



**U.S. Department of Energy
Advanced Research Projects Agency – Energy**

**Request for Information (RFI)
DE-FOA-0002170**

on

Municipal Solid Waste Management and Materials Redeployment

Objective:

The Advanced Research Projects Agency – Energy (ARPA-E) in the US Department of Energy is seeking novel ideas and information concerning:

- a) Waste-To-Materials and Energy (WTM&E) technologies to produce materials (such as cementitious ashes, metals, and critical materials like rare earth elements and precious metals), heat, and power from either unsorted or autonomously classified Municipal Solid Waste (MSW) in Waste-to-energy (WTE) plants
- b) Waste-To-Crude Fuels (WTCF) technologies to produce a refinery blend stock and/or marine-grade bunker fuel oil from mixed plastic/paper streams
- c) Waste-To-Carbon (WTC) technologies such as enhanced/catalyzed hydrothermal carbonization of unsorted MSW and/or Municipal wastewater (MWW e.g., sewage) to produce carbon/char-like products

Critically, ARPA-E is interested in technologies that would lead to *economically viable* processes and/or value-add products (e.g., cementitious or pozzolanic precursors, refinery blend stocks, char and tire-fillers). ARPA-E seeks input from technical experts, researchers, and end-users of MSW technologies (such as power plants, factories, utilities, manufacturers), waste-to-energy operators, engineering disciplines (chemical/process, mechanical, environmental, electrical), material scientists (concrete scientists/chemists), computer and robotic scientists, social sciences, and related disciplines. Consistent with the agency's mission, ARPA-E is seeking clearly disruptive, novel technologies early in the R&D cycle, and novel integration strategies for existing technologies.

Please carefully review the REQUEST FOR INFORMATION GUIDELINES below and note in particular: the information you provide will be used by ARPA-E solely for program planning, without attribution. THIS IS A REQUEST FOR INFORMATION ONLY. THIS NOTICE DOES NOT CONSTITUTE A FUNDING OPPORTUNITY ANNOUNCEMENT (FOA). NO FOA EXISTS AT THIS TIME. Respondents shall not include any information in their response to this RFI that might be considered proprietary or confidential.

Background:

The U.S. generates more than 260 MM tons¹ of MSW annually, which represents more than 2.5 Quads

¹ Note that there are widely differing totals.

Reference: "Advancing Sustainable Materials Management 2015 fact Sheet" EPA

https://www.epa.gov/sites/production/files/201807/documents/2015_smm_msw_factsheet_07242018_fnl_508_002.pdf



[1 Quadrillion BTU (Quad) = 1.055×10^{18} J] of embodied thermal energy. On average, Americans produce 4.4 lb MSW/day². Over the past two decades, recycling, composting and Waste-To-Energy (WTE) technologies have helped offset the increasing need for landfilling or combustion without energy recovery³. However, MSW management is a growing challenge as 52.5%⁴ is still landfilled and recyclables export options have become limited⁵.

For the purposes of this RFI, ARPA-E is specifically interested in municipal solid waste⁶. Other waste streams and topics that are not of interest at this time include manure, construction/demolition materials, and hazardous materials.

Landfilled MSW has significant embedded energy (estimated to be 1.4 Quads), and is estimated to release significant greenhouse gas (GHG) emissions, 1.4×10^6 metric tonnes of methane⁷. ARPA-E is therefore interested in technologies that enable MSW to be diverted from landfills (to avoid emissions) and instead take advantage of embedded energy and/or value-add products to make the process economical. Specifically, three strategies are of interest:

- a) Waste-To-Materials & Energy (WTM&E) technologies to produce materials (such as cementitious ashes, metals, rare earth elements), heat, and power from unsorted MSW or recyclables in WTE plants;
- b) Waste-To-Crude Fuels (WTCF) technologies to produce a refinery blend stock and/or marine-grade bunker fuel oil from mixed plastic/paper streams; and
- c) Waste-To-Carbon (WTC) technologies such as enhanced/catalyzed hydrothermal carbonization of unsorted MSW with Municipal Wastewater (e.g., sewage) to produce carbon/char products

ARPA-E is also interested in information about several other complementary areas to strategies a- c above:

- d) Technologies and approaches (e.g artificial intelligence and others) that enable characterization, classification and prediction of MSW streams from source to facility.
- e) Life cycle assessments (LCA) of plastics and paper without the option to export. Inclusion of logistics, wastage and cleaning of recyclables.

Other waste management strategies that are not of interest for this RFI: Composting, Landfill design, including gasification on landfills, gasification of plastics, conventional pyrolysis, or any biological

² "Waste-to-Energy from Municipal Solid Wastes" Report U.S Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy BETO, August 2019.

³ Quantity of Municipal Solid Waste Generated and Managed. <https://cfpub.epa.gov/roe/indicator.cfm?i=53>

⁴ https://www.epa.gov/sites/production/files/2019-03/documents/infographic_full-060513_v4.pdf

⁵ "2017 California Exports of Recyclable Materials", CalRecycle California Department of Resources and Recovery, February 2019.

