P (if the 2°P is not used, it should be counted as an additional processing loss). To compare differences among energy processing pathways that provide FES for society, we defined five major categories of energy use: 1°P process loss, 1°P input loss, 1°P end-use conversion loss, 1°P final energy service (1° FES), 2°P final energy service (2° FES, potential). We define 1°P $\text{ERoEI}_{\text{fes}}$ as the fraction of energy in the unprocessed feedstock that provides FES (this implies the 2°P is not used and is considered a process loss). More generally, the maximum $\text{ERoEI}_{\text{fes}}$ for a given pathway is the fraction of the FES (provided by the 1°P + 2°P) derived from the unprocessed feedstock. Description of these terms can be found in the "Definitions" section below while processing steps are described in Additional file 1: Table S4.

Results

We previously determined that a total of 14.2 Tg/y of biomass feedstock could be produced sustainably in NY while accounting for competing land uses, production potential of the soils on the available land, and for recent technical advances in production efficiency [2]. Converted to cellulosic ethanol, this feedstock would displace 16% of the 2015 state motor fuel or final energy [15, 23]. However, this saleable retail product does not represent FES experienced by society because the ethanol must go through another conversion process to provide transportation in an ICE. To determine whether this pathway is most cost-effective and/or energy efficient use of our annual sustainable, regenerative, and land-limited feedstock, we compared 11 different conversion pathways to assess relative FES from the same total of potentially available sustainably produced biomass feedstock.

Biomass feedstock conversion to bioenergy products

There are many energy conversion pathways that could provide multiple FES for society from the NY sustainable bioenergy feedstock potential [2]. Primary energy product (1°P) conversion scenarios included the following *energy carriers*: (1) cellulosic ethanol, (2) pelleted cellulose, and (3) electricity (from cellulose as chips, pellets, or cellulosic ethanol in CHP). For each energy carrier, we specify the scale of the system for conversion (Additional file 1: Table S5). As a baseline of current feedstock conversion, we present an operating green wood chip electric power plant (Lyonsdale, NY) and two maize grain ethanol plants. The simple conversion efficiency (Additional file 1: Table S5) represents the energy in saleable primary energy product divided by the energy in the unprocessed feedstock. The simple conversion efficiency ranged from 22 to 100%. However, this value does not reflect the quality of the primary energy product (e.g., electricity or maize grain), system losses, or the inputs required for harvesting or processing. In this context, field-dried maize grain is 100% because all the grain harvested is, in principle, useable in a grain stove, provided there were no harvest losses. Clearly, the simple conversion efficiency only represents saleable bioenergy product, not net energy.

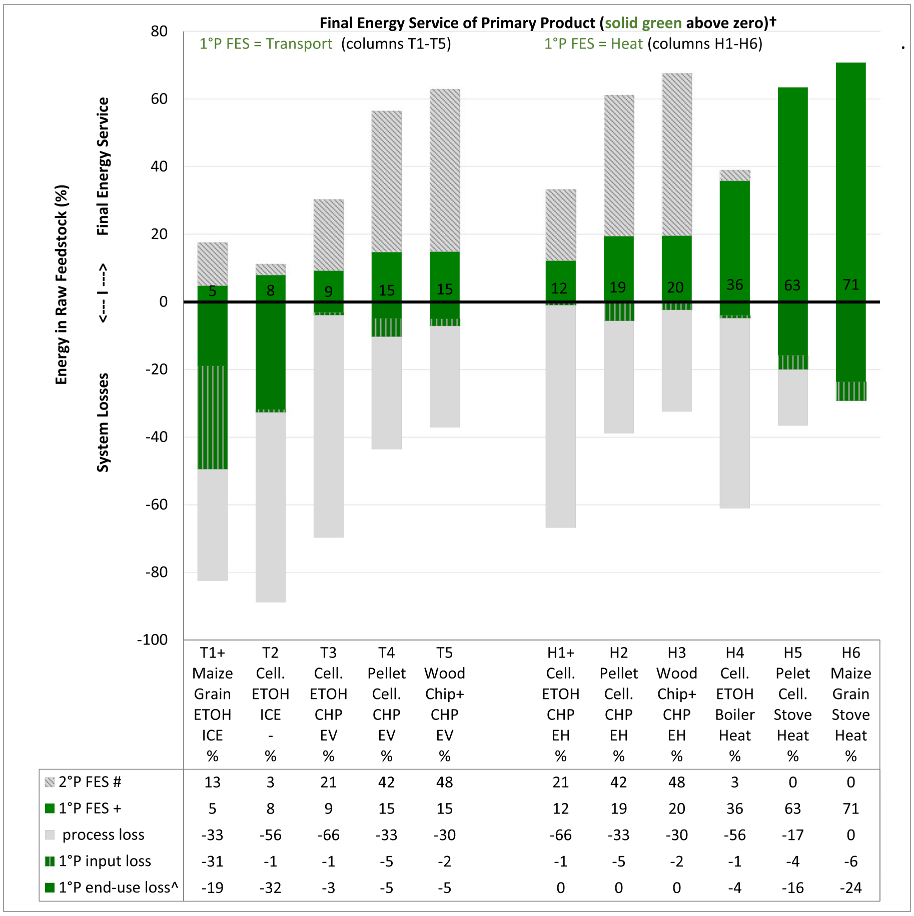
To compare the differing energy requirements for each pathway, we converted major inputs and products into energy per unit feedstock (GJ/Mg, Table 1). Inputs included embodied energy of the harvest equipment plus supplemental (external) energy required for growing and harvesting the feedstock, transporting unprocessed feedstock to the processing plant, converting feedstock to bioenergy with other energy sources, and transporting processed fuel to a retailer. Parasitic and auxiliary losses during conversion are counted as processing losses. Products included the 1°P and 2°P that resulted from processing the feedstock. Secondary products currently used included electricity from cellulosic ethanol or DDGS for feed, and potentially products like waste heat or pelleted DGS for heat. ERoEI ranged from 1.8 for maize ethanol to 43.5 for cellulosic ethanol (Table 1). As ERoEI is a simple calculation of primary product divided by other (external to the primary feedstock) inputs, the fewer the external inputs, the greater the ratio.

