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solutions that transform

PyroPOX: A Reliable Pathway for the Conversion of Municipal Solid Waste to Cost-Competitive Low-Carbon Fuels and Chemicals

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GTI Energy Overview

GTI ENERGY

*We occupy a unique space between **tradition** and **innovation***

- Moving energy systems solutions from **concept to market**
- Where partners go to **de-risk experimentation**
- Expertise in integrated systems and **low-carbon gases, liquids, infrastructure and efficiency**

Valued Partners

175+

80+ years of experience and leadership in energy production, storage, delivery and use

Research & Development

$1B+

In the past decade

Leading and convening collaborative R&D

Innovation & Commercialization

1,300+

Patents

500

Products

750+

Licensing Agreements

10+ Industry Collaboratives

OTD · UTD · ETP Emerging Technology Program · LCRI Low-Carbon Resources Initiative · Project ASTRA · Hydrogen Technology Center · CH4 Collaboratory · H2@Scale · HyPER · VERITAS · Open Hydrogen Initiative

We develop, scale and deploy solutions in the transition to low-carbon, low-cost energy systems

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GTI Energy is a leading energy research and training organization

SOURCE · MAKE · MOVE · STORE · USE

500+ Enterprise Employees

TOP WORK PLACES 2019 · 2020 · 2021 · 2022 · 2023 — Chicago Tribune

We work collaboratively to address critical energy challenges impacting gases, liquids, efficiency and infrastructure

- OTD Operations Technology Development
- UTD Utilization Technology Development
- ETP Emerging Technology Program
- LCRI LOW-CARBON RESOURCES INITIATIVE

GTI Energy Gasification Heritage

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Renewable Energy Transition

Syngas to Power
- Integrated-Gasification Combined Cycle
- Gasification to Direct Super-Critical CO2
- Partial Oxidation Turbine

Syngas to Products
- Fuels
- Chemicals
- Synthetic Natural Gas

Feedstocks
- Coal
- Biomass

Early PDU

HYGAS Pilot Plant

U-GAS Pilot Plant

RENUGAS Pilot Plant

Shanghai Plant - 1995

Flex Fuel
Test Facility

R-GAS™ Pilot Plant

Advanced Gasification
Test Facility

Shanxi - 2020

R-GAS™ 800
tpd Demo

IGT

1941 · 1950 · 1960 · 1970 · 1980 · 1990 · 2000 · 2010 · 2020

gri

gti

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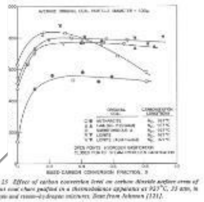
Lab Facility - 1947