⁶ Municipal Solid Waste (MSW) (also called trash) consists of everyday items such as product packaging, yard trimmings, furniture, clothing, bottles and cans, food, newspapers, appliances, electronics and batteries. Sources of MSW include residential waste (including waste from multi-family housing) and waste from commercial and institutional locations, such as businesses, schools and hospitals. The Environmental Protection Agency's (EPA) definition of MSW does not include industrial, hazardous or construction and demolition (C&D) waste [EPA]. Under the current RFI, we are interested in yard trimmings, specially for the c) strategy,

⁷ Powell J.T & Chertow M.R. "Quantity, Components and Value of Waste Materials Landfilled in the United States" *Journal of Industrial Ecology* 23.2 (2018) 466-479.

pathway approach.

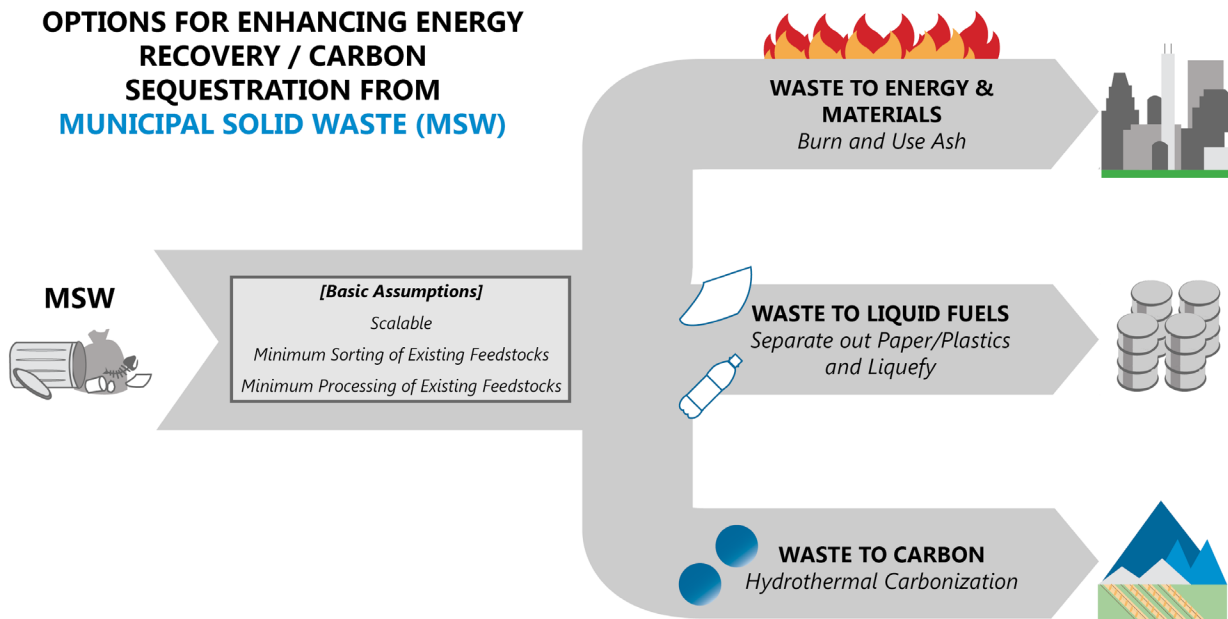


Figure 1. Simplified material flow diagram for the strategies of interest to ARPA-E under current RFI.

A) Waste to Materials and Energy (WTM&E)

A.1 Motivation for approach

- **Energy security.** Potential to generate more than 1.4 Quads/yr from unsorted MSW feedstock and employ the thermal energy released in incineration to produce supplementary cementitious materials for construction. The US produces ca. 100 million tons of cement at an energy cost of more than 0.4 Quad.
- **Economic competitiveness.** Improved plant economics by demonstrating cost-effective incineration of MSW to produce valorized materials, power and heat. In addition, avoidance of MSW ash landfill transport and tipping fees. For example, income from valorized ash by using up front (pre-combustion) precursors to reduce variability in the composition of the resulting MSW ash. Worthwhile noting that conventional WTE plants may undergo a revenue paradigm shift in the upcoming years as baseload power markets are expected to



continue on a downward trend.

- **Increased materials security.** Both coal fly ash and steel slag, which are reactive pozzolans that are used in the construction sector, are in decline. With a yield of ~0.3 tons ash per ton of MSW, the U.S. has the potential to produce more than 78 million tons of MSW ash per year, which compares favorably with the calculated 100 million tons of cement produced annually. More than half of the resulting MSW ash is composed of silica (SiO_2), alumina (Al_2O_3), and lime (CaO)⁸.
- **Reduction of GHG.** The production of cementitious building materials contributes 7% to the global GHG emissions⁹. The production of MSW ash may result in the displacement of significant amounts of GHG arising from the production of virgin construction materials. This novel framework provides a direct replacement of CO_2 released from virgin cement operations which is based on hydrocarbon use (average of 0.5-1.0 tons of CO_2 per ton of cement). Expanded use of WTM&E would also bring the added value of avoiding CH_4 and CO_2 releases from landfills. Carbon Capture and Storage (CCS) technologies, like saline storage deployed near WTM&E facilities may reduce¹⁰ or have a negative net GHG emissions relative to current combustion of methane in landfills.
- Waste to energy technologies like incineration are feedstock agnostic and can handle unsorted MSW streams. Currently, recycling facilities run into vast amounts of rejected materials due to poor public compliance. These unrecyclable materials have already been transported to the recycling plant causing a negative impact in the life cycle metrics of conventional waste recycle processes.