Final energy services accomplished for society

Converting retail products into FES for society causes additional energy loss. We focused on two major societal energy needs: transport (distance driven in an average passenger vehicle) and heat (space heating for buildings) . While the simple conversion efficiency ranges from 22 to 100% of the primary retail product (22% from converting existing green wood into electricity to no conversion for 15.5% MC maize grain for direct use in a pellet stove, Additional file 1: Table S5), it only represents losses from conversion of primary feedstock to saleable product (excluding external inputs). The simple ERoEI includes the inputs but lacks context for a saleable product (Table 1). For example, maize ethanol has an ERoEI of 1.8 because it uses 5.9 GJ/Mg of external inputs for processing while cellulosic ethanol has an ERoEI of 43.5 because its only input is harvesting costs and all its processing costs come from parasitizing its incoming feedstock (Table 1). In this case, the maize ethanol plant "produces" more "transportation fuel" out of a Mg of maize grain (as a function of its additional inputs) than the cellulosic ethanol plant produces out of a Mg of cellulose (as a function of it parasitizing its incoming feedstock, compare 1°P of maize ethanol as it relates to its harvested feedstock with the 1°P of cellulosic ethanol as it relates to its harvested feedstock, Additional file 1: Table S5). This comparison of two "transportation fuel pathways" illustrate that simple conversion efficiency is a measure of saleable retail product (to do a specific kind of work, e.g., you cannot put corn grain into a gas tank) while ERoEI is a metric of internal efficiency but indicates neither the quantity nor quality of the fraction of feedstock to effect FES for society. These metrics are for producers of saleable energy products, not FES realized by the end-user.

Neither of these metrics assist the consumer (society, policy makers) in identifying the most efficient way to travel by car or heat a home because they do not include the conversion to FES. For example, an electric vehicle is 75% efficient while an internal combustion engine is 20% efficient, both values are simple end-use conversion efficiencies disconnected from the efficiencies of upstream conversion steps of energy carriers. To address this issue, we analyze the fraction of energy expended or lost throughout the feedstock-to-final-energy-service pathway and constrained be the energy content of the unprocessed feedstock (Fig. 1). Comparing five transportation pathways (column T1–T5, Fig. 1) and six heat pathways (column H1–H6, Fig. 1) from the same biomass feedstock, transportation FES utilized 5–15% of the unprocessed feedstock energy while heat FES utilized 12–71% of the unprocessed feedstock energy (FES from the 1°P-solid green fraction above zero in Fig. 1). In Fig. 1, sections above and below zero that contain green (solid or striped) represent saleable bioenergy product (FE). However, solid Kelly green below zero indicates end-use conversion losses ("1°P end-use loss"—fraction of unprocessed feedstock energy that is a loss incurred by the consumer using the 1°P in their 75% efficient EV or 20% efficient ICE) and striped Kelly green below zero represents supplemental energy inputs used to convert the feedstock to a primary product ("1°P input loss"—fraction of unprocessed feedstock energy that was brought in by the producer from an external energy source to process the fuel). That is, we deducted high-quality energy inputs from our resultant high-quality FE of our 1°P, in attempt to "replace" the high-quality of inputs, internally supporting the next generation of renewable energy production, independent of external sources. In the case of cellulosic ethanol which does not use many external energy inputs (excepting those used to grow, harvest, and transport the biomass feedstock, Table 1) its source of energy to convert the feedstock to a primary product is derived directly by "parasitizing" the feedstock during conversion as shown in Fig. 1 by the relatively large "process loss"—fraction of feedstock lost during processing, solid gray bar below zero in T2, T3, H1, and H4. Likewise, potential co-products (2°P FES, striped gray above zero) if not used would be considered a "process loss" and added to the solid gray below zero. In Fig. 1, the simple conversion efficiency represents the marketable outcome of feedstock conversion regardless of external inputs (striped green + solid green divided by the total of all bars), while the ERoEI represents the ratio of the energy in the FE to the energy in the external inputs (ratio of solid green divided by striped green). Our $\mathrm{ERoEI}_{\mathrm{fes}}$ is unique in that it expands the analysis from simple FE production to the limits of the sustainable feedstock availability and the actual FES delivery (in this case, limited to transportation and space heating with current FES infrastructure).