Dr. James L. Johnson



Skive - 2007

Zaozhuang - 2007

Yima - 2012

SunGas RENEWABLES

HALDOR TOPSØE
CATALYSING YOUR BUSINESS

AEROJET ROCKETDYNE

ANDRITZ

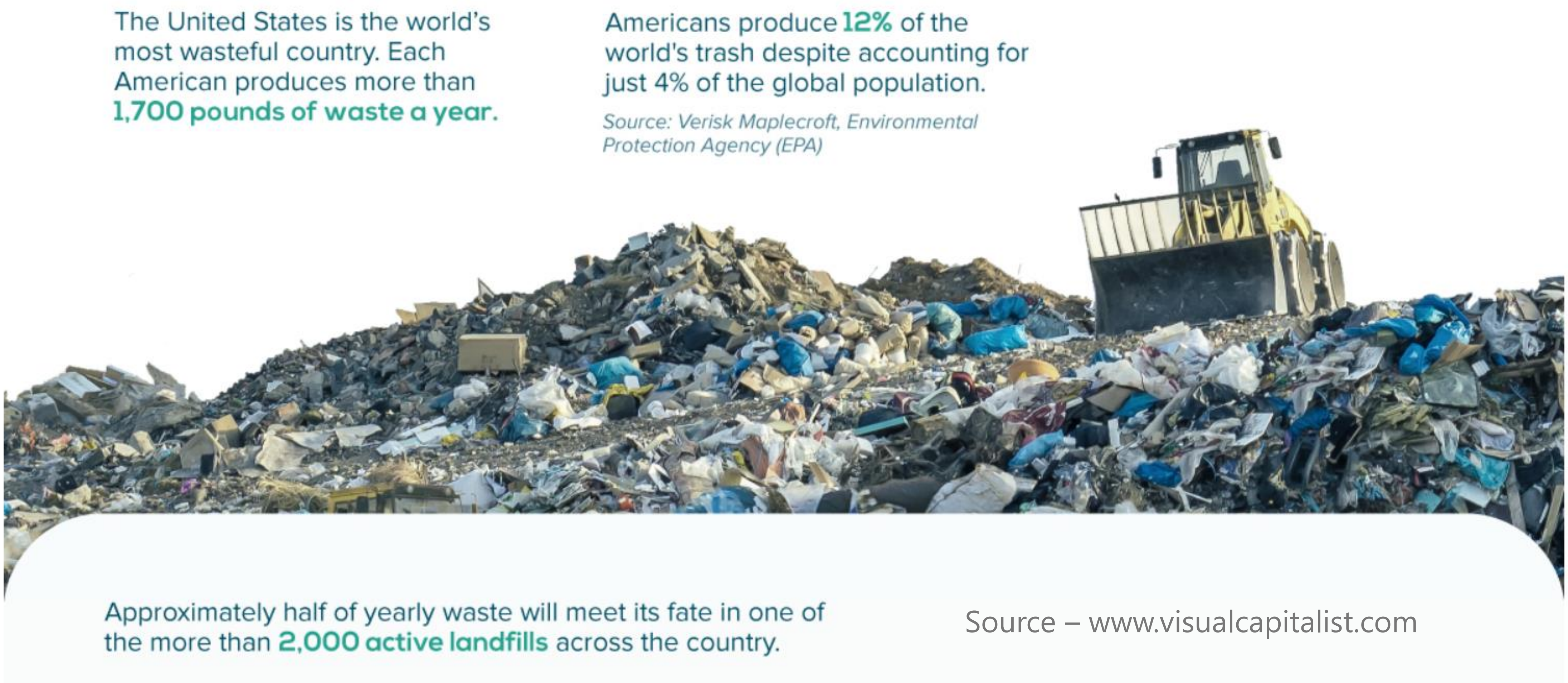
e.on

UPM

GreatPoint ENERGY

SES
SYNTHESIS ENERGY SYSTEMS

MSW Feedstock Resource



Source – www.visualcapitalist.com

- **MSW** could generate a considerable tipping fee (~$58/ton) but is heterogeneous, hard to handle, and contains plastics