A.2 State-of-the-art technologies and technology gaps

As the amount of MSW steadily increases in the US, recycling, composting and combustion with energy recovery (WTE) technologies have effectively offset the related increase in landfilling needs. However, recycling presents the challenge of consumer compliance in the segregation process, difficulty of separation from composite materials (that cannot be recycled) and costly recycling processes. On the other hand, WTE technologies are usually uneconomical due to high plant CAPEX¹¹, OPEX, low efficiency in the conversion of the embedded calorific energy into electricity, and the increasing costs of MSW ash landfilling. Existing WTE facilities landfill ca. 10 million tons of ash at cost of \$100-\$150 USD/ton (tipping fee plus logistics).

Another barrier for widespread adoption of WTE technologies in the US has been the negative public perception of environmental pollution (hazardous emissions, smell, noise, vermin/pests, lights, truck traffic, community “eye-sore”) which has led to limited plant locations. Current WTE facilities average > 30 years old. Legacy WTE facilities were designed to reduce the volume of municipal solid waste and

⁸ Lam C.H.K., et al “Use of Incineration MSW Ash: A Review” *Sustainability* 2 (2010) 1943 -1968

⁹ Bloomberg News “Cement Companies are Starting to Get a \$33 Trillion Headache” 21 Jul 2019

¹⁰ Chandel M.K. et al “The potential of waste-to-energy in reducing GHG emissions” *Carbon Management* 3.2 (2012) 133-144

¹¹ 2017 SWANA Excellence Award Entry Waste to Energy

<https://swana.org/Portals/0/Awards/2017/Winners/Excellence2017-WtE-gold.pdf>



generate electricity as a co-product. Later, these facilities were re-engineered to increase efficiency, increase metal recovery, and reduce air/water emissions.

The possibility of increasing WTE plant revenue by selling the MSW ash stream has been hindered by the variability in the composition of the resulting pozzolanic product. Previous MSW ash R&D has been focused on the use of ashes that result solely from the MSW without co-feeding additives, like formation of aggregate in concrete, filler applications like garden stones, road base, paving materials, cement clinker, limited batch size cement and cement blend stock, and glass ceramic applications. However, these materials have not found wide-acceptance by the cement industry. There is a need to explore novel “ash distillation” technologies to recover separated species from Ca, Si, Mg, Fe, Au, and critical materials.

Besides MWS incineration, other WTE technologies that have been investigated are MSW pyrolysis and MSW gasification. Different from incineration (which require an excess of air for combustion), pyrolysis is a thermal process carried out in the absence of air and produces gas (CO, H₂, CH₄, and light hydrocarbons), solid (ash and coke) and liquid products (bio-oil and water).

Gasification is a partial oxidation process that requires less air (or steam) than the stoichiometric amount for complete combustion. Similar to pyrolysis, syngas is also produced (CO, H₂) in addition to other gases (e.g. CO₂, CH₄, N₂) and solid products (ash and slag). While plasma gasification is more efficient from an energy and emissions standpoint, it requires high operating temperatures 1500-2000 K¹². Gasification technologies for MSW are still under development.

A.3 Areas of interest

- Precursor selection/formulation. Novel additive/additive mixtures that would be added prior to combustion need to be widely available and inexpensive. Of interest is the understanding of the co-firing behavior of the different additives in combination with various trash mixtures.
- ARPA-e is interested in the effect of the additive (type, formulation and dosing) on process performance - combustion efficiency, energy balance, flue gas emissions (specifically NO_x), ash composition, equipment integrity (e.g., slagging, abrasion, corrosion).
- Additive/co-feed material balance optimization. Decision-making frameworks/control models that will allow the intelligent manipulation of the feed of additive/additive mixture as a function of other independent variables like the composition of the MSW/recyclables (influent), flue gas (effluent), and MSW ash (effluent).

¹² Pieta I.S. et al. “Waste into Fuel – Catalyst and Process Development for MSW valorization” Catalysts 8, (2018) 113