In Fig. 1, after assessing process and conversion losses, the 1°P FES (numbers listed above zero for each column) ranged from 5 to 71% of the raw biomass delivered as services to society, specifically 5–8% for transport by ethanol in an ICE (Fig. 1, column T1 and T2), or 9–15% for transport by EV (Fig. 1, column T3–T5), or 12–71% for space heating (in home or business; Fig. 1, column H1–H6). The more efficient the use of the finite sustainable and renewable raw resources (in this case, 274,825 TJ sustainably harvested biomass per year), the greater the proportion of NY primary energy consumption (3, 932,829 TJ in 2015) can be reduced with concomitant impacts. Converting this biomass to ethanol for a primary transportation service could displace 16% of motor gasoline [23]. For primary heat service, producing pellets could displace 53% of residential primary space heat. Producing pellets for electricity for transport or heat



	T1+ Maize Grain ETOH ICE %	T2 Cell. ETOH ICE - %	T3 Cell. ETOH CHP EV %	T4 Pellet Cell. CHP EV %	T5 Wood Chip+ CHP EV %	H1+ Cell. ETOH CHP EH %	H2 Pellet Cell. CHP EH %	H3 Wood Chip+ CHP EH %	H4 Cell. ETOH Boiler Heat %	H5 Pellet Cell. Stove Heat %	H6 Maize Grain Stove Heat %
▨ 2°P FES #	13	3	21	42	48	21	42	48	3	0	0
■ 1°P FES +	5	8	9	15	15	12	19	20	36	63	71
□ process loss	-33	-56	-66	-33	-30	-66	-33	-30	-56	-17	0
▥ 1°P input loss	-31	-1	-1	-5	-2	-1	-5	-2	-1	-4	-6
■ 1°P end-use loss^	-19	-32	-3	-5	-5	0	0	0	-4	-16	-24

Fig. 1 Social comparison of energy investment—proportion of final energy services potentially realized (above zero) to system losses (below zero) as percentage of energy in the same harvested feedstock across multiple conversion pathways. † For description of terms and processing steps, see Materials and Methods or Additional file 1. + Columns T1-T5: Final Energy Service (FES) from the 1°P is Transportation; Columns H1-H6: FES from 1°P is Heat. # 2°P FES is a potential for co-product to deliver FES (diagonal stripes above zero); if not used, this potential co-product should be joined with light grey below zero representing additional process losses. ^ Losses during transformation of primary fuel to provide FES (e.g. an ICE turns ethanol into heat in vehicle engines on the highway: for all intents and purposes this heat is not recoverable though a fraction warms passengers in winter months) as separate from useable heat co-products potentially captured at conversion (diagonal stripe above zero) in large quantities at CHP sites. *CHP*, combined heat and power; *EV*, electric vehicle; *EH*, electric heat; *ICE*, internal combustion engine; *Cell*, cellulose; *ETOH*, ethanol; *2°P FES*, secondary product (co-product) with the potential to provide additional energy services; *1°P FES*, portion of the primary product that results in a FES; *FES*, Final Energy Service (transport, heat)

could displace 12.2% of NY electricity production. Using this bio-electricity in vehicles could displace 38.7% of motor gasoline use, which is more than twice the energy benefit of producing ethanol and using it for transport in ICE. If the waste heat was used from this bio-electricity, it could displace an additional 27.7% of residential space heating demand (or 21% of residential space heating + hot water demand).