MSW Feedstock Resource

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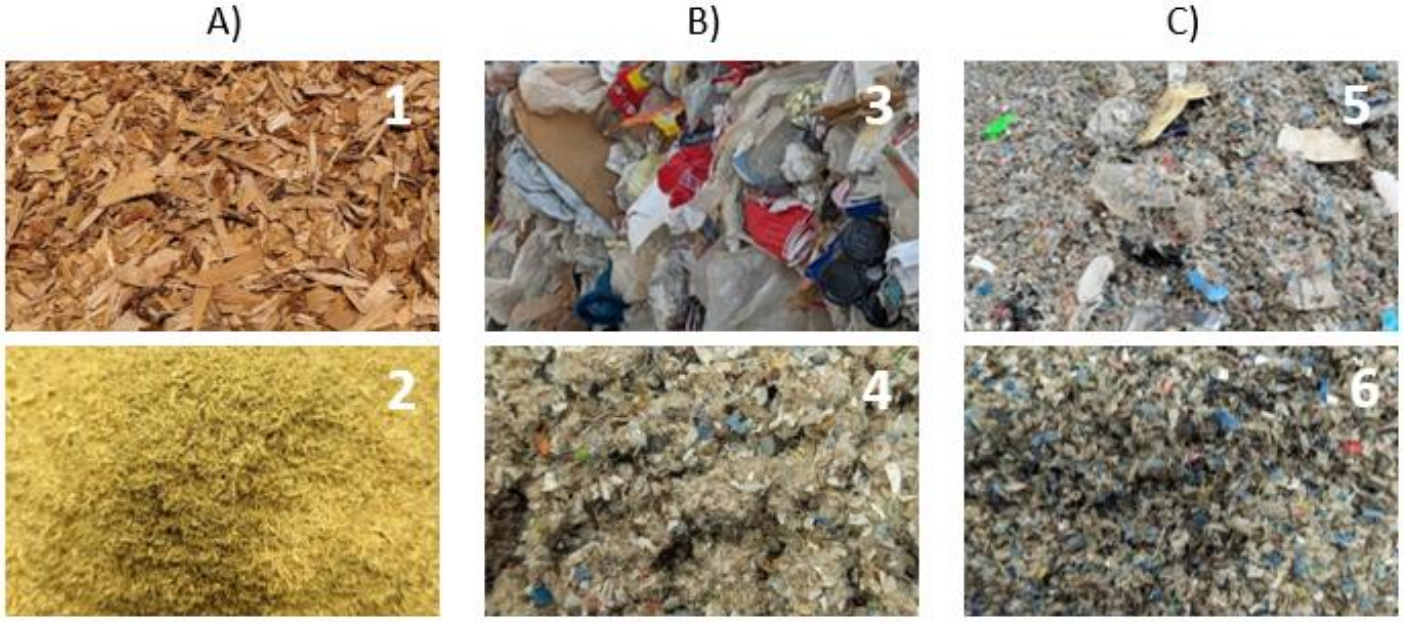
- **The Opportunity:** Large municipalities send very significant amounts of MSW to landfill every year.
- **Example:** Los Angeles:
  - Generates over 30 million tons of waste every year – of this, 11 million tons per year is non-recyclable MSW, and is sent to landfill (Los Angeles County Department of Public Works, 2022)
  - A 1000 TPD facility would never run out of feedstock in the LA area (330,000 tons/year, assuming 90% availability)
  - MSW can generate a considerable tipping fee (~$58/ton)
- **The Challenge:** MSW is heterogeneous, hard to handle, and contains plastics. Cost-effective, practical reliable conversion technology is needed.

Comparing Biomass, MSW, and Waste Plastics

- Biomass: Loblolly Pine, Southern Georgia, USA
- MSW: Recycle Ann Arbor, MI.
  - Only paper and plastic fractions
- Plastics:
  - 90 wt%: “waste plastic” from EFS Plastic in Ontario, Canada
  - 10 wt%: film plastic - meat packaging - Sealed Air Corporation, SC

As received

After grinding



A) Biomass (Loblolly pine), B) MSW; C) Plastic.

Example Pellets:

Biomass (50%): MSW (50%)

Biomass (50%): Plastic (50%)

Biomass (50%): MSW (25%): Plastic (25%)

Comparing Biomass, MSW, and Waste Plastics

- MSW and Plastics waste displayed similar high ash content and low fixed carbon content.
- Significant differences between biomass ash and ash from the two other feedstock types

Sample ID		Biomass		MSW		Plastic waste	
Proximate Analysis result (wt.%)							
	Method	adb[1]	db[2]	adb	db	adb	db
Inherent moisture content	ISO 11722: 2013 [5]	5.4	–	1.5	–	0.9	–
Ash yield	ISO 1171: 2010 [6]	1.0	1.0	12.7	12.9	7.8	7.9
Volatile matter content	ISO 562: 2010 [7]	81.1	85.8	81.1	82.3	87.2	88.0
Fixed carbon content	By difference	12.5	13.2	4.7	4.8	4.1	4.1
Bulk density (kg/m³)							
Bulk density		228.3		183.3		145.8	

