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OVERVIEW

Modularized production of fuels and other value-added products from distributed, wasted, or stranded feedstocks

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Distributed, wasted, or stranded feedstocks, when converted and upgraded into fuels, could replace about 6% of the U.S. demand for liquid fuels, which is about 25% of the net import of petroleum by the United States. We review the current state of modular approaches for conversion of these feedstocks, including the technology and economics associated with processing carbon-containing waste and stranded, carbon-containing gas. The wide geographic distribution of the feedstocks will require technology that can be scaled down effectively and that can be manufactured, installed, operated and monitored in ways that gain economies of mass production rather than economies of throughput scaling.

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1 | INTRODUCTION

Carbon, now discarded in the form of municipal solid waste, sewage sludge, manure, food waste, and stranded gas sums to about 6% of the carbon that is used as petroleum-derived fuel in the United States (Table 1). To convert that wasted carbon into liquid fuels requires new chemical transformations similar to those that have been developed for converting biomass into fuel. However, because of the geographic dispersion, high cost to consolidate, low (negative) economic value and heterogeneity of the wasted and stranded carbon, the new processes must be run at much smaller scale than envisioned today for a biorefinery.

This review summarizes discussions, from a workshop sponsored by the U.S. Department of Energy, on the availabilities of now-wasted resources, the technological developments that would be needed to convert them economically, the technical and non-technical challenges that would encumber a new enterprise based on technical developments, and a possible roadmap for next steps.

The renewable fuels industry is still nascent. The feedstocks are expensive, variable and most are difficult to convert. Much of the market does not value sustainability as an attribute worth the additional cost compared to non-renewable resources. Moreover, the feedstocks acceptable for manufacturing renewable liquid fuels have changed over the past 35 years

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TABLE 1 Stranded, dispersed carbon in the United States comprises three, broad categories[a]

Type of waste	Example sources	Availability (MBOE/year)	Site capacity (BOE/day)	Conversion process	Technical challenge
Dry[b]	Municipal solid waste, ag. and forest residue	200	2–20	Pyrolysis/hydrotreating	Heterogeneity of feedstock and products
Wet[c]	Food, sludge, manure	100	2–150	Hydrothermal liquefaction; hydrotreating; anaerobic digestion	Large slate of products
Gaseous[d]	Stranded gas, biogas, CO_2	120	1–10 (CO_2); 70–1,500 (CH_4)	Reforming; FT synthesis	Number and type of co-products
Total		420			
U.S. annual petroleum demand[e]		7,000	136,000[g]		
U.S. net import of petroleum[e]		1,700			
Fuel demand of the 250 million U.S. cars[e,f]		2,800			
Energy demand of the 114 million U.S. homes[e]		2,000			

Note. BOE = barrel of oil equivalent; EPA = Environmental Protection Agency.

[a] BOE = 6.1 GJ of heating value.

[b] MSW: U.S. EPA estimate of 134 million tons/year of landfill (US Environmental Protection Agency, 2016a) at 4600 BTU/lb (Chin & Franconeri, 1980); Forest residue: DOE 2016 Billion ton study estimate of 14 million tons/year (US Department of Energy, 2016, table 3.24) at 7600 BTU/lb (US Department of Energy Office of Energy Efficiency and Renewable Energy, 2006); Ag residue: DOE 2016 Billion Ton study estimate of 9.1 million tons/year (US Department of Energy, 2016, table 5.1) at 5800 BTU/lb (US Department of Energy Office of Energy Efficiency and Renewable Energy, 2006)

[c] DOE Biofuels and Bioproducts from wet and gaseous waste streams (US Department of Energy Bioenergy Technologies Office, 2017, table 2.1).

[d] DOE Biofuels and Bioproducts from wet and gaseous waste streams (US Department of Energy Bioenergy Technologies Office, 2017, table 2.1) plus 46 MBOE projected from converting CO_2 from ethanol production as calculated in Table 3.

[e] Energy demand estimates from Energy Information Agency Annual Energy Outlook, 2015 (US Energy Information Agency, 2015)

[f] Vehicle estimate from U.S. Department of Transportation (2013)

[g] Average throughput of the 137 refineries operating in the United States in 2017 (US Energy Information Agency, 2017a)

from food crops (oil seeds, corn) to energy crops (lignocellulosics and algae). That evolution in feedstocks for renewable fuels responded to the demands of economics, social justice (e.g., the food vs. fuel controversy), and environmental justice (e.g., the water-fuel nexus) associated with diverting massive quantities of resources needed to substitute even small fractions of the annual demand for petroleum. The changes also reflect an increasing command over the technology available for converting feedstocks that are not particularly energy dense (<20 MJ/kg) into gasoline-like and diesel-like fuels (>40 MJ/kg).

Here, we discuss extending the progression of feedstocks to carbon-containing materials that are now wasted or economically stranded. This approach, which we have nicknamed "*Energy Everywhere,*" would, in some cases, solve two problems concurrently—production of fuels and obviating waste. The utilization of waste feedstocks, which are distributed throughout economically developed countries like the United States, (US Department of Energy Bioenergy Technologies Office, 2017) could also help create environmental benefits, for example, retarding the encroachment on domestic prairie lands of purpose-grown biomass feedstocks.

The resources under consideration here span three states of matter: gases (natural gas and concentrated carbon dioxide), wet (>50 wt% water: food waste, algae, sewage sludge), and solids (municipal solid wastes, agricultural and forest residues). Carbon dioxide, is included because of the promise of technologies to upgrade it using renewable energy (Malik, Singh, Basu, & Verma, 2017). In principle, assuming 70% energy efficiency in the conversion process, which is a plausible goal (Zhu, Biddy, Jones, Elliott, & Schmidt, 2014), those resources can be converted into a fuel precursor with a higher heating value equivalent to about 6% of the ~7 billion barrels of petroleum used annually in the United States (Table 1), equaling about 25% of the net imports of petroleum by the United States (ca. 2016), which is enough to satisfy about 15% of the combined, annual demand of the U.S. fleet of cars or 20% of the energy demand of the U.S. inventory of residences. We note that the values in the table represent only about half of the available resources because the other half typically sees some other beneficial use (e.g., fertilizer for manure, recycling for plastic waste). That diversion of material is, of course, susceptible to economics and national needs, so the estimate in the table likely underestimates the total addressable market for the technologies to be described below.

Their conversion will require technology that can deal with heterogeneous inputs—even sorted waste contains many extraneous materials—in locations that are often remote from industrial infrastructure that might supply utilities or accept co-products. Moreover, the delivery rate of the feedstock will necessarily be much smaller than that which has been considered for biorefineries: waste resources are available at the equivalent of less than about 100 BOE/day instead of greater than 10,000 barrels per day (bpd) envisaged for large bio-refineries. For reference, the 140 or so petroleum refineries in the U.S. process

TABLE 2 Comparison of renewable energy production facilities

Facility	Feedstock	Energy product	Example	Renewable capacity/MW
Wood-based biorefinery (IEA Task 42, 2013)	Forest residue	Bio-oil	BDI—BioEnergy international AG	250
Industrial ecocenter (Gulipac, 2016)	Industrial effluents	Electrical power, avoided wastes	Kalundborg Eco industrial park, Denmark	80
Landfill gas to power (US Environmental Protection Agency, 2016d)	Landfill gas	Electricity, fuel gas	Average of 652 U.S.-based Landfill gas projects	40
Anaerobic digester(US Environmental Protection Agency, 2016b)	Biogas	Electricity, fuel gas	Average of 95 U.S.-based Anaerobic digester projects	1.7
Municipal waste water treatment plant	Sludge	Bio-oil	Discussed here	0.14 ≈ 2 BOE/day

Note. The enthalpy of combustion of 1 barrel of oil is ~6.1 GJ, so producing 1 BOE/day is equivalent to 70 kW of power = 6.1 GJ/86400 s. BOE = barrel of oil equivalent.

100,000–500,000 bpd. Capital costs for the small facilities are not likely to follow the usual 0.7-power law scaling of the chemical and petroleum industries. The energy efficiency of the conversion process has been set at 70% comparable to that found experimentally (Snowden-Swan et al., 2016; Zhu, Albrecht, Elliott, Hallen, & Jones, 2013) because process losses will be much large and opportunities to utilize waste heat will be much small at small scale. For comparison an energy efficiency of 88% has been estimated for modern petroleum refineries (Wang, 2008).

In 2015, a consortium of U.S. Department of Energy national laboratories and academic institutions started to analyze a different approach: small scale conversion of biomass, replicated and distributed, to match the geographic and temporal distribution of the feedstock, combined with collection and central processing of the intermediate, fuel precursors. Previous analyses (Bergin, 2003; US Department of Agriculture, 2011) have shown benefits to such an approach, but have been based on conversion processes that still relied on access to large markets for the disposition of co-products and the supply of utilities. The new opportunity, confirmed by workshop discussions, is to mass manufacture hundreds to thousands of small, modular plants and benefit from the economies of mass manufacturing rather than from economies of plant scaling.

The discussion in the workshops diverged from centralized, waste-to-energy approaches (Table 2), to consider instead an approach that relies on mass production and modular design to enable an economical route for converting distributed, waste carbon to liquid fuels and chemicals.

Below, we review the resources to be converted, the economics of small-scale conversion, the potential stakeholders, the technical gaps, and a roadmap for risk reduction.

2 | THE ENVISAGED RESOURCES

The dispersed feedstocks we are considering are all either stranded or are currently discarded as waste. They fall into three broad classes: dry, wet, and gaseous (Table 1), representing molecules that range from fully reduced (CH_4) to fully oxidized (CO_2), with intermediate average oxidation states presented by the liquid phase and solid feedstocks (e.g., sugar-derived carbohydrates). Evidently, for reasons of stoichiometry and thermodynamics, the feedstocks require very different conversion technologies.

Wet and dry wastes represent the bulk of the opportunity space. However, they are challenging to convert because of their heterogeneity and impurities (including ash, metals, etc.). Moreover, existing technologies convert such materials into complex oils that need further upgrading, typically by the addition of hydrogen to remove heteroatoms (O, N, S) and to saturate carbon–carbon bonds. That upgrading using current, conventional approaches, does not offer an obvious route to distributed operation primarily because of the intractability of the feedstock and the challenges of handling high-pressure H_2.