It is crucial to recognize that these energy co-products (diagonal striped gray bar above zero; Fig. 1, specifically columns T3, T4, T5, H1, H2, H3) could potentially be utilized and would increase the system efficiency substantially. Currently, only the electric co-product produced by the cellulosic ethanol plants and the feed co-product of DGS produced by the maize ethanol plants are used. In the case of the waste heat from CHP systems, it is more realistic to be used for industry processes then residential space heat. For example, previously, the Lyonsdale green wood chip power plant sold the heat co-product to a neighboring paper plant to dry paper. However, the paper plant has recently installed a natural gas dryer and no longer uses the waste heat from the Lyonsdale plant. In most cases, the diagonal striped gray bar above zero is an opportunity for improved planning and utilization of energy resources. However, as stated above, if not used (and most are not), this fraction should be added to the solid gray bar below zero and considered a process loss.

Our analysis of FES is broken into two parts to differentiate between the FES derived from the primary energy product 1°P FES (e.g., Fig. 1, column T2: transport by cellulosic ethanol in an ICE or 8% of the initial feedstock energy) plus the unused potential of the co-product 2°P FES (e.g., Fig. 1, column T2, unused electricity or 3% of initial feedstock energy) for a total of 11% of feedstock. If this same cellulosic ethanol (Fig. 1, column T3) were used to generate electricity, 9% of the initial feedstock energy would be used for transportation services (1°P FES) and additional 21% of initial feedstock energy could potentially be used in the form of heat at the centralized electric power plant (as opposed to decentralized waste heat lost on the road by individual ICE vehicles). If, however, this same cellulose was pelleted to 5% MC (Fig. 1, column T4), combusted in a CHP, 15% of the initial feedstock energy would be used for transportation services (1°P FES) and an additional 42% of the initial feedstock energy could be used as waste heat (hypothetical 2°P FES). In this comparison, the same feedstock nearly doubles its primary transportation services (Fig. 1, 8% for column T2 and 15% for column T4). In this scenario, the "waste" heat products are also concentrated at the site of the electric generating plant (not dispersed on the road by ICE) and if made useable, increase the overall FES to be 57% of the raw feedstock (Fig. 1, column T4) compared to 11% (Fig. 1, column T2). Thus, the different pathways greatly differ in the feasibility of using energy co-products such as waste heat to provide a secondary energy service to society.

In summary, for transport, wood chips or pellets in combined heat and power systems provided the greatest amount of 1°FES for society. For heat, pellets or maize grain provided the greatest amount of 1°FES for society. However, the amount of FES produced for six pathways triples if co-products can be used productively, for example, in combined heat and power systems. If co-product (heat) can be used, the FES provided by CHP (with pelleted cellulose or wood chips) for either transport or heat is similar to using pelleted cellulose in distributed residential heating systems (Fig. 1). However, unlike the direct heat scenarios, the CHP scenario provides a variety of energy products, notably electricity with its diverse utility.

Across all feedstock and conversion processes, the 1°P FES ranged from 5 to 71% of the initial energy in the unprocessed feedstock. Because EROEI_{fes} is a measure of efficiency expressed in terms of total energy input (feedstock + process inputs) and the total feedstock is limited by the land area and biomass yield, EROEI_{fes} could be used as a rough metric to compare social benefit derived from the same finite area of land. That is, efficiency in the end-use of any feedstock will directly reduce the demands on the finite land base. While EROEI_{fes} can be applied to any feedstock for comparison across energy resources (renewable and non-renewable) and types of FES, it is not a measure of the financial cost to citizens for purchasing energy products.

Cost effectiveness

To assess end-use cost, we compared current prices for fossil fuel, ethanol, and electricity for vehicle transport (Table 2) or home heat (Table 3).

Given current residential electric prices and the efficiency of electric vehicles to turn electricity into transport, the electric vehicle is much more cost effective mode of transportation at $3.76 per 100 km as compared to $11.23 by ethanol in an ICE. According to the NY Department of Motor Vehicles (NY DMV), there are over 9 million vehicles registered in the state and nearly 7000 are EV (< 0.1%). Meanwhile, the New York State Energy Research and Development Authority (NYSERDA) has a goal of 1 million EV by 2025 [38]. This cost effectiveness of EV is based purely on the residential market price for electricity and does not include any additional sale of waste heat captured at the electric generating plant. Notably, we did not account for energy or cost to make an EV or ICE, nor did we extend this analysis to more efficient trains for transportation and the associated infrastructure associate with either road or rail systems.

For home heating, maize grain is nearly as cost-effective as natural gas with the added benefit that it is a renewable resource. While our EROEI_{fes} methodology does not compare the externalities associated with growing maize to the externalities of mining natural gas (greenhouse gas emissions, water contamination, land-use etc.), given current markets, technology, and subsidies, this analysis illustrates that maize grain is cost-equivalent for rural areas. In more densely populated areas, we hypothesize that the EROEI_{fes} of natural gas for electric generation combined with "waste" heat use for space heat or hot water would make it both resource and cost efficient.