[1]-adb- Air dry basis; [2]-db- Dry basis, [3]- Not determined

Sample ID / Properties	Biomass ash	MSW ash	Plastic waste ash
Ash fusion temperatures (oxidising atmosphere) (°C)			
Initial deformation temperature	1190	1130	1160
Sphere temperature	1210	1150	1170
Hemispherical temperature	1250	1190	1180
Flow temperature	1310	1210	1210
Ash fusion temperatures (reducing atmosphere) (°C)			
Initial deformation temperature	–	1120	1140
Sphere temperature	–	1140	1150
Hemispherical temperature	–	1180	1160
Flow temperature	–	1210	1190
XRF results (wt.%)			
Al_2O_3	31.69	10.09	10.38
CaO	5.19	17.64	20.64
Cr_2O_3	0.03	1.83	0.89
Fe_2O_3	3.63	8.61	5.56
K_2O	0.63	0.42	0.65
MgO	2.03	1.90	4.36
MnO	0.03	0.18	0.13
Na_2O	0.15	7.16	5.68
P_2O_5	0.92	0.36	0.38
SiO_2	48.65	48.20	45.88
TiO_2	1.51	2.34	3.51
V_2O_5	0.05	0.01	< 0.005
ZrO_2	0.09	0.01	0.02
BaO	0.25	0.07	0.20
SrO	0.24	0.02	0.04
ZnO	0.02	0.09	0.16
SO_3	4.73	0.54	0.51
Loss on ignition	0.16	0.53	1.00

Process Concept: **PyroPOX**

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- Observations: Feeding biomass, MSW, and other waste feedstocks of interest into pressurized gasifiers has been found to be very challenging – there have been recent failures by commercial organizations.
- Operation at high pressure is required for all gasification concepts other than gasification-to-power.
- Only gasification followed by synthesis allows for conversion of waste feedstocks with high thermal efficiency and maximum revenue generation.
- If these feedstocks can be **pyrolyzed** first, at temperatures up to about 650 C, then only the fixed carbon and ash will remain in the solid phase.

Process Concept: **PyroPOX**

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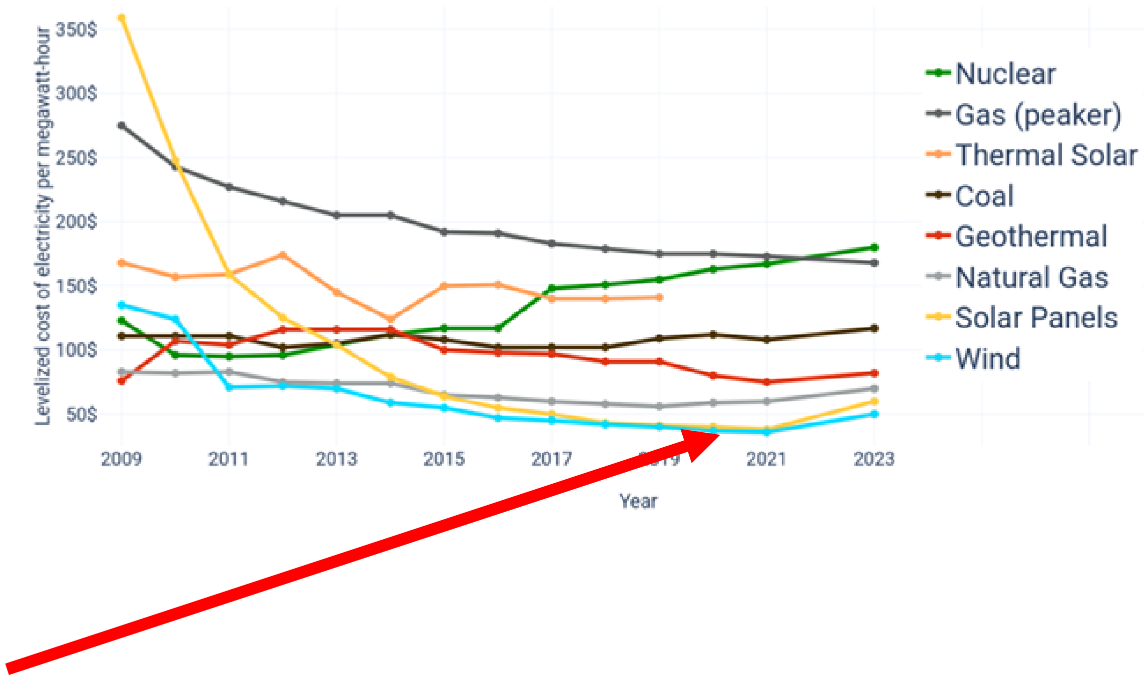
- CONTINUED:
- Biomass, mixed MSW fractions, and plastics wastes: 80-90% by mass of the feedstock can be pyrolyzed to a stream of hot, volatile process vapor.
- Ash and fixed carbon can be recovered separately and represent sequestered carbon if landfilled/buried.
- Tars, methane, etc. fully converted in downstream **POX** (partial oxidation) step – **PyroPOX**
- Based on preliminary TEA work, the PyroPOX approach could replace multiple feedstock-conditioning steps and would make solids conversion simpler and easier.
- Could reduce the CAPEX of the gasifier island (including feedstock conditioning, handling, and pressurized feeding) of a gasification-to-X facility **by about 50%.**