For natural gas, the production of liquid fuels typically involves primary processing (reforming to make synthesis gas) followed by secondary conversion (e.g.,Fischer-Tropsch synthesis or fermentation). Historically, to be economically viable, processes have operated at very large scales requiring capital investments of billions of dollars (equivalent to thousands of barrels per day at installed capital costs of ~$50,000–100,000 per bpd. Smaller, modular versions of these processes (e.g.,Velocys [Deshmukh et al., 2010]) have been proposed but do not yet appear to offer compelling economics at the scales envisaged here. A single-step process combining both primary and secondary stages (Yoneyama, San, Iwai, & Tsubaki, 2008) could provide a transformational change in economics (with respect to both the initial investment and operating costs), but has yet to be realized.

Converting oxidized gases back into fuel means adding hydrogen to remove oxygen and forge C–H and C–C bonds. If the product fuel is to help decrease the emission of greenhouse gases then the hydrogen must come from water, and the energy to

TABLE 3 Third generation resources

Waste	Supply million BOE/year	Fraction of U.S. oil demand[a] (%) [fraction of U.S. imported oil[b] (%)]	Value/G$ year^{-1} @ $30/BOE	Sources in the United States
Agriculture and Forest[c]	40	0.6 [2.4]	1.8	>2,100,000[d]
Municipal Solid Waste[c]	160	2.3 [9.4]	6.9	~20,000[e]
Manure[c]	63	1 [3.7]	2.8	~100,000[f]
Food waste[c]	27	0.4 [1.6]	1.2	22,000[g]
Sewage[h]	10	0.1 [0.6]	0.5	~15,000
Flared Gas[i]	25	0.4 [1.5]	0.03	
Biogas[c]	63	1 [3.7]	2.6	16,000[j]
Carbon dioxide[k]	32	0.5 [1.9]	1.4	
Total	420	6 [25]	17	209[l]

Note. BOE = barrel of oil equivalent; G$ = 10^9 USD.

[a] EIA estimate of total U.S. consumption in 2015: (US Energy Information Agency, 2016a, 2016b, 2016c)

[b] 7,080 million barrels/year. EIA estimate of total U.S. imports in 2015: (US Energy Information Agency, 2016a, 2016b, 2016c).

[c] 2,700 million barrels/year. (US Department of Energy Bioenergy Technologies Office, 2017).

[d] Number of farms in the United States in 2012(US Department of Agriculture, 2012).

[e] Number of municipalities in the United States (US Census Bureau, 2012).

[f] Sum of U.S. dairy farms (US Department of Agriculture, 2008) (75,000) and concentrated animal feeding operations (US Government Accounting Office, 2008) (12,000).

[g] Food manufacturing establishments in the United States (2007) (US Census Bureau, 2007).

[h] Seiple, Coleman, and Skaggs (2017).

[i] GTI, utilizing a conversion for methane to CO_2 equivalent.

[j] Sum of wastewater treatment plants plus the 264 farm-based (US Environmental Protection Agency, 2016b) and 632 landfill-based digesters (US Environmental Protection Agency, 2016c).

[k] 15.5 Billion gallons of ethanol per year (US Energy Information Agency, 2017b), 1 mol CO_2 per mol ethanol *ex* glucose ($C_6H_{12}O_6 \rightarrow 2\ C_2H_5OH + 2\ CO_2$) which is nearly the same as the ratio that results from a life cycle analysis (Muñoz et al., 2014); CO_2 converted to CH_2 using renewably sourced protons and electrons.

[l] Ethanol Producer Magazine (2018).

drive the reaction "uphill" must come from renewable sources. Dry reforming of methane has been suggested to average the thermodynamic states of methane and carbon dioxide but, this process would yield a significant decrease of net greenhouse gas emissions from the use of the product fuel only if both reactants were biogenic or derived from waste (e.g., digester gas or landfill gas), requiring just the sort of distributed processing facility discussed below.

An alternate use of reduced gas feedstocks is to fuel a vehicle (e.g., garbage trucks powered by landfill gas) or to generate electricity or heat. The U.S. Department of Agriculture has studied farm-based anaerobic digestion of manure (Lazarus, 2008) and has identified reasons to be optimistic about the technology but the high capital expense of such a facility, typically exceeding $300/cow or about 0.64 $/$W_{th}$.[1] That expense, combined with the decreasing costs of other forms of renewable electricity, have continued to impede broad utilization of farm- waste conversion technologies (Zaks et al., 2011). Deriving electrical power from digester gas at municipal wastewater treatment plants and landfill sites is a commercial offering by generator-set vendors such as Caterpillar, Dresser-Rand, Capstone, and other manufacturers of robust engines. Those applications have progressed because wastewater treatment plants are large customers for electrical power. A more recent analysis (Summers et al., 2015) has considered the conversion of a dairy waste to diesel fuel by combining fermentation of the waste with hydrothermal liquefaction but the plant size (>10,000 BOE/day) was not practicable (it is much larger than could be fed by a single source of dairy waste). Co-digestion of food wastes with farm-based dairy waste would help to improve the economic viability due to the considerable income from gate fees (Sanscartier, MacLean, & Saville, 2011).

As shown in Table 3, a significant amount of renewable fuel might be sourced from the waste streams that comprise the broad categories in Table 1. As in Table 1, the heating value of the available supply stream of each feedstock has been lowered by 70% to account for energy losses stemming from the conversion process. Due to the low energy densities and sparse distributions of these wastes, it has proved uneconomical to collect them into centralized facilities that exhibit conventional economies of scale. The conventional scale is reflected in reports such as "The Billion Ton Study" (US Department of Energy, 2011).

3 | THE CASE FOR ECONOMIES OF SMALL UNIT SCALE FOR ENERGY TECHNOLOGIES

Conventional chemical processing facilities and refineries are designed to exploit economies of scale, which lead to smaller costs per unit of production, but only if the larger scale of production matches the supply of feedstock and the market for

TABLE 4 Comparison of economics for scaling up and numbering up

Desired characteristics of a waste-to-fuel plant	Scaling up	Numbering up
Low capital expense	"0.7-power" scaling rule applies to large, stick-built facilities	Linear scaling rule; mass manufactured, standard units decrease in cost as number of units increases; plants affordable to small-medium sized enterprises with USDA-like financing
Low operating expense	Small but only when averaged over a large throughput	Amenable to automation and telemetry that reduce staffing costs
Distributed, safe, reliable operation	Favors centralized facilities with frequent service checks	Replicated, small scale, redundant facilities that minimize disruptions
Accommodates daily and seasonal fluctuating feedstock	Favors continuous operation	Units can be rapidly added or removed with market conditions
Minimal rejected energy (operable in locations remote from industrial utility grids)	Energy efficiencies gained via recycle and export of waste heat	Amenable to intensified, nonthermal processes that afford low T/low P exhaust streams
Adaptable to different feedstocks	Requires plant-wide re-optimization	Adaptation via modular architecture
Acceptable financial risk	Stage-gated scaling	Risk reduced by reducing the capital outlay required to implement the technology

Note. USDA = U.S. Department of Agriculture.

product. Recent analyses (Ricci-Rossi, 1985; Sievers, Seifert, Franzen, Schembecker, & Bramsiepe, 2017) suggest that circumstances can favor economies of manufacturing, particularly when they are automated, when the structure and timing of the market requires a more flexible production facility and when transportation of the feedstock is a significant expense.

Indeed, there is some validation that collection and use of a distributed, low-energy content stream can make technical and economic sense. For example, in 2014, the USDA, EPA, and DOE had counted about 2,000 biogas-to-electricity facilities (US Department of Agriculture et al., 2014), covering about one sixth of possible sites. Similarly, according to the U.S. EPA (US Environmental Protection Agency, 2016c), in 2016, there were more than 650 sites that valorize landfill gas at an average energy throughput equivalent to the heating value of about 40 BOE/day (US Environmental Protection Agency, 2015).

The conditions addressed by *Energy Everywhere* appear to benefit from the approach of mass manufacturing (Table 4). Consider, for example that there are about 140 refineries currently in operation in the United States (US Energy Information Agency, 2016a), while there are more than 15,000 municipally owned wastewater treatment plants (University of Michigan Center for Sustainable Systems, n.d.) serving roughly the same population.

With appropriate choice of technology (areal vs. volumetric rate processes), the cost of a small modular/mass produced plant can *decrease* faster with scale at small scale (power law with an exponent of 0.8–1) than do stick-built plants (power law with an exponent of 0.6–0.7) (Figure 1).

Production runs of small, modular units allows for design for manufacture, implemented through assembly lines amenable to continuous improvement in process and product design as manufacturers/operators obtain experience with production and design. The improvements can lead to significant, additional cost savings over long production runs; however, cost savings become apparent even at the beginning of a production run (Argote & Epple, 1990). Automation promises further operational and economic efficiencies, enabling the use of a cluster of modular units to reach a highly tunable capacity as a single facility.

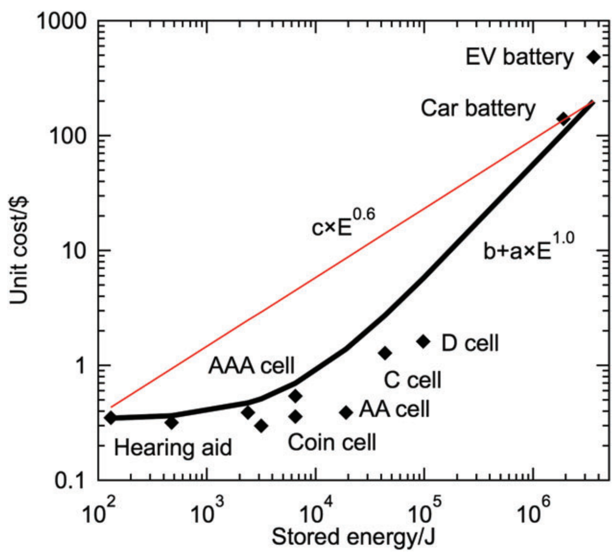

FIGURE 1 Cost of batteries follows an allometric scaling law ($n = 1$) at larger sizes. Similar scaling is found for other devices such as heat exchangers. Prices and characteristics of the batteries were drawn from publicly available information

The flexibility of small unit scale allows gradual deployment over time, location of units adjacent to feedstocks, shorter lead times for projects, adjustment of production to demand, as well as built in redundancies (all output is not lost if one unit fails). For conversion of wastes to fuels, the design and deployment of conversion technologies to operate in modular systems could prove to be disruptive, as has occurred in other industries.