Table 2 Cost effectiveness of transport system

Fuel^	Price	Unit	Energy used	Units	MJ/unit	Unit	MJ/100 km	$/100 km
Ethanol	$0.79	Liter	14.2	Liters/100 km	80	Liter	1132	$11.23
Gasoline	$0.81	Liter	9.3	Liters/100 km	122	Liter	1132	$7.57
Electric	$0.18	kWh	20.5	kWh/100 km	4	kWh	74	$3.76

This analysis does not include any price premium to purchase/maintain an electric vehicle compared to internal combustion engines

^EIA indicated that gasoline and electric include taxes. It is unclear if ethanol price reflects taxes. None of these prices reflect the subsidies for any processes inherent in any pathway. Gasoline and electric prices were average residential prices in NYS from 2008 to 2018 [36, 37], while the ethanol price from NYSERDA Biomass Roadmap [23]

Table 3 Cost effectiveness of heat systems

Type	Price	Unit	End-use conversion efficiency (%)	$/MJ
Electricity	$0.18	kWh	99	$0.052
Fuel oil	$0.87	Liter	85	$0.027
Wood pellets	$0.27	kg pellets	80	$0.018
Natural gas	$0.53	Cubic meter	90	$0.015
Maize grain	$0.16	kg maize grain	75	$0.013

Discussion

This case study demonstrates a methodology for analyzing the efficiency of renewable energy systems to meet societal needs. By understanding the potential production of sustainably harvested bioenergy feedstock and comparing energy system efficiency across a range of final energy services (FES) for society, policy makers can begin to grapple with developing energy supply-chains systems that effect the greatest good from the finite land base. Upstream of our analysis, we established sustainable, intensification, and extensification goals for rural innovation of crop and forest production on the available NY land base [2]. In the $\text{ERoEI}_{\text{fes}}$ process, external inputs were replaced by high-quality FE, thus deducting the available FE to provide FES to society. Then, the $\text{ERoEI}_{\text{fes}}$ was applied to multiple energy conversion pathways to accomplish the two types of FES for society (transport and heat). From the results (e.g., Fig. 1), specific opportunities to maximize FES from a finite feedstock can be identified. These opportunities exist both within a single pathway and among different pathways. Additionally, pathways with high system efficiency are likely to be more cost-effective and have fewer negative externalities due to spreading the externalities over a greater amount of FES provided for society. In contrast to our focus on energy services, previous energy analyses such as ERoEI have primarily focused on the supply of energy products. For example, our analysis demonstrated that using pelleted/chipped cellulose to produce electricity for transport provides 2-fold more FES (from just the primary product) than using cellulosic ethanol as a motor fuel from the same feedstock grown on the same quality and quantity of land area in NY (Fig. 1). Furthermore, transport by electricity costs the consumer half as much to drive 100 miles than by gasoline, whereas ethanol is nearly three times more expensive than transport by electricity (Table 2). Additionally, if the waste heat was used at the site of this electric power production (e.g., drying paper at a paper mill), nearly 60% of the energy in the raw biomass could be utilized to provide final energy services needed by society.

ERoEI is an appropriate methodology for prioritizing development of energy supplies for society. A century ago, ERoEI of domestic oil and gas was twice that of today [20, 39]. Traditional ERoEI methodology allows decision-makers to discern differences in quality of acquiring a resource, differences in the cost to extract the energy, and therefore differences in cost to produce marketable units of fuel. However, contemporary concerns about energy supply go beyond immediate economic impacts and include many types of environmental impacts with direct and indirect costs (e.g., particulate matter (PM) impacts on health, GHG emission impact on climate, and water depletion and contamination) as well as impacts on future generations (e.g., depletion of non-renewable resources). ERoEI is useful, but does not typically consider greatest FES to society. This analysis meets the need for a more comprehensive methodology to support analysis of entire energy supply chains to help decision-makers support policies that deliver the greatest FES for societal benefit.