Process Concept: **PyroPOX**

- Implementation:
- It is not practical to introduce air into the pyrolysis stage – this would leave high concentrations of N_2 in the syngas.
- Indirect heating is not practical – heat transfer from external combustion to a pyrolysis reactor does not scale well.
- BUT: Renewable electrical power has already become the most affordable source of electricity in many regions where wind and solar have been built out at utility scale.
- **Pyrolysis powered by renewable electricity is cost-effective, can reduce the size of the air separation facility needed by a gasification facility, reduces CAPEX, and provides a nitrogen-free process vapor stream.**

Trends in the cost of electricity, by source, through 2023 – from Lazard, Inc.



Enabling Tech: **GTI's Wolverine™ Twin-Pyrolysis-Auger**

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- Waste stream pyrolysis requires a robust, flexible solution that provides very high operability and rates of heat transfer to the feedstock.
- Wolverine™ is based on previous DOE-funded biomass conversion work involving a paired, inter-digitated auger system
- Twin auger devices are already used in challenging applications like polymer melting, blending, and extrusion. Also Funke, et. al: Pyrolysis of waste tires
- Very high rates of convective heat transfer can be achieved – comparable with bubbling fluidized beds.
- Heat transfer from electrical heating system to process is maximized by taking advantage of all available surface area – unique approach has been developed.

ELSEVIER
Contents lists available at ScienceDirect
Chemical Engineering & Processing: Process Intensification
journal homepage: www.elsevier.com/locate/cep

Modelling and improvement of heat transfer coefficient in auger type reactors for fast pyrolysis application

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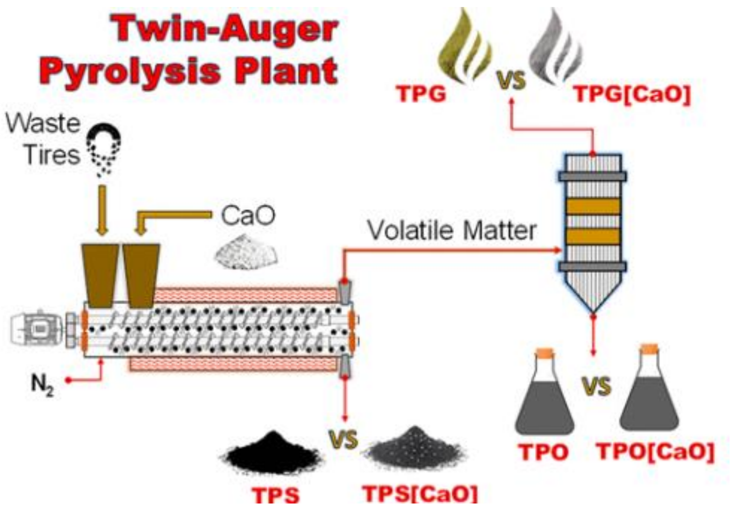
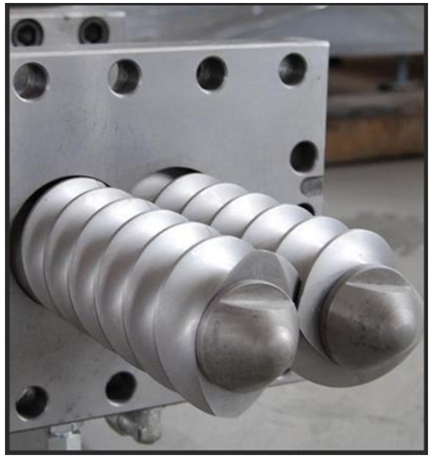
Institute of Catalysis Research and Technology, Karlsruhe Institute of Technology, Germany