Technologies that operate at mild conditions (ambient temperature, atmospheric pressure or autogenous pressures) are likely to be well suited to broad deployment because they could be safer and easier to distribute to areas not equipped with an existing grid for sourcing or sinking process heat. However, many of the approaches applied to the conversion of biomass have been developed to exploit more severe process conditions (e.g., pyrolysis, thermally-activated, high pressure hydrodeoxygenation), under the assumption that they would be deployed in large (equivalent to ~10,000 barrels of oil per day) biorefineries that would resemble "stick-built" refineries or chemical plants and that would be operated by crews of trained technical staff. Examples of distributable (down-scalable) processes that run under the desired, less severe conditions include electrochemically activated upgrading (Jackson, Lam, Saffron, & Miller, 2014; Lam, Lowe, et al., 2015), particularly when combined with the water-laden, conductive products of hydrothermal liquefaction. It is the promise of such, less conventional technologies that inspired the workshop on modular processing of waste carbon whose deliberations are summarized here.

4 | IMPEDIMENTS TO MODULARIZATION

Modular systems are most beneficial for processes where there is a commensurate local demand for the product or little penalty for combining the outputs of different facilities to meet the demands of a region. In fact, the latter condition holds for biomass and the waste carbon considered here—it is expensive, and potentially noxious, to ship the feedstock but the infrastructure is already in place to ship the fuel-like product (tanker trucks, rail cars etc.).

It is difficult to challenge traditional industrial process of designing for economies of unit scale. A "lock-in effect" can occur where established practices dominate, inhibiting the adoption of newer, more effective technologies. The new technology must represent a disruptive innovation (Chrisensen, 1997) to displace the incumbent practices and then needs to cope with the usual risks of innovation (technology risks, competitive risks, market risks, financial risks, regulatory/political risks and timing risks).

Modular systems need to be designed: they are not mere miniatures of a larger unit. Likely, process intensification for conversion technologies will be an important aspect of the system design, but intensified unit operations (Stankiewicz & Moulijn, 2000) have not yet been standardized for chemical processes and will therefore require research. Additional research is needed to provide the fast, accurate analytical methods and controls that will be needed to contend with the heterogeneity and complexity of the most cost-advantaged feedstocks.

To achieve economic flexibility and range at a scale that would address the opportunities summarized in Table 3, the manufacturing of modular systems itself may need to be designed to be reconfigurable, in contrast to a dedicated manufacturing system suited for very high-volume production (say, >1,000,000 units) with little modification over time. Instead, we envisage assemblies of modules into mass customized skids (Hu et al., 2011).

5 | POTENTIAL STAKEHOLDERS

To realize the production of fuels from waste or stranded feedstocks requires the establishment of a new value chain (Figure 2).

The *custodian* may be the owner of the feedstock or the enterprise that collects and processes it such as a wastewater treatment plant. In the case of municipal waste, likely, the custodian will be the municipality who will expect to benefit from follow-on valorization. The operator of the treatment facility will also want to be assured that the downstream processing will not affect the facility and will be reliable enough to warrant the changeover from historical disposal to the new system.

The *processor* is the owner/operator of the distributed processing facility. The processor needs to be assured of a steady supply of sufficient quality feedstock and of a steady off take of the various product streams. The processor is responsible for meeting environmental and code regulations for the construction and operation of the facility.

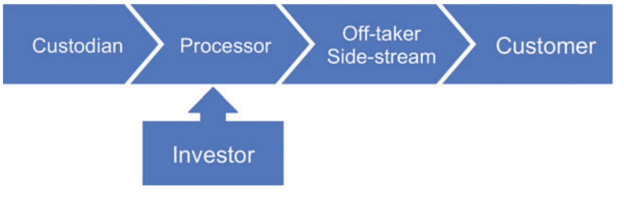

FIGURE 2 Potential stakeholders in a waste-to-fuel enterprise

While we envisage, eventually, a processing plant frugal enough to be afforded by a small business or even an individual—the scale of material throughput is roughly equal to those of farm-based manure digesters mentioned above and of craft-production of beer in the United States (73 bbl/day/brewery = 139 million barrels/year ÷ 5,200 breweries [Brewers Association, 2016]). The overall system might evolve into a franchise/leasing arrangement in which an *investor* bundles the purchase of replicate facilities to benefit from a quantity discount and to centralize operational experience and negotiate more favorable off-take arrangements. The processor would then contract with the investor to secure a lease or franchise for one or more facilities. Vertical integration of those links in the value chain is also possible, for example, the Metro Vancouver has partnered with the Water Environment and Reuse Foundation and Pacific Northwest National Laboratory to evaluate and, potentially, implement technology for converting municipal sewage sludge into fuel (Snowden-Swan et al., 2016; Water Environment and Reuse Foundation, 2014). Of course, processing and combustion of the methane-rich gas from municipal anerobic digesters, to produce heat and power, is practiced currently (American Biogas Council, 2014). *Energy Everywhere* envisages the eventual production of products that are more valuable than fuels.

At least initially, we assume that the product fuel will not be a drop-in replacement but rather will be blended into a fuel by an *off-taker*—an established fuel supply company who has the expertise to formulate standard fuel and channel it to market. It is the off-taker who will integrate the output of the plants, perhaps by using a fleet of tanker trucks that visit the plants in succession to gather their products as needed. We note that the production rate of each facility 1–10 BOE/day is similar to that of the hundreds of thousands of stripper wells in the United States (National Energy Technology Laboratory, 2015), which are serviced in just such a fashion.

Finally, because of the heterogeneity of the feedstock and because of its chemical composition, there will likely be co-streams of product too voluminous and too valuable to ignore. Therefore, the overall enterprise may include *side-stream players* who focus on the process gas, gray water, and minerals.

6 | TECHNOLOGY GAPS

Discussions at three, recent workshops (Ames Laboratory, 2015, 2016; Bioeconomy Institute Iowa State University, 2015) and our own preliminary analyses have identified five challenging aspects (Table 5) of distributed processing of waste that we believe merit attention at the level of basic science research. Those challenges will be described in more detail in a subsequent report.

The two, largest waste streams we are considering are heterogeneous (even sorted MSW will contain effluvium that can impede chemical conversion) and refractory (if the waste decomposed rapidly, then landfills could be designed to be self-emptying). Therefore, the processing facilities will need to be equipped with: (a) upstream separation, preprocessing and control processes to regulate the amount of impurities entering the process; and (b) downstream separation and control processes to make the product slate saleable (i.e., converted into conversion ready feedstocks). Some of the separations will be merely physical (e.g., rejecting metals and plastics that are better recycled more conventionally). Others will require preprocessing (e.g., comminution) or chemical discrimination (e.g., leaching). Quantification of the mass flow rate and heating value of the refined feed stream will be needed to permit control of the downstream reactors, so they achieve acceptable levels of conversion and selectivity.

Because the facilities may be located remote from industrial parks, they will need to operate independent of common utilities (e.g., steam grids, hydrogen grids) either as inputs of high enthalpy feeds or as sinks for waste heat. Moreover, the process will be co-located and run by the staff of the feedstock processor, who will likely not be tolerant of, or facile with, other industrial processes. Therefore, we call out, as a research need, the development of processes and catalysts that can operate at temperatures and pressures much lower than those found in conventional refinery processes. Low temperature catalysis is an active area of research but has focused on the conversion of high value, somewhat delicate molecules like pharmaceutical intermediates (Lam, Li, et al., 2015).

TABLE 5 Technical challenges impeding distributed processing of wastes to fuel

Challenge/technical need	Examples of basic research needs
Separation processes and controls to facilitate the conversion processes	Remote, online quantification of types and flow rates of feedstock solids and suspensions
Catalytic conversions that occur with high thermodynamic efficiency and high selectivity at near-ambient conditions	Research on low temperature catalysis and chain reactions in condensed reaction media, particularly containing water
Separation processes facilitating product valorization	Thermodynamics of, and transport in, the complex, product mixtures, robust, effective membranes(Advanced Manufacturing Office US DOE, 2015; Kiss et al., 2016)
Water recovery and clean-up, again with high energy efficiency	Membrane science, particularly for separating water from both polar and nonpolar organics
Novel, reactors that afford process intensification, either through enhanced transport or reaction with separations	Enabling materials (Advanced Manufacturing Office US DOE, 2015); multiscale modeling (Advanced Manufacturing Office US DOE, 2015)

The processing of the envisaged feedstocks, even those that are ostensibly dry, will produce water (Fermoso, Pizarro, Coronado, & Serrano, 2017), which will solubilize the other, polar products (oxygenates, amines, etc.). Therefore, accurate models of the processes will require development of constitutive relations for thermodynamics and transport that account for the nonidealities of mixtures containing water.

The potential detrimental properties (e.g., toxicity, corrosion, volatility, etc.) of feedstocks and of the product slate must be examined in detail, together with any unwanted emission and/or the disposal of byproducts.

Finally, because the processes will need to operate as efficiently as possible, separation operations based on differences in chemical, mechanical (e.g., pressure),or electrical potential (e.g., dialysis) rather than differences in temperature will be preferred. Therefore, we expect that membrane science as well as other types of extractions and phase transfers will contribute signally to the design and operation of the facilities.

7 | STRATEGY FOR RISK REDUCTION

Providing *Energy Everywhere* will require significant research and development, not merely the assembly of technologies. Therefore, it will incur costs as it traverses the stages of risk reduction from concept to implementation. Here, we describe how the paradigm shift, from economics of throughput scaling to the economics of manufacturing scaling, helps address the challenges of securing the required financial investments.

First, we recognize that the current economic, regulatory and investment environments do not encourage wildcat investments. The low prices commanded by energy commodities (petroleum, natural gas) and the volatility in those prices make it difficult to engage the attention of the natural, strategic partner for *Energy Everywhere*, namely the major oil and gas companies. Failures of some recent, high profile ventures and specious claims by others also highlight the inherent risk in investing in new technologies and first-of-a-kind commercial facilities. Moreover, environmental sustainability of fuels does not yet offer a competitive differentiation without compelling economics. Finally, much of the concern about domestic energy security has been allayed by the success in the United States of hydraulic fracturing in the production of previously inaccessible but very large sources of domestic petroleum.