CONVENTIONAL WTE APPROACH
NOVEL WTE & M APPROACH

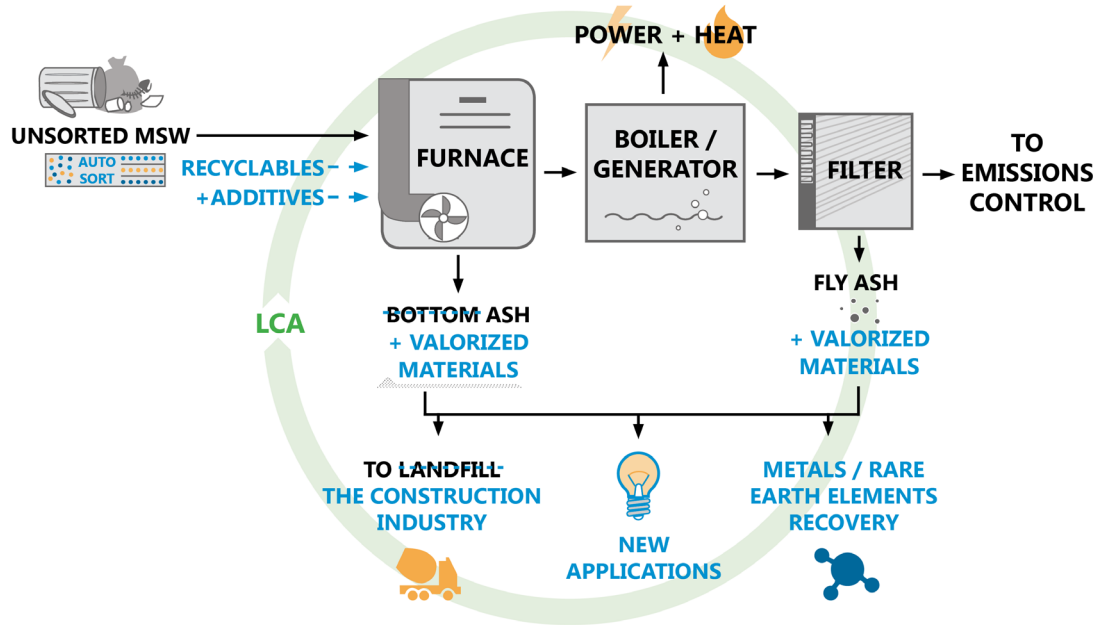


Figure 2. Comparison of conventional WTE process (in black) vs. potential enhancements in the envisioned WTM&E process (in blue)

- MSW ash formulation optimization. Characterization and testing of resulting MSW ash to formulate a product that meets specification of the cement industry. Can the resulting ashes be used as a stand-alone binder or is it limited to admixture? Is dilution a solution for some of the impurities?
- Process design. Determining processing design parameters, such as optimal plant scale and heat integration will be critical in the co-firing of cement additives with MSW. Also, the optimization of WTM&E plant operational parameters to produce construction materials. In addition, reactor engineering to address the need/potential need for corrosion/fouling resistant advanced materials to built the WTM&E (e.g. ceramics). Design should address potential integration with onsite/nearby Carbon Capture Utilization and Storage (CCUS) operations/initiatives. Also, new designs for metals and critical materials (precious metals, rare earth elements) recovery and emissions control (e.g., catalysts for nitrogen and sulfur species removal).
- Real time process diagnostics (sensors, imagers, AI) – for both the unsorted MSW influent stream and the effluent streams (flue gas, MSW ash).
- Life cycle assessments (LCAs) will have a critical role in the program to determine energy, environmental and cost impacts.



B) Waste To Crude Fuels (WTCF) from plastic/paper streams

B.1 Motivation for approach

- Energy Security. Paper and plastic streams represent 25.9 % and 13.1 %¹³ of MSW, respectively. The majority of plastic and paper is landfilled, exported, or incinerated. Domestic recycling rates for plastic and paper are 2.5% and 40%, respectively. These materials present high energy densities, the embedded energy in these unrecovered materials is more than 1 quad/yr. The value of this energy is maximized by converting it to a liquid fuel.
- Technology advances processing paper and plastic that have been slurried in refinery intermediate streams, and converted to liquid products via thermal/and or catalytic unit operations.
- Market driver: Adoption of low-sulfur fuel specifications for marine fuel. This change creates a market for a low-sulfur bunker fuel, while increasing demand and price for low-sulfur distillates.

B.2 State-of-the-art technologies and technology gaps

Many “waste-to-liquid-fuel” thermal processes have been explored, including torrefaction, solvolysis, pyrolysis^{14, 15}, and gasification followed by catalytic conversion. In parallel, there was work in the 70’s through late 90’s using extensions of refinery processes, such as hydrogenation, and thermal and catalytic cracking. The plastic and paper were slurried in a variety of organic stream and then processed. This work, and more recent testing suggests the potential for selecting intermediate refinery streams with suitable chemistries (i.e., aliphatic vs aromatic, specific boiling point ranges, etc.) to promote the overall conversion process.

Solution	Description and status	Insufficiencies
Landfill	53% of US refuse	Land use, GHG emissions, water impacts
Recycle (Note: exports are included in US recycle rates)	US “recycles” 9% of plastic. Domestic plastic recycle rate is ~2.5%, other ~7% is exported (2015, before China ban) US “recycles” 67% paper/paperboard. Domestic	High cost (> \$50/ton) for waste sorting. Decline in market and commodity prices. Contamination related to single-stream recycling

¹³ EIA. 2018. "Total MSW generation in the United States by type of waste, 2015."

¹⁴ Quesada L. et al “Characterization of fuel produced by pyrolysis of plastic film obtained of municipal solid waste” *Energy* 186 **2019**

¹⁵ Thahir R. “Production of liquid fuel from plastic waste using integrated pyrolysis method with refinery distillation bubble cap plate column” *Energy Reports* 5 **2019**



	recycle rate is ~40%, other 27% is exported.	
Export	Send the waste management problem overseas	This option is in flux, with China exiting but other (primarily Asian) countries entering the market
Mass burn	13% of US refuse	Unpopular and thermodynamically inefficient (< 25%), but many legacy facilities produce electricity and some cogenerate.
Gasification	Energem (fluidized bed) commercial; several large pilots in past and new entrants (Aries)	More sorting/feed prep and higher CAPEX/OPEX cost than mass burn. Due to the higher cost projects may need to produce higher-value products such as chemicals.
Pyrolysis	Commercial units (esp Japan). Single stage thermal and “catalytic pyrolysis” processes have been developed. Two-stage processes (pyrolysis followed by hydrogenation) also investigated at small scale	Difficult economics even with high tipping fees. Make less valuable light gases, low-quality liquids, and solid by-product/char.