Enabling Tech: **GTI's Wolverine^{TM} Twin-Pyrolysis-Auger**

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- Why did we call it "Wolverine"?
- A wolverine is a very tough arctic scavenger – it frequently chews up the bones of much larger animals to extract all remaining nutrition, even if the carcass is frozen solid.
- In the same way, the twin-pyrolysis-auger will carry out comprehensive devolatilization of challenging feedstocks, followed by gasification or partial oxidation of the volatile gases

Enabling Tech: **GTI's Wolverine™ Twin-Pyrolysis-Auger**

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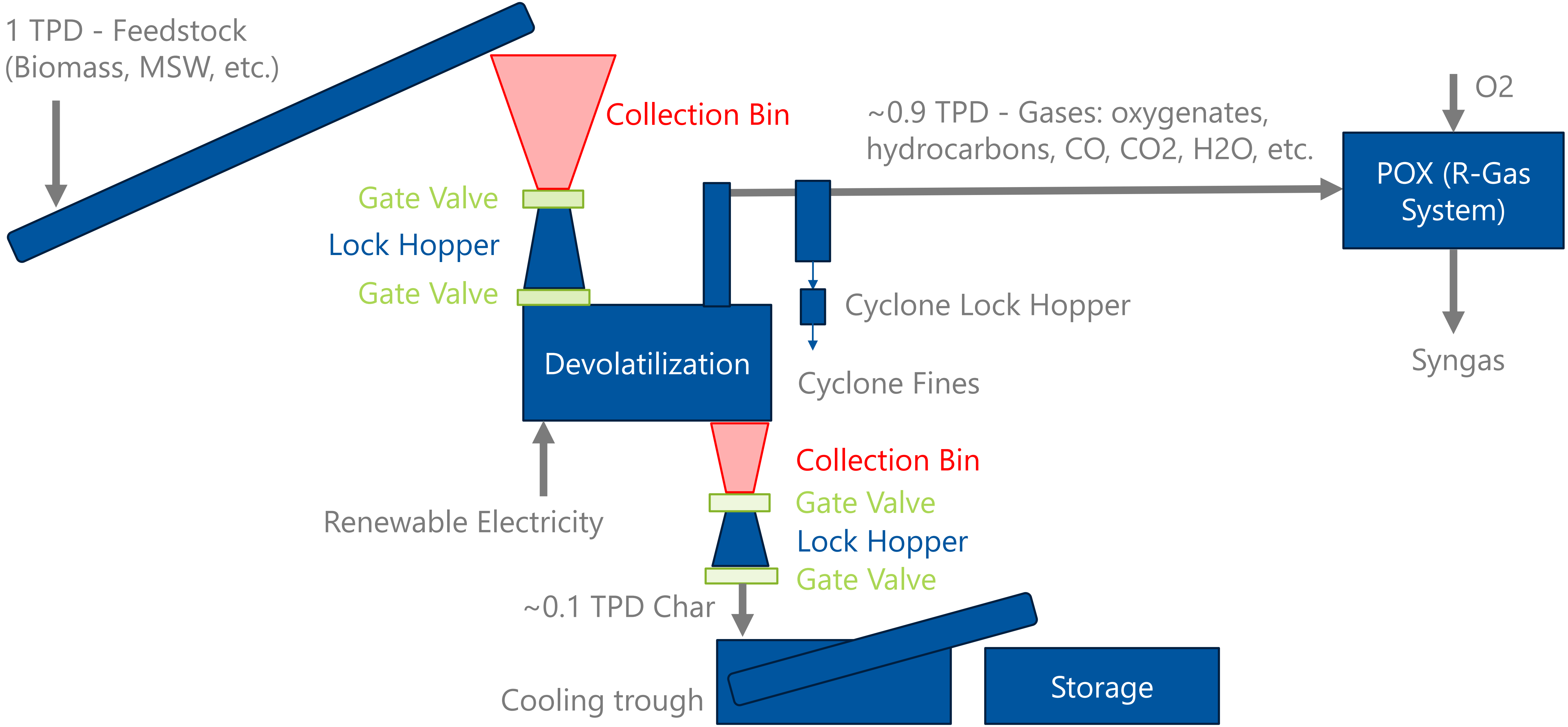