Therefore, the attention of investors, be they public or private, can only be drawn to ventures in this arena that offer the promise of returns that compensate for the inherent risks of such projects, which means significant returns on investment in 5–10 years (10-fold for private investments, greater than 1.6-fold for public investments (McKinsey&Company, 2009). We appreciate that sharing (leveraging) the cost—and risk—by co-funding the development through private equity, guaranteed loans, and research grants becomes possible once the venture can exhibit seven factors: (a) proven technology; (b) long-term feedstock supply; (c) product off-take contracts; (d) sound project financials; (e) externally vetted engineering plans; (f) an investment grade engineering/procurement/ construction contract; and (g) an experienced operator.

The petrochemical industry employs a staged trajectory to de-risk a project:

bench → pilot → semi-works → commercial

which entails increasing investments (Figure 5) and which can, at best, remove technical risk (market risks, competitive risks, timing risks all remain).

The extension of facilities for chemical and petrochemical projects usually benefit from economies of scaling, typically according to an allometric relation in which the fixed capital investment increases with production scale raised to a power, n, where $1 > n \approx 0.7$ (Figure 4).

The larger customer base for the small plants would advantage them with the learning rate of mass production, which is noticeably larger (Argote & Epple, 1990) (~20% progress ratio) than that found for stick-built plants (National Energy Technology Laboratory, 2013) (~5% progress ratio). In addition, the economics of operating small-scale plants benefit from an inherent flexibility in deployment and dynamic range (turn-up/turn-down). The effects of the different learning rates are compared (Figure 3) for the costs of stick-built plants and modular facilities.

To estimate the cost of the hardware required to launch the enterprise envisaged here, namely the manufacturing and operation of many distributed units (numbering up). We have made assumptions about the cost for research and development and the rate of learning in the manufacturing process. The latter decreases the cost of producing the units to be deployed. Experience in many fields of manufacturing (Argote & Epple, 1990; Cunningham, 1980; Garcia & Bray, 1997; Rijksdienst voor Ondernemend, 2006; Smith & Larsson, 1989; Wright, 1936), including production of ethanol from corn (Chen & Khanna, 2012; Hettinga et al., 2009) suggests that each doubling in the number of manufactured units decreases the labor required to produce the Nth unit, Y_N, by the learning rate, ϕ (Argote & Epple, 1990; Wright, 1936):

$$Y_N = Y_1 N^{log_2(\phi)}$$

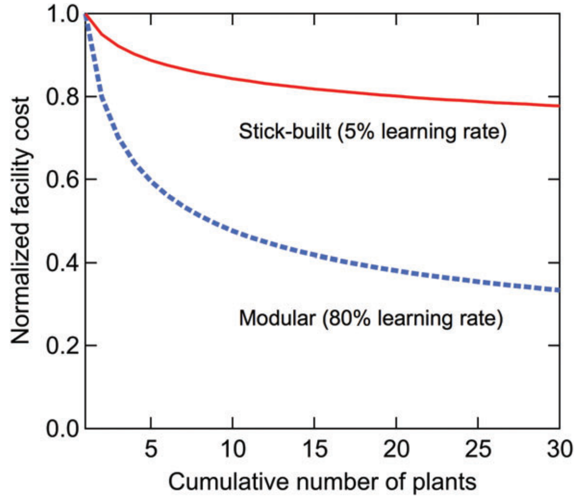

FIGURE 3 Comparison of learning curves characteristic of stick-built and modular facilities

where Y_1 is the cost to produce the first unit and N is the cumulative number of units produced. The example in Figure 4 assumes $\phi = 80\%$, which is the value assumed by the DOE in its call to fund a Modular Chemical Process Intensification Institute for Clean Energy Manufacturing (US Department of Energy Office of Energy Efficiency and Renewable Energy, 2016). The unit cost for the scaled-up, stick-built facility in Figure 4 has been assumed to follow power-law economics with an exponent of 0.7.

Figure 4 indicates that scaling up will afford more economic manufacturing at large scale, provided that the only metric considered is the cost per unit of product manufactured. Investors in a new enterprise, like *Energy Everywhere*, however, will consider risk-weighted, time-discounted return on their total investment, including research, development, and deployment.

De-risking in traditional staging is gradual and comes at the cost of decreasing design flexibility (Figure 5). The trajectory for removing technical risk for modular facilities is accelerated because it front-loads the research and tooling investment, which serves to remove much of the technical risk. Subsequently, capacity is added by replicating the pioneer unit, at decreasing cost per unit as the installations proceed.

bench $\rightarrow$ commercial plant 1 … n

Moreover, installation of the facilities can closely follow the market demand, thereby enhancing the discounted cash flow of the enterprise because each unit should be immediately in service. In addition, the modular facilities can be turned-up and turned-down in response to local conditions and markets. The turn-up/turn-down of facilities employing modular technology may not be significant when averaged over a national scale, but it will strongly affect the economics of the individual installations.

The envisaged first, modular plant, which might have a throughput as small as one barrel of oil equivalent per day ($\lesssim$7 L/h $\approx$ 2 mL/s), need not be even 10 times larger than a bench scale research facility. Therefore, compared to the sequence typical of processes that are scaled up, initial field installations should be practicable at costs that are small. The first modular plant will serve to validate and shake-down its performance so almost all the technical risk is removed once it is fielded. Even so,

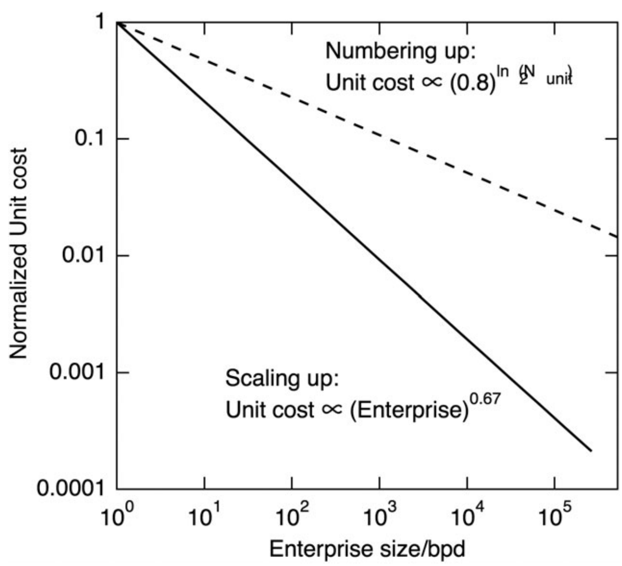

FIGURE 4 Comparison of the incremental costs via scaling- and numbering-up

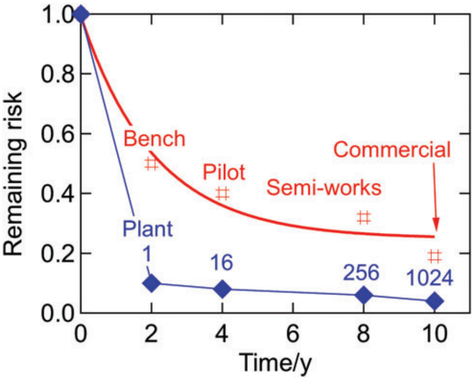

FIGURE 5 Notional risk profiles for the two types of plants: Stick-built (thick, #) and modular construction (thin, ◆): Most the risk is resolved in the first deployment for modular systems

the benefits of numbering up will be realized if the overall enterprise (manufacturing of the plants and their use) only if the learnings from the early iterations (in cost, efficiency, reliability, etc.) are effectively adopted into the later, installed facilities.

The base case illustrated in this analysis corresponds to the development of a stick-built plant whose installed cost is \$52,000 per barrel per day (bpd). The capacity cost has been set equal to that reported for a small refinery recently constructed in the continental United States (Scheyder, 2016) (\$430 million for 8,000 bpd); it is also comparable to the value calculated from allometric process cost functions for a refinery consisting of units required to distill, crack, hydroprocess, and alkylate conventional petroleum fractions (Kaiser & Gary, 2009). The enterprise based on numbering up modular units consists of a collection of plants that each produce 1 bpd at a capital cost of \$135,000 per bpd for the first unit and an 80% rate of manufacturing learning that applies to the labor but not the hardware. The capacity cost for the modular facility is a very approximate estimate of the sum of the cost of a small scale hydrothermal liquefaction unit, extrapolated to this small scale from a recent estimate (Snowden-Swan et al., 2016), plus an estimate for an electrochemical upgrading unit extrapolated from the capital cost of an appropriately sized flow battery (70 kW, which corresponds to increasing the energy content of a ton of bio-oil at 30 MJ/kg to that of a petroleum, 45 MJ kg^{-1} day^{-1}) less the cost of the electrolyte (Viswanathan et al., 2014). Recent work shows that bio-oils can be upgraded electrolytically (Jackson et al., 2014; Lam, Lowe, et al., 2015; Li et al., 2012). We reiterate that this cost estimate is approximate and subject to uncertainties in the scaling relations, the rate of learning, the costs of the equipment and labor. An analysis of the boom in ethanol production from 2000–2010 has shown that there was an effect of learning, much as envisaged here, with a learning rate of about 12% (Chen & Khanna, 2012; Hettinga et al., 2009) instead of the 20% that is more typical of labor intensive industries. The sensitivity of the estimates to those uncertainties is probed in the discussion below.

Both technology paths include costs for research, development and deployment:

Stick-built: \$130 million = \$10 million for research plus \$20 million for piloting plus \$100 million for the first fielded unit (semiworks).

Modular: \$10.1 million = \$5 million for research plus \$5 million for tooling plus \$0.13 million for the first fielded unit.

For those assumptions, the cross-over in investment costs (capital plus research) between the two approaches (Figure 7) occurs near 13,000 bpd, which is in the range that has been considered for integrated biorefineries. Plants smaller than the cross-over would be more economic if they were based on modular technology; traditional, scaled-up, stick-built plants would be cheaper for single installations larger than the cross-over.