Alternative Technologies

Solution	Description and status	Insufficiencies
Solvolytic, hydro-thermal or supercritical water de-polymerization	Goal is monomer recovery for polymer production. Solvent may act reactant (water, methanol, creosote, ethylene glycol)	Monomer recovery requires high quality feed (source separation, minimal contamination). Costs significantly higher than virgin material
Pyrolysis of plastics, paper products followed by co-processing in refinery operations	Hydrotreating, hydrocracking, FCC	High costs, poor fuel quality, lower yield with pyrolysis + refining
1-step Direct Liquefaction (DL), extension of coal liquefaction	Exxon’s Donor Solvent (EDS) technology was probably the most developed example; H-Coal and Solvent Refined Coal were also piloted in the 80’s. Coal was slurried in tetralin or other donor solvent, heated and exposed to high H ₂ partial pressures without catalyst to produce a hydrocarbon	1-step DL processes for coal displaced by 2-step DL. 1-step DL had lower distillate yield, poor fuel quality (high aromatics, significant PAH, unstable, corrosion problems).



	liquid product with broad boiling point range, and +1000 °F stream. The donor solvent served 2 functions – chemical carrier for H ₂ , and “solvent” to dissolve the coal matrix. Researchers (including precursors to DOE) showed 1-step liquefaction worked for wood and paper back in the 80’s.	Economics for coal to liquids required very large scale (>20,000 TPD).
Direct Liquefaction for coal (2-step)	US researchers established technical feasibility for wide range of coals and coal blends with resid, heavy oil, bitumen, waste plastics. HTI process was commercialized in China for coal. Researchers there have been investigating co-liquefaction of coal and plastic.	Plants require very large scale to be economical. Shenhua plant is 6000 tpd, and economics may be marginal
Thermal depolymerization with hydrocracking	Rheinbraun pilot hydrogen – first stage “visbreaking” with H ₂ and recycled product oil; Veba Oel 1 st stage reactor with H ₂ and recycled hydrotreated oil, and 2 nd stage hydrotreater; DuPont 2-stage screw reactor with thermal depolymerization	Pilot plants in 80-90’s abandoned due to high costs
IH ²	“Stand-alone” self-contained process to convert biomass to ASTM-grade gasoline and diesel. Uses modified hydrotreating/hydrocracking technology. Biomass slurried in recycled naphtha-range stream to slurry wood and react with H ₂ in a 2-stage process.	In development. Targeting larger scale for economics (500-1500 TPD plants). Primarily intended for biomass. Capable of processing up to 20% plastic
REUSE concept (Co-processing plastics/paper products in refinery unit operations)	<u>Thermal cracking/visbreaking</u> with crude, tetralin, decalin, 1-methylnaphthalene, VGO <u>Hydrocracking</u> with crude, tetralin, mineral oil, VGO, heavy aromatic solvent/LCO blend, resid <u>FCC</u> with crude, BTX, tetralin, aromatic-enriched FCC oil, LCO, VGO, resid <u>Coking</u> with resid	Lab scale only

There are several technical challenges:

- Optimize solvent and conversion process for a mixed feed with a range of plastics and paper composition.
- Build facilities that are consistent with the amount of waste that can be economically collected



and transported to the facility. We anticipate the plant size will be in the range of 300-500 ton/day.

- Scale down the conversion processes by a factor of 20-100, and reduce CAPEX costs through integration/intensification, simplification, and modularization.
- Produce a saleable liquid fuel product, most likely targeting resale back to a refinery as a blend stock, or for use as a low-sulfur marine bunker fuel.

Previous processes required very large facilities (> 6000 TPD) to be economic. Transportation costs limit the scale for a waste-to-liquids facility. *Per capita* plastic and paper product waste generation are each ~200 lb/yr. A facility sized for 1-2 million people within ~30-mile radius would process 300-500 ton/day mixed waste feed. Net revenue would be ~\$30-100 MM range, assuming \$75/bbl oil, \$50/ton tipping fee, and no subsidies. Plant CAPEX will likely need to be below \$50,000/bbd capacity at this scale. By comparison, CAPEX for a 100-300,000 bbl/d refinery is ~\$25,000/bbd capacity.

B.3 Areas of interest

- Process design – System needs to be modular and repeatable to keep costs down. Reactors need to be downsized by a factor of 20-100 compared to typical refinery scales. Thermal integration will be critical. Small-scale hydrogen production is required for hydrocracking systems, which will also require reforming light gases.
- Process capable of tolerating mixed/contaminated feed. Need to minimize collection/sorting costs for waste plastic and paper products. Positive small-scale tests with mixed plastic wastes in hydrotreating and FCC processes.
- Solvent optimization – Solvent must be inexpensive. It needs to have correct boiling point range, solvent properties (dissolve/dissociate plastics, minimizing need for front-end size reduction/screening/material handling), and ideally be upgraded with high yield in the process. Previous processes used hydrogen-donating solvents that were reactive and expensive, resulting in high operating costs. Alternatively, processes “cooked” plastics in their “own juice”. A self-generated solvent is unlikely it will have optimal physical and chemical properties. The proposed process will screen internal refinery streams to identify the slate of mixtures for various waste stream compositions. Lab-scale tests have demonstrated the utility of several internal refinery streams (BTX, LCO, VGO, etc), which have a wide range of boiling points, aromatic/aliphatic content, and other properties that can be tailored to match the mixed waste stream composition.
- Catalyst optimization – conversion/yield/recycle rate will depend on catalyst type/loading; H₂ pressure; residence time, etc. Dual-function hydrocracking catalysts need to optimize acid functionality/strength and pore size distribution to address C-C bond cracking due to steric constraints with high MW plastics. Ditto for metals to end-cap radicals. FCC catalysts need to be optimized for higher MW feed. Both processes need to consider heteroatoms

that come with plastics and paper products, including plasticizers, UV stabilizers, halogens, higher oxygen.