This analysis pragmatically draws from several existing types of analysis by expanding the boundaries of traditional ERoEI methods. Specifically, by using sustainably harvested biomass, we prevented many harmful social and environmental externalities. Sustainability criteria of intensification and extensification of the NY landbase included consideration of competing uses for land, maintaining other ecosystem services such as food, feed, and fiber production and returning nutrients to the landscape [2]. We then compared different processing and end-use efficiencies of this same limited energy feedstock resource to produce final energy services (not energy products). Our analysis was (1) simpler than exergy analysis, (2) more expansive than ERoEI analysis, (3) able to compare business-as-usual and best available technologies, and (4) able to create a first-order quantification of how society might live within its sustainable supply of resources. We quantified different existing energy conversion systems with their financial cost and FES benefit within the political and geographical boundary of NY to assist policy makers in developing more efficient use of the state's finite resources for currently defined demands with currently available energy conversion and use technologies. From increased productivity in rural land practices to improved efficiency of transportation in urban areas, $\text{ERoEI}_{\text{fes}}$ provides a method to connect rural and urban innovation to meet societal energy service needs.

Most ERoEI analyses are motivated by the underlying importance of energy to the economy. If energy prices are low, the economy can flourish. For example, some suggest an ERoEI of < 7 causes a rapid decline in material wealth [40]. Using up high-energy fuels or deciding to transition to renewables is thought to be crippling to the economy [22]. The ERoEI of the results herein ranges from 1.8 to > 43 (Table 1), indicating several of our renewable energy scenarios evaluated are above this limit. This ERoEI range in our study is compatible with the range of ERoEI in a recent study of biomass-based energy production (ERoEI = 1.2 to < 23 for ethanol and biogas systems, [41]). It should be strongly noted that the ERoEI as usually used does not provide utility for assessing FES not the services gained from a finite feedstock or land area. For example, while the cellulosic ethanol in this study has an ERoEI of 43.5, this is due primarily to it parasitizing the finite feedstock. Because bioenergy feedstock production is land-limited, a high ERoEI derived by parasitizing the finite feedstock does not provide much FES to society.

In contrast, our $\text{ERoEI}_{\text{fes}}$ methodology shifts the focus from acquisition of energy resources to assessment of effective delivery of FES to society from a sustainable supply. Thus, $\text{ERoEI}_{\text{fes}}$ moves beyond the idea of product conversion efficiency (e.g., convert raw feedstock to "transportation fuels" by combining two solid feedstocks such as coal + maize grain to generate a liquid fuel suitable for ICE transportation). $\text{ERoEI}_{\text{fes}}$ re-frames RoI or ERoEI from the theme of simple energy conversion (to be purchased by society) to energetic and cost effective delivery of FES for society. However, while we accounted for the energy costs associated with sustainably growing, harvesting, processing, transporting, and converting biomass, we did not analyze the financial subsidies or externalities associated with the entire costs of any energy project, nor did we analyze existing or new capital costs or construction of shared infrastructure such as highways or rail tracks. Despite this limitation of scope, we think that the results of ERoI_{fes} provide better guidance for policy makers than does ERoEI as it has been applied in the past to energy products. Recognizing that energy is the underlying driver of all activities, policy makers have an opportunity to direct initiatives to increase profitability of farms/forests by increasing the utility of biomass throughout the supply chain and recycling local dollars spent on energy, while decreasing emissions and providing more FES per unit of sustainably harvested renewable resources in the state. By combining innovations in rural production with increased efficiency of end-use, society can do "more with less," which is critically important as human populations demand more from our biophysically limited and finite land base and as societal concerns grow around increased climate variability impacting yield.

By focusing on types of energy services required by society, $\text{ERoEI}_{\text{fes}}$ provides comparison among pathways to provide specific types of FES from various feedstocks. In particular, $\text{ERoEI}_{\text{fes}}$ identifies specific opportunities to accomplish maximum FES from any finite energy supply (such as fossil, nuclear, or biomass). For example, a fleet of ICE vehicles disburses its waste heat along roadways. In contrast, a fleet of EV concentrates the waste heat at the site of electric generation, making it more feasible to be used by a cooperating industry to accomplish heat-based work (e.g., drying paper at a paper mill co-located with the power plant with unused heat products). However, as in the case of the DDGS, clearly, there are other societal sources of energy derived from the land (food) with very different metrics of FES. Because of our focus on transportation and space heating energy demand, we analyzed the use of DDGS as a fuel to produce energy. However, due to its protein content, it is more valuable as an animal feed and for the same reason is a problematic fuel for combustion due to potential production of air pollution via NOx unless adequate pollution control technologies are used. More broadly, we recognize that all of the feedstocks utilized in this report could support a diversity of other materially based objectives in addition to transportation and space heating.

$\text{ERoEI}_{\text{fes}}$ achieves the following: (1) compares energy delivery pathways and FES, (2) internalizes processing energy costs as a fraction of the starting feedstock and deducts external energy inputs from high-quality primary energy products, (3) identifies effective energy delivery efficiencies, and (4) provides a foundation for comparing other environmental or social implications of different energy services. In this case, we demonstrate analysis of cost effectiveness and fossil fuel replacement value. We can envision comparing air quality attributes such as GHG and PM emissions of these different conversion processes next.