At first glance, the results presented in Figure 6 appear to contradict the lower unit costs associated with scaling up shown in Figure 4. The apparent inconsistency arises because we compare here the *enterprise* costs, not just the unit capacity costs. The former costs include the upfront costs of research, development and deployment. To understand better the effects of each of the parameters employed to construct Figure 6, we performed a sensitivity analysis on the results. To make calculating the intercept easier, we assumed that the costs for the modular approach followed a smooth, integrable learning curve that has the functional form originally proposed by Wright (Argote & Epple, 1990; Wright, 1936). The observation of learning as a function of enterprise size, not just the number of units manufactured has been found in the analysis of ethanol production mentioned above (Chen & Khanna, 2012; Hettinga et al., 2009).

$$FIC_{\mathrm{mod}}(c) = U_{\mathrm{mod}} + \int_0^c V + KX^{\log_2(\phi)} dX$$

The cumulative fixed investment cost, FIC_{mod}, for a modular enterprise with capacity, c, would then include upfront costs, U_{mod}, (R&D, tooling, etc) and the unit costs not susceptible to learning, V.

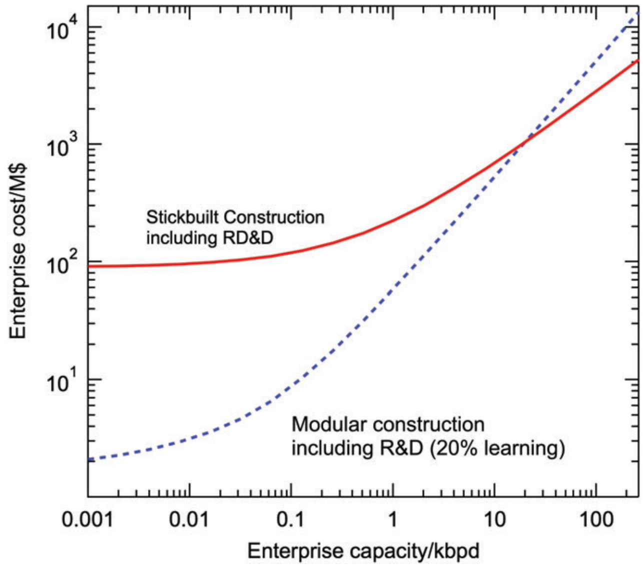

FIGURE 6 Comparison of the cumulative enterprise costs of implementing stick-built (solid) and modular enterprises (broken) as a function of the size of the enterprise

We also assumed that the stick-built (SB) facility followed an allometric costing curve, with exponent, a, that could be extrapolated to production scales several orders of magnitude smaller than that of the reference refinery mentioned above (B_{ref} = \$53,000/bpd, c_{ref} = 8,000 bpd). Therefore, its fixed investment costs, FIC_{SB}, would equal the facility cost at capacity, c, plus the upfront costs, U_{SB}:

$$FIC_{\text{SB}} = U_{\text{SB}} + B_{\text{ref}}\left(\frac{c}{c_{\text{ref}}}\right)^{a}$$

The cross-over occurs when $FIC_{\text{mod}} = FIC_{\text{SB.}}$ As mentioned above, the base case parameters (Table 6) yielded a cross-over scale of about 13,000 bpd.

By varying the parameters in sequence, we found that cross-over scale is most sensitive to the scaling exponent, the learning rate for numbering up, the capacity cost of the stick-built facility and the fixed (non-labor) cost of the modular facility. It is much less sensitive to the upfront costs of research and tooling (Figure 7).

We do not suggest that a modular approach will be more economical than the canonical approach (scaling up) if the enterprise consists of one large (>10,000 bpd) continuous facility. However, there are detailed analyses (Ricci-Rossi, 1985; Sievers et al., 2017). that suggest that even a large plant based on pre-fabricated modules can offer savings of ~15% on capital costs and installation over a stick-built plant.

For Energy Everywhere, a modular approach does appear to be warranted because the enterprise will consist of many thousands of quite small (~1 bpd) distributed facilities, each operating independently and each subject to a local schedule of arrival of feedstock and demand for product.

The sensitivity analysis indicates that a rational decision between the two approaches will require much more detailed, application- and implementation-specific knowledge of manufacturing learning and the functional form of the economics across so large a range in scale. The impetus for that research is the recognition that conventional, large facilities (i.e., biorefineries) are not suitable for the geographically distributed, third-generation resources (Table 3) targeted here.

Development of *Energy Everywhere* would likely follow the trajectory that accelerates and de-risks the development path because it targets existing sources of renewable carbon that are small individually but that sum to a significant fraction of the U.S. energy demand.

TABLE 6 Costing parameters

Parameter	Low value	Base value	High value
Power law exponent, a	0.63	0.7	0.77
Learning rate, ϕ	0.72	0.8	0.88
Capacity cost for stick-built plant, c_{ref}	\$47,000	\$52,000	\$57,000
Labor cost for 1st modular unit	\$45,000	\$50,000	\$55,000
Fixed cost for modular units	\$45,000	\$50,000	\$55,000
Upfront costs			
U_{SB}/M\$	117	130	143
U_{mod}/M\$	9.1	10.1	11.1

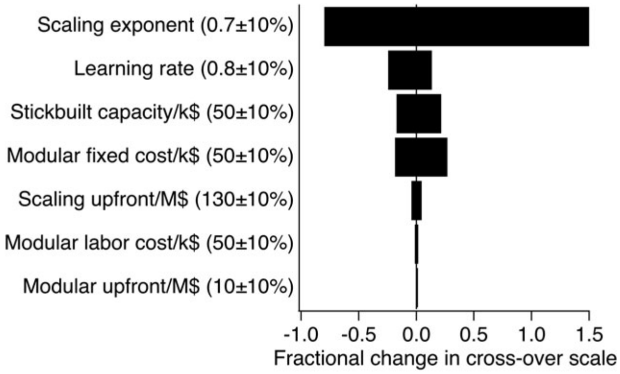

FIGURE 7 Sensitivity analysis for the dependence of the scale at which stick-built and modular technologies cross-over

Deployment through numbering up should also facilitate market testing and, because the small scale of the units affords flexibility, for probing a wide range of sites and feedstocks. Even so, we foresee first approaching the "easy" opportunities, such as sewage sludge (Seiple et al., 2017) and biomass waste, rather than a much more heterogeneous feedstock such as municipal solid waste. That approach is reminiscent of the one employed by LanzaTech (Lanzatech, 2015), which uses a combination of laboratory-based and mobile facilities to vet new sites and new feed streams before commissioning a permanent facility. In addition, Lanzatech uses its experience to validate its risk mitigation strategy.

8 | TECHNOLOGY ROADMAP

Scope: The roadmap below targets a distributed biofuel industry in a timeframe short enough to appeal to economic investors and with simultaneous consideration of the underlying science and the regulatory issues that will be encountered in deployment. The three phases of work described below derive from a generic roadmapping paradigm described by Sandia National Laboratory (Garcia & Bray, 1997). We include this section to emphasize that the successful implementation of the technology described above will require the participation of stakeholders beyond the academy and government.

8.1 | Phase I. Planning and participation

We recognize that we are proposing the establishment of a multifaceted enterprise that will need to span at least five groups of stakeholders in the value chain: custodians of the feedstock, processors, off-takers of the product, side-stream players, and the investors.

Therefore, a roadmap should not deal only with the science or engineering research but also include detailed discussions with representatives of those stakeholders to refine the estimates of the feedstock availability, its seasonal composition, value, and current customers (i.e., alternate uses). An industry/stakeholder-led advisory committee could be assembled to help to clearly define the problem statement and solution parameters. An overarching, advisory committee might be composed of representatives from companies, such as waste management companies, and municipal waste management agencies. These stakeholders would be engaged in the road-mapping process—ultimately serving as the demonstration partners. Parallel surveys of the processors and regulators would provide boundary conditions on the operability of the process, its criterion emissions, and concerns of potential abutters. The off-takers and side-stream players set the regional markets for the principal and secondary products, so their input is needed to refine the techno-economic analyses.

Based on discussions at the workshop (Ames Laboratory, 2015), we believe that both financial stakeholders and regulators would appreciate seeing a working prototype combined with a plausible business plan rather than just detailed technical plans for the new technology. Therefore, instead of exceedingly systematic planning to identify technical and logistical gaps, we advocate an approach of "planning to throw one away" to rapidly gain practical experience with prototypes. We deem that this seemingly more casual/agile approach is warranted because the transition from bench to field scale is much smaller than is typical in the chemical and refining industries. In this instance, it will be the design for manufacture, not design for scale-up that will gate market entry. Our preliminary estimates for both the potential size and value of the markets encourage us to propose commissioning initial technical research in parallel with the surveys.

The Planning and Participation phase of the Roadmap would produce the refined stakeholder assessments, an initial techno-economic assessment and early examples of the component technologies to help preview what may be possible.

8.2 | Phase II. Research and Development

The DOE national labs that participated in the workshops drafted a preliminary organizational chart and research activities that drew from technical insights developed by industrial projects and projects that have been supported by the Department of Energy and through internal investments at the national laboratories. Preliminary plans outlined technology platforms for dealing with gaseous, wet, and solid feedstocks as well as the disciplines needed to advance the technologies and address the technical gaps described above. The discipline-based activities would include both experimental and modeling work.

The staff and facilities to approach the entire opportunity space are distributed across National Laboratories and universities. The R&D organization chart would likely be staffed to cover parallel research activities for each of the three types of feedstocks through crosscutting, disciplinary activities such as those called out above as technical challenges.

We suggest starting with sludge, manure and other wet wastes (e.g., residuum from food processing), as much for the limited competition for them as for the value their removal would afford in many localities nationwide. As candidate products, we suggest starting with chemicals and heavier fuels (distillate, bunker) the former because of their higher value; the latter because their demand is projected to increase and because their customers (long haul transportation, airlines) have fewer alternatives to decrease their carbon footprints.