- By-product management – process co-produces multiple by-products, including hydrogen sulfide (H₂S), ammonia, halogens (HX), and wastewater. Need technologies appropriate for this scale to manage byproducts.

C) Waste-to-Carbon or Char-like Materials (WTC)

C.1 Motivation for approach

- Demonstrate the cost-effective conversion of MSW products to produce a valorized, solid char, a.k.a. a torrefied material.^{16, 17} Although processes such as hydrothermal carbonization (HTC) have been known for more than a century,¹⁸ using it as a method to transform biowaste into stable, valuable product has noticeably increased only recently.¹⁹ A simple schematic is shown below:

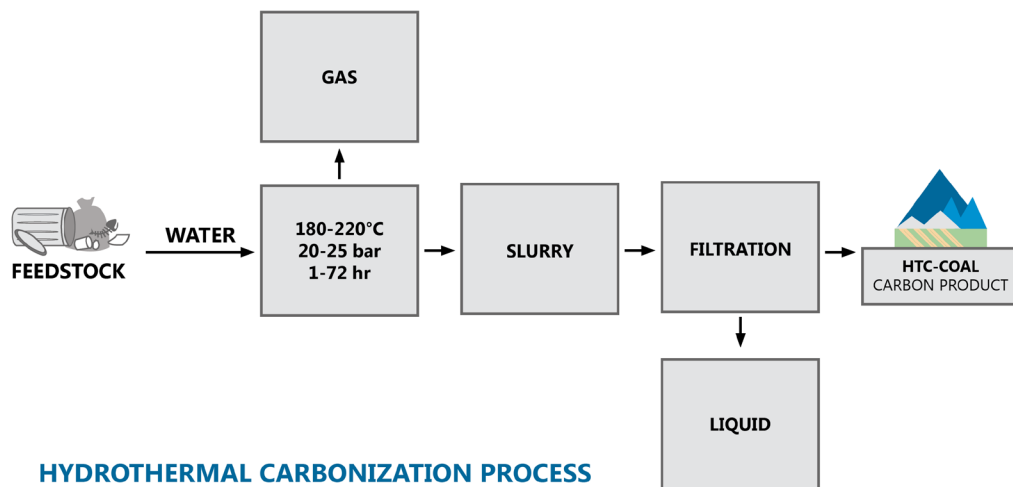


Figure 3. Simplified block diagram of hydrothermal carbonization process

¹⁶ Basso, D., Castello, D., Baratieri, M., Fiori, L.; Hydrothermal Carbonization of Waste Biomass: Progress Report and Prospect, 21st European Biomass Conference and Exhibition, Conference Proceedings, 1478-1487 (2013); ISSN: 2282-5819

¹⁷ Triyono B. et al "Utilization of mixed organic-plastic municipal solid waste as renewable solid fuel employing wet torrefaction" *Waste Management* 95 **2019**

¹⁸ Bergius, F.; Die Anwendung hoher Drucke bei Chemischen Vorgangen und eine Nachbildung des Entstehungsprozess der stein

¹⁹ Titirici, M.-M., Arne, T. Antoniette, M., New J. Chem. 31, 787-789 (2007); Berge, N., Ro, K., Mao, J., Flora, J.R.V., Chappell, M., Bae, S.: *Environ Sci Technol* 45, 5696-5703 (2011)



- Processes such as HTC have high feedstock flexibility in form, composition and moisture content, so these do not require an energy intensive drying step before processing.²⁰ The reactions are autogenous with no additional pressure added.
- Hydrochars can be used in a range of different applications, such as fuel, functionalized carbonaceous materials (activated carbon) or as a soil amendment to increase soil fertility while providing a long-term carbon sink.²¹
- In addition to acting as a carbon sink, the production of MSW char may result in the displacement of significant amounts of GHG arising from the production of other soil amendments such as fertilizers, and prove to be a simpler, more energy efficient, and better approach than current CCS technologies. One ton of charcoal obtained by HTC avoids 2.2 tons of CO₂ in the atmosphere.
- Hydrothermal processes are exothermic thermochemical conversion processes that have the potential to be very low energy methodologies. The HTC process releases about a one-third of the energy content of the feedstock with the rest remaining in the solid product.

C.2 State-of-the-art technologies and technology gaps

Torrefication processes like hydrothermal carbonization (HTC), are thermochemical treatments of biomass in pressurized water at relatively low temperature, usually between 180°C and 250°C or above saturated pressure. The aim of the process is the conversion of biomass into coal-like fuel, which is often called biocoal or HTC-coal. The chemical transformation that occurs during hydrothermal treatment initiate decarboxylations, hydrolyses dehydrations, and polymerization (aromatization) resulting in a decrease in the Oxygen/Carbon (O/C) ratio shown in the van Krevelen Diagram:

²⁰ Funke, A., Ziegler, F.: Hydrothermal carbonization of biomass: A summary and discussion of chemical mechanisms for process engineering. *Biofuels, Bioprod Bior* 4, 160-177 (2010); Libra, J.A., Ro, K.S., Kammann, C., Funke, A., Berge, N.D., Neubauer, Y., Titirici, M.-M., Fuhner, C., Bens, O., Kern, J., Emmerich, K.-H.: *Biofuels* 2(1), 89-124 (2011)