Availability of inexpensive energy has promoted specific types of economies of scale. Economies of scale may reduce capital costs for energy-intensive materials such as concrete and steel as well as labor, but are predicated on a system of transporting inputs and outputs while also concentrating by-products. For example, New York City (NYC) was formerly powered by suite of coal-fired combined heat and power plants that provided heat and electric needs located throughout the city. As a result of the fuel type, location, and technology, there was a concentration of PM emissions damaging air quality in a densely populated area. To reduce human health impacts, coal power plants were moved outside the densely populated city and imported by the grid. However, the city still needs to be heated with other fuels (with their associated emissions). In effect, in an effort to move coal-based electric production out of the city to reduce PM exposure, twice as much fuel is being used in the winter (with associated air and waste heat emissions shifted to the site of the electric production and then also air emissions from the fuel used in the city for heating). To note, NYC recently banned #6 diesel for heating due to its air quality impacts [42], and now, natural gas is the primary source of heat (and could make higher quality electricity in the city while also providing heat if natural gas combined heat and power were instituted across NYC). One could certainly imagine strategizing feedstock and scale of CHP to address air quality considerations and meet heat and electric needs without wasting the heat associated with remote electric power plants. Of NY primary energy consumption, 27% is lost as waste heat and T&D loss from just electric generation. The annual 1,482,000 TJ statewide electric conversion loss [15] could displace much of the heat demand in this northern climate. Approximately 65% of residential energy use (546,244 TJ/year) is for primary space heating (49%) and hot water (16%) [32]. "Waste" heat from cellulosic pellet CHP could displace 21% of current residential heat and hot water needs, providing a very large opportunity to increase system efficiency.

Some types of energy are easier to acquire than others, but still, society would benefit by designing energy systems that deliver greatest FES from the finite supply of energy resources. While this paper focuses on biomass, maximizing the use of each joule (renewable and nonrenewable) implicitly reduces pressures on land resources, air quality [43], water resources [44], greenhouse gases [24], processing costs, availability of resources to future generations, and more. Efficient use of energy not only conserves energy, but also reduces externalities intrinsic to energy pathways. EROEI_{fes} is a framework for assessing feedstock-to-final-energy-service efficiency to help decision-makers maximize societal benefit from feedstock and assess social and environmental co-impacts [45] from collecting and processing different feedstocks, and may also help minimize costs to provide energy services via available technological and policy instruments [46]. In this study, we have laid the foundation for analysis of the environmental co-benefits that result from more efficient systems and for further detailed analysis of alternative end-use energy products such as food or animal feed derived from the same finite land base. ERoEI_{fes} creates a step-by-step methodology to compare pathways to minimize resource depletion of finite resources.

Ultimately, ERoEI_{fes} is a way of identifying opportunities for increased efficiency both within and among energy pathways and comparing primary and secondary FES products across pathways, to better support society's need for energy services and provide a foundation for analysis of financial and environmental performance across systems. While we analyzed existing and near-term energy conversion and end-use technologies, we do not advocate for any of the particular land use or conversion technologies and we acknowledge that there is a multitude of potential uses of the land (e.g., sheep grazing with solar panels) or mechanisms to derive greater or different FES (e.g., heat pumps for space heating, electric train transport). Additionally, as we have not previously framed societal energy in terms of FES, this is a new approach to thinking and designing energy systems within a sustainable supply of feedstock. As agriculture and forestry are the most sensitive industries to a changing climate, and as society is dependent on those industries for food, feed, fiber, and fuel, we must minimize our demands by increasing our efficient use so to be more resilient in years of low yields due to extreme weather events. Additionally, by "intensifying" and "diversifying" the FES per unit of feedstock, we minimize the associated emissions from resource use and reduce pressures on the finite land base. In sum, in contrast to the idea of limitless intensification of farming and forestry, we propose innovation across the rural-urban continuum, including climate-smart agriculture along with intensification of end-use efficiency from the same quantity of product at the farm gate and/or oil well. Across all biomass types and conversion processes, the ERoEI_{fes} is an internally accountable and effective foundation for decision-makers to compare FES delivered to society and thus develop policies that reap the most benefit for urban communities per unit feedstock and/or finite land area.