We further suggest the use of municipal sewage sludge as the initial feedstock. It is broadly distributed (Seiple et al., 2017) and its valorization would provide benefits both from the sale of the products and savings on waste disposal. We recommend initially focusing on non-supercritical hydrothermal liquefaction as the front-end for processing the initial candidate feedstocks because of its omnivorism (Elliott, 2007; Lu, Yang, Wang, & Yang, 2010), ready scalability (Barreiro, Gómez, Hornung, Kruse, & Prins, 2015; Inoue, Okuma, Masuda, Yasumuro, & Miura, 2012), tolerance of wet feedstocks, and demonstrated production of a tractable bio-oil (Elliott, 2007; Goudriaan & Peferoen, 1990) with an attractive greenhouse gas footprint (Connelly, Colosi, Clarens, & Lambert, 2015) (see Appendix). Examples of feedstocks that have been processed with hydrothermal liquefaction include wood (Zhixia Li et al., 2015), cellulose (Nan, Shende, Shannon, & Shende, 2016), microalgae (Barreiro et al., 2015; Brown, Duan, & Savage, 2010; Connelly et al., 2015; Faeth, Valdez, & Savage, 2013), macroalgae (Zhou, Zhang, Zhang, Fu, & Chen, 2010), food waste (Anouti, Haarlemmer, Déniel, & Roubaud, 2016), sewage sludge (Snowden-Swan et al., 2016), and municipal solid waste (Chiaberge et al., 2014). Another process, IH$^{2®}$ from the Gas Technology Institute (Marker et al., 2014), offers some of those benefits but requires high pressures (>160 bar) of hydrogen, and therefore poses a safety concern and a logistical issue (getting the product to its customers).

Hydrothermal liquefaction is compatible with anaerobic digestion, because the aqueous phase from liquefaction can be used in digesters to improve the energetic balance (Posmanik et al., 2017). When sewage sludge is used as a feedstock, the digestion infrastructure may already be present since it is currently the go-to technology at wastewater treatment plants. The bio-oil from hydrothermal liquefaction can be upgraded by conventional thermally activated catalytic processes (Elliott, 2007; Posmanik et al., 2017; Snowden-Swan et al., 2016; Zhu et al., 2013), however, the process requires high pressure hydrogen. Instead, we suggest pairing hydrothermal liquefaction with electrochemically activated hydrogenation of the oil (Jackson et al., 2014; Lam, Lowe, et al., 2015; Li et al., 2012). While this new method requires considerable development of both catalysts and reactors, it promises a route to upgraded products that is likely more downscalable and safer than the use of high pressure hydrogen gas.

The work could be sequenced conventionally in phases corresponding roughly to low, medium and high levels of technology readiness (TRL). The Research and Development phase (low TRL will characterize the component processes and produce constitutive relations that could be used to project the operation of "brass-board" prototypes from bench scale experiments. The Development phase (medium TRL) will produce works-like prototypes and designs for manufacture of the production units, along with catalyst formulations, operating correlations, control algorithms, and the intellectual property that will afford successor participants both freedom to practice and a proprietary competitive advantage. The last phase (higher TRL) will deploy works-like and perhaps made-like prototypes at the facilities of the custodian/processors, initially fed with a slipstream of the actual feedstock.

Instead, we advocate for a development process that follows the precepts of Lean Start-up (Blank, 2017): the rapid construction of a minimally viable prototype that can be field tested and discussed concretely with the stakeholders in the value chain to rapidly and frugally devise refinements.

8.3 | Phase III. Epilogue

In the best case, the roadmap culminates in a demonstration of the technology to manufacturers or investors. The research and development activities will therefore be redirected towards deployment and demonstration. In addition, the third phase of the roadmap will focus on capturing and disseminating the lessons learned and exploiting the value that accumulates during the previous two phases. The stakeholder input gathered in Phase 1 plus the contacts engendered in the surveys will serve as a prelude to the marketing/partnering required to build businesses based on *Energy Everywhere.* Administration of the third phase could include establishing a persistent centralized research activity to contend with technical support to serve the continuing, common needs of an *Energy Everywhere* enterprise. Ideally, that research would be funded directly by the stakeholders to make it responsive to their needs.

In any event, Phase III will produce and execute a spinout plan that documents the offerings and value of an incipient *Energy Everywhere* enterprise.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

ENDNOTE

[1]An average adult cow weighs 1,400 lbs (635 kg) and produces around 120 lbs (54 kg) of wet manure per day (Tyson & Mukhtar, 2015), the heating value of which is about 4 MJ/kg (Cooperative Extension System, 2012), therefore the cost of the digestion system at \$300 per cow is about 0.12 $\$/W_{th}$. The downstream biogas-fueled turbine costs about 0.40 $\$/W_e$ according to offerings posted on the web (Alibaba, 2018) for a total of $\$0.64/W_e$. For reference the current installed price of a small wind-powered generator is about $\$1/W_e$ (Agricultural Marketing Resource Center, 2015).

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REFERENCES

Advanced Manufacturing Office US DOE. (2015). *Process intensification workshop.* Retrieved from https://energy.gov/sites/prod/files/2016/03/f30/2015%20DOE%20AMO%20Process%20Intensification%20Workshop%20Report_0.pdf

Agricultural Marketing Resource Center. (2015). *Wind energy profile.* Retrieved from https://www.agmrc.org/renewable-energy/renewable-energy/wind-energy-profile/

Alibaba. (2018). *160KW continuous power China natural/LPG/biogas electric gas generator.* Retrieved from https://www.alibaba.com/product-detail/160KW-Continus-Power-China-Natural-LPG_60728992937.html

American Biogas Council. (2014). *A Snapshot of RNG and the market.* Retrieved from https://www.americanbiogascouncil.org/biogasProcessing/rngMarket_snapshot.pdf

Ames Laboratory. (2015). *Chemical conversion via modular manufacturing: Distributed, stranded and waste feedstocks.* Retrieved from https://www.ameslab.gov/workshops/chemical-conversion-modular-manufacturing

Ames Laboratory. (2016). *Workshop on fundamental science needs for waste to chemical conversion*. Retrieved from https://www.ameslab.gov/workshops/fundamental-science-agenda

Anouti, S., Haarlemmer, G., Déniel, M., & Roubaud, A. (2016). Analysis of physicochemical properties of bio-oil from hydrothermal liquefaction of blackcurrant pomace. *Energy and Fuels*, *30*, 398–406.

Argonne National Laboratory. (2017). *The greenhouse gases, regulated emissions, and energy use in transportation (GREET) model*. Retrieved from http://greet.es.anl.gov

Argote, L., & Epple, D. (1990). Learning curves in manufacturing. *Science*, *247*, 920–924.

Barreiro, D. L., Gómez, B. R., Hornung, U., Kruse, A., & Prins, W. (2015). Hydrothermal liquefaction of microalgae in a continuous stirred-tank reactor. *Energy and Fuels*, *29*, 6422–6432.

Bennion, E. P., Ginosar, D. M., Moses, J., Agblevor, F., & Quinn, J. C. (2014). Lifecycle assessment of microalgae to biofuel: Comparison of thermochemical processing pathways. *Applied Energy*, *154*, 1062–1071.

Bergin, S. P. (2003). *Annual Report for the Fischer-Tropsch Fuels Production and Demonstration Project Agreement Number DE-FC26-01NT41099*. Retrieved from http://www.osti.gov/scitech/servlets/purl/820557

Bioeconomy Institute Iowa State University. (2015). *Modular manufacturing for bioprocessing*. Retrieved from https://www.biorenew.iastate.edu/modularmfg/

Blank, S. (2017). *Why the lean start-up changes everything*. Harvard Business Review, May, 3–9.

Brewers Association. (2016). *National beer sales & production data*. Retrieved from https://www.brewersassociation.org/statistics/national-beer-sales-production-data/

Brown, T. M., Duan, P., & Savage, P. E. (2010). Hydrothermal liquefaction and gasification of *Nannochloropsis* sp. *Energy and Fuels*, *24*, 3639–3646.

Chan, Y. H., Tan, R. R., Yusup, S., Lam, H. L., & Quitain, A. T. (2016). Comparative life cycle assessment (LCA) of bio-oil production from fast pyrolysis and hydrothermal liquefaction of oil palm empty fruit bunch (EFB). *Clean Technologies and Environmental Policy*, *18*, 1759–1768.

Chen, X., & Khanna, M. (2012). Explaining the reductions in US corn ethanol processing costs: Testing competing hypotheses. *Energy Policy*, *44*, 153–159. https://doi.org/10.1016/j.enpol.2012.01.032

Chiaberge, S., Leonardis, I., Fiorani, T., Cesti, P., Reale, S., & De Angelis, F. (2014). Bio-oil from waste: A comprehensive analytical study by soft ionization FTICR mass spectroscopy. *Energy and Fuels*, *28*, 2019–2026.

Chin, N., & Franconeri, P. (1980). *Composition and heating value of municipal solid waste in the spring creek area of New York City*. Paper presented at the National Waste Processing Conference, Washington, DC.

Chrisensen, C. M. (1997). *The innovator's dilemma*. Harvard Business Review Press.

Connelly, E. B., Colosi, L. M., Clarens, A. F., & Lambert, J. H. (2015). Life cycle assessment of biofuels from algae hydrothermal liquefaction: The upstream and downstream factors affecting regulatory compliance. *Energy and Fuels*, *29*, 1653–1661.

Cooperative Extension System. (2012). *What are typical values for the higher heating value of manure scraped from cattle feedyard surfaces?* Retrieved from https://articles.extension.org/pages/38755/what-are-typical-values-for-the-higher-heating-value-of-manure-scraped-from-cattle-feedyard-surfaces

Cunningham, J. A. (1980). Management: Using the learning curve as a management tool: The learning curve can help in preparing cost reduction programs, pricing forecasts, and product development goals. *IEEE Spectrum*, *17*, 45–48.

Davis, R. E., Fishman, D. B., Frank, E. D., Johnson, M. C., Jones, S. B., Kinchin, C. M., … Wigmosta, M. S. (2014). Integrated evaluation of cost, emissions, and resource potential for algal biofuels at the national scale. *Environmental Science & Technology*, *48*, 6035–6042.

Deshmukh, S. R., Tonkovich, A. L. Y., Jarosch, K. T., Schrader, L., Fitzgerald, S. P., Kilanowski, D. R., … Mazanec, T. J. (2010). Scale-up of microchannel reactors for Fischer-Tropsch synthesis. *Industrial and Engineering Chemistry Research*, *49*, 10883–10888.

Elliott, D. C. (2007). Historical developments in hydroprocessing bio-oils. *Energy and Fuels*, *21*, 1792–1815.

Ethanol Producer Magazine. (2018). *U.S. ethanol plants*. Retrieved from http://ethanolproducer.com/plants/listplants/US/Operational/All/

Faeth, J. L., Valdez, P. J., & Savage, P. E. (2013). Fast hydrothermal liquefaction of *Nannochloropsis* sp. to produce biocrude. *Energy and Fuels*, *27*, 1391–1398.