Enabling Tech: **GTI's Wolverine™ Twin-Pyrolysis-Auger**

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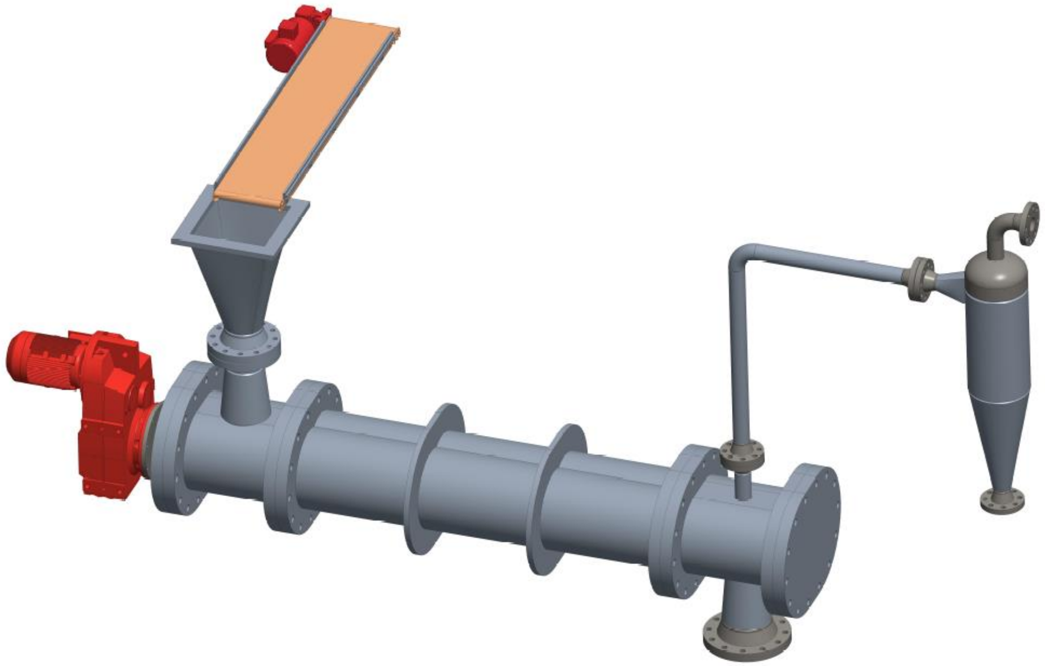

- Use of two augers and optimized heating approach increases available heat transfer area by a factor of 3-5 relative to single-screw heated auger systems.
- Can carry out comminution and devolatilization simultaneous and thereby eliminates the need for costly feedstock preparation steps like hammermilling.
- Demo scale: MSW shredded to 2" screen size; no need to remove fines.
- Designed to operate at the same pressure as the POX and synthesis stages (300-500 psig) – no need for gas cooling or compression upstream of the POX stage.
- The pressure shell remains at ambient temperature and is separated by insulation from the heated screw assembly, which turns in its own heated auger sleeve.