Conclusion

We argue that understanding the system efficiency of limited energy feedstocks to supply final energy services to society is essential to support effective energy system planning and policy. ERoEI_{fes} compares the delivered energy services to society from finite energy resources. Using the maximum potentially available and sustainably harvested biomass in New York State and applying the ERoEI_{fes} methodology, we compared 11 bioenergy pathways to produce either transport or heat as primary work. We demonstrate that the 1°P FES ranged from 5 to 15% for transport and 12 to 71% for heat (residential or commercial). The primary product from wood chips or pellets in combined heat and power systems provided the greatest amount of transportation benefit for society by means of electric vehicles. The primary product from pellets or maize grain in pellet boilers or grain stoves provided the greatest amount of home heating for society. However, the final energy services for six pathways is more than 2-fold higher if co-products can be used productively, for example, in combined heat and power systems. If co-product (heat) can be used, the FES (1°P FES + 2°P FES) provided by pelleted cellulose or wood chips in CHP systems (providing high quality electricity for diverse uses) is similar to using pelleted cellulose in distributed residential heating systems. Across all biomass types and conversion processes, the ERoEI_{fes} is an effective foundation for decision-makers to compare final energy services delivered to society and thus develop policies that reap the most benefit per unit feedstock.

Definitions

Allocation of energy in the raw feedstock to conversion losses and final energy services

- *1°P process loss* quantifies the fraction of the initial feedstock energy lost from converting the raw feedstock to the 1°P. This includes parasitic losses but does not include the potential 2° P such as use of waste heat (see 2°P FES below).
- *1°P input loss* quantifies the fraction of the initial feedstock energy lost from accounting for the external inputs (including biomass production, transport to conversion site, drying, transport of 1°P to consumer, and conversion). It may also include 1 or more conversion steps. For example, while pelleted cellulose can be burned directly for heat as a primary product, it may also fuel an electric power plant for other kinds of FES. Notably, this loss is deducted from the energy in the 1°P in an effort to replace the high quality of the energy inputs.
- *1°P end-use loss* quantifies the fraction of the initial feedstock energy that is lost during end-use conversion of the 1°P. For example, an ICE vehicle is 20% efficient in converting the saleable product of ethanol into transportation; 80% of the energy in the ethanol is lost as waste heat from the engine. We do not consider this “waste” heat as a potential co-product.
- *1°P final energy service (1° FES)* quantifies the fraction of the initial feedstock energy that actually does work for society (vehicle transport, space heating) by the 1°P (The 1°P is composed of three parts: (1) the FES, (2) the 1° end-use loss, and (3) the 1° input loss).
- *2°P final energy service (2° FES)* quantifies the fraction of the initial feedstock energy that has the *potential* of being a co-product to deliver FES for society (e.g., pelleted DGS from maize grain ethanol, kilowatt hour from cellulosic ethanol production, and waste heat from electric power generation). However, if these potential co-products are not used (e.g. waste heat), they would be added to the 1°P process loss (see above).
- Other terms:
    - ○ *Energy return on energy invested (ERoEI)*. Total energy output/total energy input
    - ○ *Final energy service (FES)*. The service provided by the energy in 1°P + 2°P (for example, distance traveled or homes heated). This value represents the numerator in ERoEI_{fes} where the denominator is the energy of the raw feedstock (in this case, sustainably harvested biomass from NY).
    - ○ *$ERoEI_{fes}$*. The proportion of the raw feedstock that results in final energy services for society. Not an energy product but an energy service resulting from the final energy product.
    - ○ *End-use conversion efficiency*. The efficiency by which the 1°P is converted into a FES (for example, a maize grain boiler is 80% efficient at turning 15.5% MC grain into heat, while an ICE is 20% efficient at turning ethanol into distance traveled).
    - ○ *Simple conversion efficiency*. Energy in desired 1°P divided by energy in primary feedstock (does not include external inputs).

Additional file

Additional file 1: Table S1. Constraints applied to account for sustainability of biomass feedstock. **Table S2.** Equipment used to harvest product for quantifying embodied energy and fuel use. **Table S3.** Stand life, average yields, and average lime and *N* rates for feedstock production. **Table S4.** Key steps in processing pathways. **Table S5.** Scale of plant and type of primary product from biomass feedstocks. **Figure S1.** Visual abstract. (DOCX 61 kb)

Abbreviations

1°P: Primary product; 2°P: Secondary product; Cell: Cellulose; CHP: Combined heat and power; DGS: Distillers Grains with Solubles; EH: Electric heat; ERoEI: Energy return on energy invested; ETOH: Ethanol; EV: Electric vehicle; FE: Final energy (an energy product); FES: Final energy services; ICE: Internal combustion ngine; J: Joule; MC: Moisture content; MLY: Million liters per year; NE: Net energy; NY: New York; PE: Primary energy; RoI: Return on investment; T&D: Transmission and distribution (electric grid)

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Authors’ contributions

All authors read and approved the final version of the manuscript.

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Availability of data and materials

From published literature.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they no competing interests.

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