²¹ Lehmann, J., Joseph, S.: *Biochar for Environmental Management – Science and Technology*. Earthscan, London (2009)

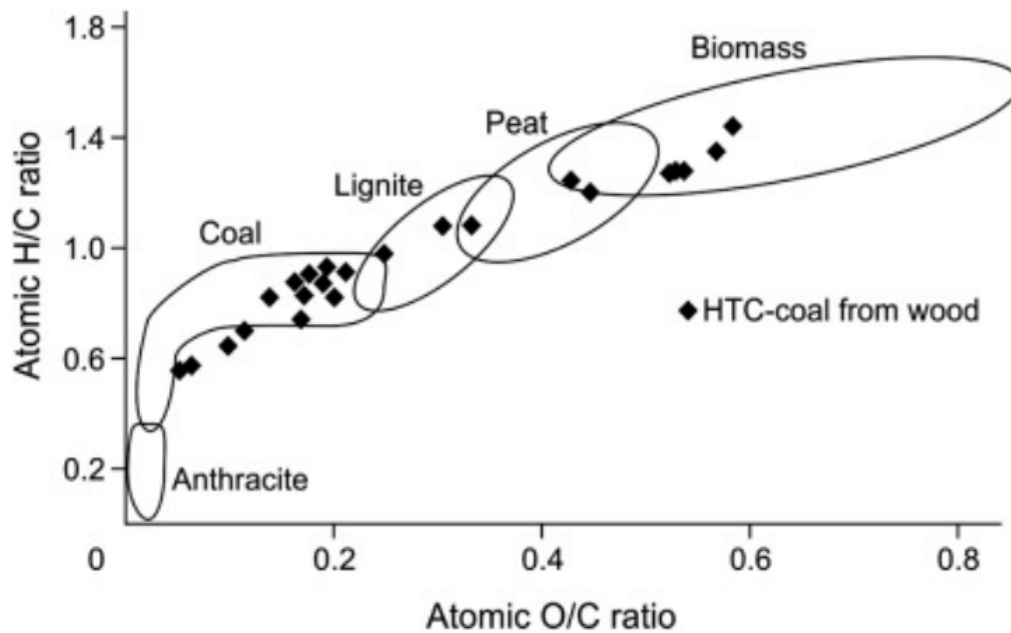


Figure 4. Van Krevelen Diagram showing O/C atomic ratio vs H/C atomic ratio

Historically, the barriers for widespread adoption of HTC technologies in the US have been batch mode operation, CAPEX, OPEX, R&D costs, and the inability to convert the aliphatic components in the biomass without the additional step of running them through an anaerobic digester. This latter step – although effective – adds complexity and expense to the overall process. At the usual operating temperatures, unless catalyzed, the carbon-hydrogen bonds in the aliphatic compounds are resistant to aromatization and charring unlike the carbon-oxygen bonds.

A number of – mainly European - companies have been founded since 2001 that practice some variant of HTC. Among them are Anataco (UK), HTCycle Technology (née AVA GmbH; Germany), C-Green (Finland), Ingelia (Spain), Suncoal (Germany) and Claren Energy (née TerraNova Energy; Germany). The largest “commercial” processing group currently is C-Green at 20,000 tons per year. Many of the others have struggled financially, been acquired or reached a scale which could make a significant impact for even a small city.

C.3 Areas of interest

- Use of general carbonaceous municipal solid waste feedstocks not merely simple biomass²² and food waste.
- Processes with the potential to convert or aromatize the lipid, fatty acid or long-chain aliphatic waste content into char without an additional anaerobic digester

²² Hernández-Soto, M.C. et al “Transformation of organic household leftovers into a peat substitute” *Journal of Visualized Experiments*, 149 **2019**



- Catalyzed or uncatalyzed processes that allow for more efficient, rapid char formation with minimum loss to liquification or gas formation
- Processes that yield +80% char yield based on feedstock dry weight content
- Inexpensive catalysts whose residue will be environmentally benign, e.g. Zn, Fe, Zr, Al, Si, or Mg oxides or their inorganic salts. Certain metal ions are known to accelerate the HTC process, significantly reducing the reaction times.
- The use of sewage, gray water, seawater²³ to manage the moisture content instead of potable water
- Scalable processes that can be run for less than \$45 per tonne.
- Non-batch, scalable processes that have the potential to operate continuously or semi-continuously

Purpose and Need for Information:

The purpose of this RFI is solely to solicit input for ARPA-E consideration to inform the possible formulation of future programs intended to help create transformative technologies that can economically turn waste into energy and valorized materials. ARPA-E will not provide funding or compensation for any information submitted in response to this RFI, and ARPA-E may use information submitted to this RFI on a non-attribution basis. This RFI provides the broad research community with an opportunity to contribute views and opinions regarding waste to energy and materials technologies. Based on the input provided in response to this RFI and other considerations, ARPA-E may decide to issue a FOA. If a FOA is published, it will be issued under a new FOA number. No FOA exists at this time. ARPA-E reserves the right to not issue a FOA in this area.