Fermoso, J., Pizarro, P., Coronado, J. M., & Serrano, D. P. (2017). Advanced biofuels production by upgrading of pyrolysis bio-oil. *WIREs Energy and Environment*, *6*, e245. https://doi.org/10.1002/wene.245

Fortier, M.-O. P., Roberts, G. W., Stagg-Williams, S. M., & Sturm, B. S. M. (2014). Life cycle assessment of bio-jet fuel from hydrothermal liquefaction of microalgae. *Applied Energy*, *122*, 73–82.

Frank, E. D., Elgowainy, A., Han, J., & Wang, Z. (2013). Life cycle comparison of hydrothermal liquefaction and lipid extraction pathways to renewable diesel from algae. *Mitigation and Adaptation Strategies for Global Change*, *18*, 137–158.

Garcia, M. L., & Bray, O. H. (1997). Fundamentals of technology roadmapping

Goudriaan, F., & Peferoen, D. G. R. (1990). Liquid fuels from biomass via a hydrothermal process. *Chemical Engineering Science*, *45*, 2729–2734.

Gulipac, S. (2016). Industrial Symbiosis: Building on Kalundborg's waste management experience. *Renewable Energy Focus*, *17*, 25–27.

Hettinga, W. G., Junginger, H. M., Dekker, S. C., Hoogwijk, M., McAloon, A. J., & Hicks, K. B. (2009). Understanding the reductions in US corn ethanol production costs: An experience curve approach. *Energy Policy*, *37*(1), 190–203. https://doi.org/10.1016/j.enpol.2008.08.002

Hu, S. J., Ko, J., Weyand, L., ElMaraghy, H. A., Lien, T. K., Koren, Y., … Shpitalni, M. (2011). Assembly system design and operations for product variety. *CIRP Annals*, *60*, 715–733. https://doi.org/10.1016/j.cirp.2011.05.004

IEA Task 42. (2013). *3-platform (vacuum gas oil, pyrolysis oil, electricity&heat) biorefinery using wood for renewable gasoline&diesel, biochar and pyrolysis oil*. Retrieved from http://www.iea-bioenergy.task42-biorefineries.com/upload_mm/1/4/6/6571b577-f057-4f96-a50c-78b393ca64c3_prmpbf16209%20LIF%20IEA%20Biorefining%20Factsheet%201%20vacuum%20A4%20v3w.pdf

Inoue, T., Okuma, O., Masuda, K., Yasumuro, M., & Miura, K. (2012). Direct liquefaction of brown coal using a 0.1 ton/day process development unit: Effect of hydrothermal treatment on scale deposition and liquefaction yield. *Energy and Fuels*, *26*, 5821–5827.

Jackson, J. E., Lam, C. H., Saffron, C. M., & Miller, D. J. (2014). *U.S. Patent No.* US2014/0110268 A1. Washington, DC: US Patent Office.

Kaiser, M. J., & Gary, J. H. (2009). Refinery cost functions in the U.S. Gulf Coast. *Petroleum Science and Technology*, *27*, 168–181.

Kiss, A. A., Lange, J.-P., Schuur, B., Brilman, D. W. F., van der Ham, A. G. J., & Kersten, S. R. A. (2016). Separation technology—Making a difference in biorefineries. *Biomass and Bioenergy*, *95*, 296–309.

Lam, C. H., Lowe, C. B., Li, Z., Longe, K. N., Rayburn, J. T., Caldwell, M. A., … Jackson, J. E. (2015). Electrocatalytic upgrading of model lignin monomers with earth abundant metal electrodes. *Green Chemistry*, *17*, 601–609.

Lam, F. L. Y., Li, M. C. L., Chau, R. S. L., Arancon, R. A. D., Hu, X., & Luque, R. (2015). Catalysis at room temperature: Perspectives for future green chemical processes. *WIREs Energy and Environment*, *4*, 316–338.

Lanzatech. (2015). *Lanzatech executive summary*. Retrieved from https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwjV6szAv7zXAhUkllQKHXAaAFUQFggoMAA&url=http%3A%2F%2Fwww.lanzatech.com%2Fwp-content%2Fuploads%2F2015%2F03%2F2-pager-2015.pdf&usg=AOvVaw2zJJfgV0NOyhlVsF4oyq9b

Lazarus, W. F. (2008). *Farm-based anaerobic digesters as an energy and odor control technology*. Retrieved from http://www.usda.gov/oce/reports/energy/AnerobicDigesters0308.pdf

Li, Z., Garedew, M., Lam, C. H., Jackson, J. E., Miller, D. J., & Saffron, C. M. (2012). Mild electrocatalytic hydrogenation and hydrodeoxygenation of bio-oil derived phenolic compounds using ruthenium supported on activated carbon cloth. *Green Chemistry*, *14*, 2540–2549.

Li, Z., Hong, Y., Cao, J., Huang, Z., Huang, K., Gong, H., … Li, Y. (2015). Effects of mild alkali pretreatment and hydrogen-donating solvent on hydrothermal liquefaction of eucalyptus woodchips. *Energy and Fuels*, *29*, 7335–7342.

Liu, X., Saydah, B., Eranki, P., Colosi, L. M., Greg Mitchell, B., Rhodes, J., & Clarens, A. F. (2013). Pilot-scale data provide enhanced estimates of the life cycle energy and emissions profile of algae biofuels produced via hydrothermal liquefaction. *Bioresource Technology*, *148*, 163–171.

Lu, W., Yang, F., Wang, C., & Yang, Z. (2010). Comparison of high-caloric fuel (HCF) from four different raw materials by deoxy-liquefaction. *Energy and Fuels*, *24*, 6633–6643.

Malik, K., Singh, S., Basu, S., & Verma, A. (2017). Electrochemical reduction of CO_2 for synthesis of green fuel. *WIREs Energy and Environment*, *6*. https://doi.org/10.1002/wene.244

Marker, T. L., Felix, L. G., Linck, M. B., Roberts, M. J., Ortiz-Toral, P., & Wangerow, J. (2014). Integrated hydropyrolysis and hydroconversion (IH2) for the direct production of gasoline and diesel fuels or blending components from biomass, part 2: Continuous testing. *Environmental Progress & Sustainable Energy*, *33*, 762–768.

McKinsey&Company. (2009). *The debate over private-public partnerships.* Retrieved from https://www.mckinsey.com/industries/public-sector/our-insights/the-right-way-to-invest-in-infrastructure

Mu, D., Min, M., Krohn, B., Mullins, K. A., Ruan, R., & Hill, J. (2014). Life cycle environmental impacts of wastewater-based algal biofuels. *Environmental Science & Technology*, *48*, 11696–11704.

Muñoz, I., Flury, K., Jungbluth, N., Rigarlsford, G., i Canals, L. M., & King, H. (2014). Life cycle assessment of bio-based ethanol produced from different agricultural feedstocks. *International Journal of Life Cycle Assessment*, *19*, 109–119. https://doi.org/10.1007/s11367-013-0613-1

Nan, W., Shende, A. R., Shannon, J., & Shende, R. V. (2016). Insight into catalytic hydrothermal liquefaction of cardboard for biofuels production. *Energy and Fuels*, *30*, 4933–4944.

National Energy Technology Laboratory. (2013). *Technology Learning Curve (FOAK to NOAK)* (DOE/NETL-341/081213).

National Energy Technology Laboratory. (2015). *Stripper well consortium looks back on fifteen years of innovative technology and partnership.* Retrieved from https://www.netl.doe.gov/newsroom/features/10-2015

Orfield, N. D., Fang, A. J., Valdez, P. J., Nelson, M. C., Savage, P. E., Lin, X. N., & Keoleian, G. A. (2014). Life cycle design of an algal biorefinery featuring hydrothermal liquefaction: Effect of reaction conditions and an alternative pathway including microbial regrowth. *ACS Sustainable Chemistry & Engineering*, *2*, 867–874.

Pegallapati, A. K., Dunn, J. B., Frank, E. D., Jones, S. B., Zhu, Y., Snowden-Swan, L., … Kinchin, C. M. (2015). *Supply Chain Sustainability Analysis of Whole Algae Hydrothermal Liquefaction and Upgrading* (ANL/ESD-15/8).

Posmanik, R., Labatut, R. A., Kim, A. H., Usack, J. G., Tester, J. W., & Angenent, L. T. (2017). Coupling hydrothermal liquefaction and anaerobic digestion for energy valorization from model biomass feedstocks. *Bioresource Technology*, *233*, 134–143.

Ricci-Rossi, G. C. (1985). Vorteile eines modularen Konzeptes bei der Anschaffung von Speisöllanlangen. *Fette, Seifen, Anstrichm*, *87*, 529–531. https://doi.org/10.1002/lipi.19850871311

Rijksdienst voor Ondernemend. (2006). Action Plan for Process Intensification. Retrieved from https://www.rvo.nl/sites/default/files/bijlagen/Action_Plan_Process_Intensification.pdf

Sanscartier, D., MacLean, H. L., & Saville, B. (2011). Electricity production from anaerobic digestion of household organic waste in Ontario: Techno-economic and GHG emission analyses. *Environmental Science & Technology*, *46*, 1233–1242.

Scheyder, E. (2016). *Newest U.S. refinery sold at a loss, hurt by oil price slump.* Retrieved from https://www.reuters.com/article/us-north-dakota-refinery/newest-u-s-refinery-sold-at-a-loss-hurt-by-oil-price-slump-idUSKCN0ZF03K

Seiple, T. E., Coleman, A. M., & Skaggs, R. L. (2017). Municipal wastewater sludge as a sustainable bioresource in the United States. *Journal of Environmental Management*, *197*, 673–680.

Sievers, S., Seifert, T., Franzen, M., Schembecker, G., & Bramsiepe, C. (2017). Fixed capital investment estimation for modular production plants. *Chemical Engineering Science*, *158*, 395–410.

Smith, D. B., & Larsson, J. L. (1989). The impact of learning on cost: The case of the heart transplantation. *Hospital and Health Services Administration*, 85–97.