REQUEST FOR INFORMATION GUIDELINES:

ARPA-E is not accepting applications for financial assistance or financial incentives under this RFI. Responses to this RFI will not be viewed as any commitment by the respondent to develop or pursue the project or ideas discussed. ARPA-E may decide at a later date to issue a FOA based on consideration of the input received from this RFI. No material submitted for review will be returned and there will be no formal or informal debriefing concerning the review of any submitted material. ARPA-E reserves the right to contact a respondent to request clarification or other information relevant to this RFI. All responses provided will be taken into consideration, but ARPA-E will not respond to individual submissions or publish publicly a compendium of responses. **Respondents shall not include any information in the response to this RFI that might be considered proprietary or confidential.**

Responses to this RFI should be submitted in PDF format to the email address ARPA-E-RFI@hq.doe.gov by **5:00 PM Eastern Time on October 8th 2019**. ARPA-E will not review or consider comments submitted by other means. Emails should conform to the following guidelines:

²³ Iñiguez, M.E. et al "Hydrothermal carbonization (HTC) of marine plastic debris" *Fuel* 257 **2019**



- Please insert “Responses for RFI for FOA DE-FOA-0002170” in the subject line of your email, and include your name, title, organization, type of organization (e.g. .. university, non-governmental organization, small business, large business, federally funded research and development center (FFRDC), government-owned/government-operated (GOGO), etc.), email address, telephone number, and area of expertise in the body of your email.
- Responses to this RFI are limited to no more than 10 pages in length (12 point font size). Please reference individual responses using letter for approach (A-C) and the question number, for example B4.
- Responders are strongly encouraged to include preliminary results, data, and figures that describe their potential methodologies.

Questions:

ARPA-E encourages responses that address any subset of the following questions of relevance to the respondent and encourages the inclusion of references to important supplementary information.

A) Waste to Materials and Energy (WTM&E)

1. Producing a consistent, higher value ash (e.g. pozzolanic material) from the WTE process:
 - i. What types of materials additives could be added pre-incineration? What are the sources and costs of such materials? Have cementitious precursors been pilot-tested in the lab or in the field?
 - ii. Are there technologies/models for predictive engineering of resulting ash composition? (mapped to the performance of the resulting cementitious material)
 - iii. What are the benefits and drawbacks of pre-sorting trash materials prior to incineration to produce a valorized ash (e.g. processing impacts, impurities)?
 - iv. Assuming pre-sorting would be technically or economically infeasible, are there technologies for trash diagnostics/characterization that could assist with the co-feed control/optimization?
 - v. Discuss what is the better approach to add value to the resulting ash: 1) addition of precursor materials prior to combustion/incineration, 2) post combustion refining of ash (no precursor co-fed during incineration), 3) other.
 - vi. Can the extraction of rare Earth elements be made more feasible?
2. Commercial viability of WTE processes:
 - i. What is the cost breakdown of a WTE plant? Are there any credible, publically available technoeconomic models? What are the major factors affecting the economics of existing WTE plants today? Comment on plant scale.
 - ii. What would the value of the valorized ash (e.g. pozzolanic material) need to be to make the overall process economical? assuming different cost scenarios of the energy produced.



- iii. How much cost savings be achieved by avoiding/significantly reducing the need for flue gas treatment/ash landfilling?
 - iv. For current WTE operators, what are the concerns in terms of corrosion, operations and emissions. How might the use of additives exacerbate or improve these issues?
 - v. What are the major social barriers to bring WTM&E solutions to the US market?
 - vi. What is the level of public compliance and participation in recycling programs? Provide measurements and trends.
3. Are there “standard” models for trash composition (e.g. by state/region) that are/can be leveraged for WTE plant design?
 4. What novel construction materials formulations and applications (e.g. ecocement, cement composites) are more resilient to aggregate impurities/contaminants?
 5. Are there emerging computational technologies to predict trash collection logistics?
 6. Comment on the reliability of existing LCA methodologies to predict energy, environmental, cost impacts of WTE processes vs. other waste management technologies. For example, do plastic recycling LCAs fail to capture the refuse and contamination of unrecyclable materials in recycling plants?

B) Waste To Crude Fuels (WTCF) from plastic/paper streams

1. What is the effect of other MSW impurities in the yield of plastic/paper-derived crude products. What are the different approaches contamination-tolerance levels?
2. Is there processing/yield information on the co-processing of blends of fossil-derived refinery feedstock and plastic/paper derived blendstocks.
3. What are the needs for catalyst/processing development?
4. What are the challenges to downsize/modularize of the process?
5. Are there credible LCA advantages to co-processing fossil feedstock with MSW-derived blendstock?

C) Waste-to-Carbon or Char-like Materials (WTC)

1. ARPA-E is seeking information on the uses of MSW-derived char, e.g. soil amendment (raw vs. refined states), as carbon sink to mitigate GHG emissions, carbon/carbon composites, novel solid fuel, or other innovative uses.



2. What are the peripheral bottlenecks to the scale-up of hydrothermal carbonization processes? Examples: continuous MSW feeding mechanism, corrosion/fouling, product forming/cooling/storage.
3. What are the effects of different water sources (e.g. municipal wastewater (MWW)²⁴, seawater, gray water, etc.) on the hydro-carbonization process and products yield?
4. Novel strategies and designs for the integration of (waste) heat sources, other low cost power sources and heat exchange in the hydrothermal carbonization process.
5. Are there benefits/disadvantages to the co-hydrothermal carbonization (co-HTC) of MSW with other feedstock like biomass, sewage?

²⁴ Municipal Wastewater (MWW) (also called sewage) is defined here as domestic, process, other wastewater, and mixtures of the previous.