Snowden-Swan, L. J., Zhu, Y., Jones, S. B., Elliott, D. C., Schmidt, A. J., Hallen, R. T., … Maupin G. (2016). *Hydrothermal Liquefaction and Upgrading of Municipal Wastewater Treatment Plant Sludge: A Preliminary Techno-Economic Analysis* (PNNL-25464).

Stankiewicz, A. I., & Moulijn, J. A. (2000). Process intensification: Transforming chemical engineering. *Chemical Engineering Progress*, *96*, 22–23.

Summers, H. M., Ledbetter, R. N., McCurdy, A. T., Morgan, M. R., Seefeldt, L. C., Jena, U., … Quinn, J. C. (2015). Techno-economic feasibility and life cycle assessment of dairy effluent to renewable diesel via hydrothermal liquefaction. *Bioresource Technology*, *196*, 431–440.

Tyson, T., & Mukhtar, S. (2015). *Liquid manure storage ponds, pits, and tanks.* Retrieved from http://articles.extension.org/pages/15476/liquid-manure-storage-ponds-pits-and-tanks

University of Michigan Center for Sustainable Systems. (n.d.) *US wastewater treatment.* Retrieved from http://css.snre.umich.edu/sites/default/files/U.S._Wastewater_Treatment_Factsheet_CSS04-14.pdf

US Census Bureau. (2007). *2007 Economic Census of the United States.* Retrieved from http://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?pid=ECN_2007_US_00CADV1&prodType=table

US Census Bureau. (2012). *2012 Census of Governments.* Retrieved from https://www.census.gov/govs/cog/index.html

US Department of Agriculture. (2008). *Profits, costs, and the changing structure of dairy farming.* Retrieved from http://www.ers.usda.gov/media/430528/err47b_1_.pdf

US Department of Agriculture. (2011). *Carbon prices and the adoption of methane digesters on dairy and hog farms.* Retrieved from http://www.ers.usda.gov/media/132205/eb16.pdf

US Department of Agriculture. (2012). *2012 Census of Agriculture.* Retrieved from https://www.agcensus.usda.gov/Publications/2012/#full_report

US Department of Agriculture, US EPA, & US DOE. (2014). *Biogas opportunities roadmap.* Retrieved from https://www3.epa.gov/climatechange/Downloads/Biogas-Roadmap.pdf

US Department of Energy. (2011). *U.S. billion-ton update: Biomass supply for a bioenergy and bioproducts industry.*

US Department of Energy. (2016). 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks

US Department of Energy Bioenergy Technologies Office. (2017). Biofuels and bioproducts from wet and gaseous waste streams: Challenges and opportunities

US Department of Energy Office of Energy Efficiency and Renewable Energy. (2006). *Biomass Energy Data Book* (ORNL/TM-2006/571).

US Department of Energy Office of Energy Efficiency and Renewable Energy. (2016). *Modular Chemical Process Intensification Institute for Clean Energy Manufacture*

US Department of Transportation. (2013). *Transportation in the US 2013*. Retrieved from http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/transportation_in_the_united_states_2013/index.html

US Energy Information Agency. (2015). Annual Energy Outlook 2015

US Energy Information Agency. (2016a). *Number and capacity of US petroleum refineries*. Retrieved from https://www.eia.gov/dnav/pet/pet_pnp_cap1_dcu_nus_a.htm

US Energy Information Agency. (2016b). *US annual supply of petroleum*. Retrieved from http://www.eia.gov/dnav/pet/pet_cons_psup_dc_nus_mbbl_a.htm

US Energy Information Agency. (2016c). *US imports by country*. Retrieved from https://www.eia.gov/dnav/pet/pet_move_impcus_a2_nus_epc0_im0_mbbl_a.htm

US Energy Information Agency. (2017a). *Number and capacity of US petroleum refineries*. Retrieved from https://www.eia.gov/dnav/pet/pet_pnp_cap1_dcu_nus_a.htm

US Energy Information Agency. (2017b). *U.S. fuel ethanol production continues to grow in 2017*. Retrieved from https://www.eia.gov/todayinenergy/detail.php?id=32152

US Environmental Protection Agency. (2015). *LFG energy project development handbook*. Retrieved from https://www.epa.gov/sites/production/files/2016-07/documents/pdf_full.pdf

US Environmental Protection Agency. (2016a). *Advancing sustainable materials management: 2014 fact sheet*. Retrieved from https://www.epa.gov/sites/production/files/2016-11/documents/2014_smmfactsheet_508.pdf

US Environmental Protection Agency. (2016b). *AgSTAR database of livestock digesters*. Retrieved from https://www.epa.gov/agstar/livestock-anaerobic-digester-database

US Environmental Protection Agency. (2016c). *Landfill gas energy project data and landfill technical data*. Retrieved from https://www.epa.gov/lmop/landfill-gas-energy-project-data-and-landfill-technical-data

US Environmental Protection Agency. (2016d). *Landfill methane outreach program*. Retrieved from https://www.epa.gov/lmop/landfill-gas-energy-project-data-and-landfill-technical-data

US Government Accounting Office. (2008). *Concentrated animal feeding operations*. Retrieved from http://www.gao.gov/assets/290/280238.html

Viswanathan, V., Crawford, A., Stephenson, D., Kim, S., Wang, W., Li, B., … Sprenkle, V. (2014). Cost and performance model for redox flow batteries. *Journal of Power Sources*, *247*(c), 1040–1051. https://doi.org/10.1016/j.jpowsour.2012.12.023

Wang, M. (2008). *Estimation of energy efficiencies of U.S. petroleum refineries*. Retrieved from https://greet.es.anl.gov/files/hl9mw9i7

Water Environment and Reuse Foundation. (2014). *Featured facility – Metro Vancouver*. Retrieved from http://www.werf.org/lift/docs/LIFT_Notes_Docs/Featured_Facility_12-11-14.aspx

Wright, T. P. (1936). Factors affecting the cost of airplanes. *Journal of the Aeronautical Sciences*, *3*, 122–128.

Yoneyama, Y., San, X., Iwai, T., & Tsubaki, N. (2008). One-step synthesis of isoparaffin from synthesis gas using hybrid catalyst with supercritical butane. *Energy and Fuels*, *22*(5), 2873–2876. https://doi.org/10.1021/ef800205c

Zaks, D. P. M., Winchester, N., Kucharik, C. J., Barford, C. C., Paltsev, S., & Reilly, J. M. (2011). Contribution of anaerobic digesters to emissions mitigation and electricity generation under U.S. climate policy. *Environmental Science & Technology*, *45*, 6735–6742.

Zhou, D., Zhang, L., Zhang, S., Fu, H., & Chen, J. (2010). Hydrothermal liquefaction of macroalgae *Enteromorpha prolifera* to bio-oil. *Energy and Fuels*, *24*, 4054–4061.

Zhu, Y., Albrecht, K. O., Elliott, D. C., Hallen, R. T., & Jones, S. B. (2013). Development of hydrothermal liquefaction and upgrading technologies for lipid-extracted algae conversion to liquid fuels. *Algal Research*, *2*, 455–464.

Zhu, Y., Biddy, M. J., Jones, S. B., Elliott, D. C., & Schmidt, A. J. (2014). Techno-economic analysis of liquid fuel production from woody biomass via hydrothermal liquefaction (HTL) and upgrading. *Applied Energy*, *129*, 384–394.

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APPENDIX: LITERATURE REVIEW OF LIFECYCLE ANALYSES OF HYDROTHERMAL LIQUEFACTION OF WET FEEDSTOCKS TO PRODUCE LIQUID FUEL

The discussion in the main document focused on the economics and available feedstocks. Converting waste to fuel can also, in principle, provide a greenhouse gas benefit because the feedstocks will either be derived from renewable resources. To estimate the magnitude of the benefit, we provide below (Table A1) a summary of lifecycle analyses from several studies that converted waste (e.g., sludge) or purpose-grown biomass (e.g., algae) into an oil via hydrothermal liquefaction. In general, it is challenging to compare individual LCA studies to one another because of a lack of transparency and differences in assumptions, such as analysis boundaries, processing technology details and performances that can lead to significantly different results. The table below lists studies from the recently published literature that were vetted to ensure they made sense from a basic LCA methodology standpoint. Several studies have been excluded from the list because their results were difficult to compare with the others. The listed studies did not include hydrothermal carbonization (char production) or other conversion technologies.

For reference, most of the entries in the table generate a significant savings—25–50% of the carbon dioxide per unit of fuel compared to petroleum-derived diesel fuels (ca 94 g $CO_{2\text{-}e}$/MJ [Argonne National Laboratory, 2017]). The major outlier is the study that discusses algae-derived fuels that appear to be significantly *more* GHG-intensive than petroleum.

TABLE A1 Summary of lifecycle analyses of fuels derived from waste carbon

Study	GHGs (g $CO_{2\text{-}e}$/MJ fuel)	Notes
Algae HTL		
Fortier, Roberts, Stagg-Williams, and Sturm (2014)	21–35	Wastewater-based algae. Range of feed solids content 10–30%. Transporting dewatered algae resulted in higher GHGs, optimized case 54.2 g$CO_{2\text{-}e}$/MJ (vs. 21 for no transport option).
Frank, Elgowainy, Han, and Wang (2013)	29	
Liu et al. (2013)	33	Unclear if this value includes combustion emissions or not.
Orfield et al. (2014)	35	Analysis is for bio-oil production. Added GHG value for upgrading stage.
Pegallapati et al. (2015)	34	Based on 2015 modeling by NREL and PNNL
Davis et al. (2014)	38	This is an update to Frank 2013
Connelly et al. (2015)	44	They also evaluate jet which only qualifies for 25% reduction when considering multiplier for aviation fuel
Bennion, Ginosar, Moses, Agblevor, and Quinn (2014)	63	Includes propane extraction of bio-oil
Mu et al. (2014)	148; 296	For wastewater-based algae and freshwater algae. Water use 0.204 and 0.043 m^3/km, for freshwater and wastewater, respectively. (petroleum diesel is 0.012 m^3/km water use.)
Waste HTL		
Snowden-Swan et al. (2016)	23–42	Depends heavily on % solids in the feed and configuration (e.g., CHG vs. no CHG)
Chan, Tan, Yusup, Lam, and Quitain (2016)	75	Palm fruit bunches. Analysis extends only to bio-oil production. Added GHG value for upgrading. Pyrolysis also examined, leading to about 2X emissions of HTL (due to drying).