Enabling Tech: **GTI's Wolverine™ Twin-Pyrolysis-Auger**

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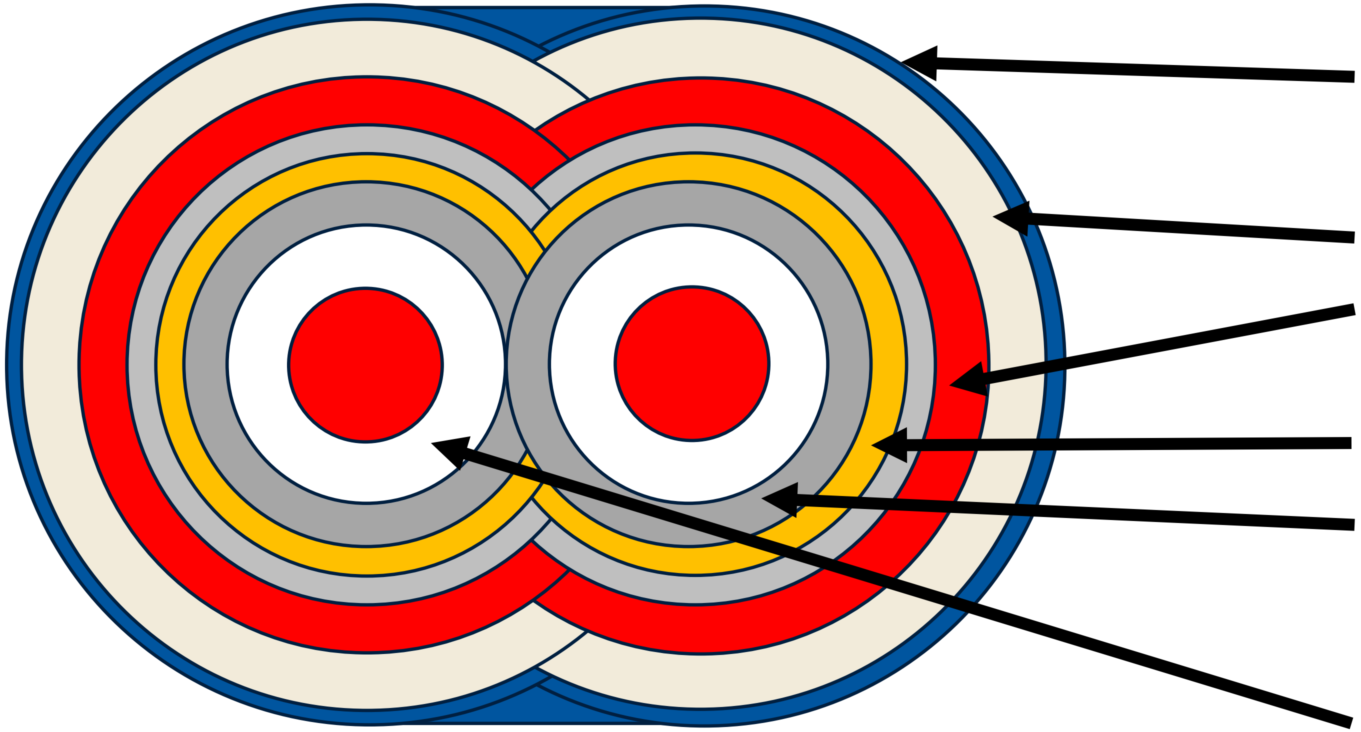

- Exterior pressure shell remains near ambient temp
- Insulation layer inside pressure shell
- Heaters in annulus around auger sleeve – auger sleeve sees up to 600 C.
- Feedstock conversion annulus (orange)
- Auger made of heavy-wall pipe, with flights welded around the outside – allows heater access to interior
- Bayonet heaters reach into augers and are located in hollow pipe comprising auger shaft

Enabling Tech: **GTI's Wolverine^{TM} Twin-Pyrolysis-Auger**

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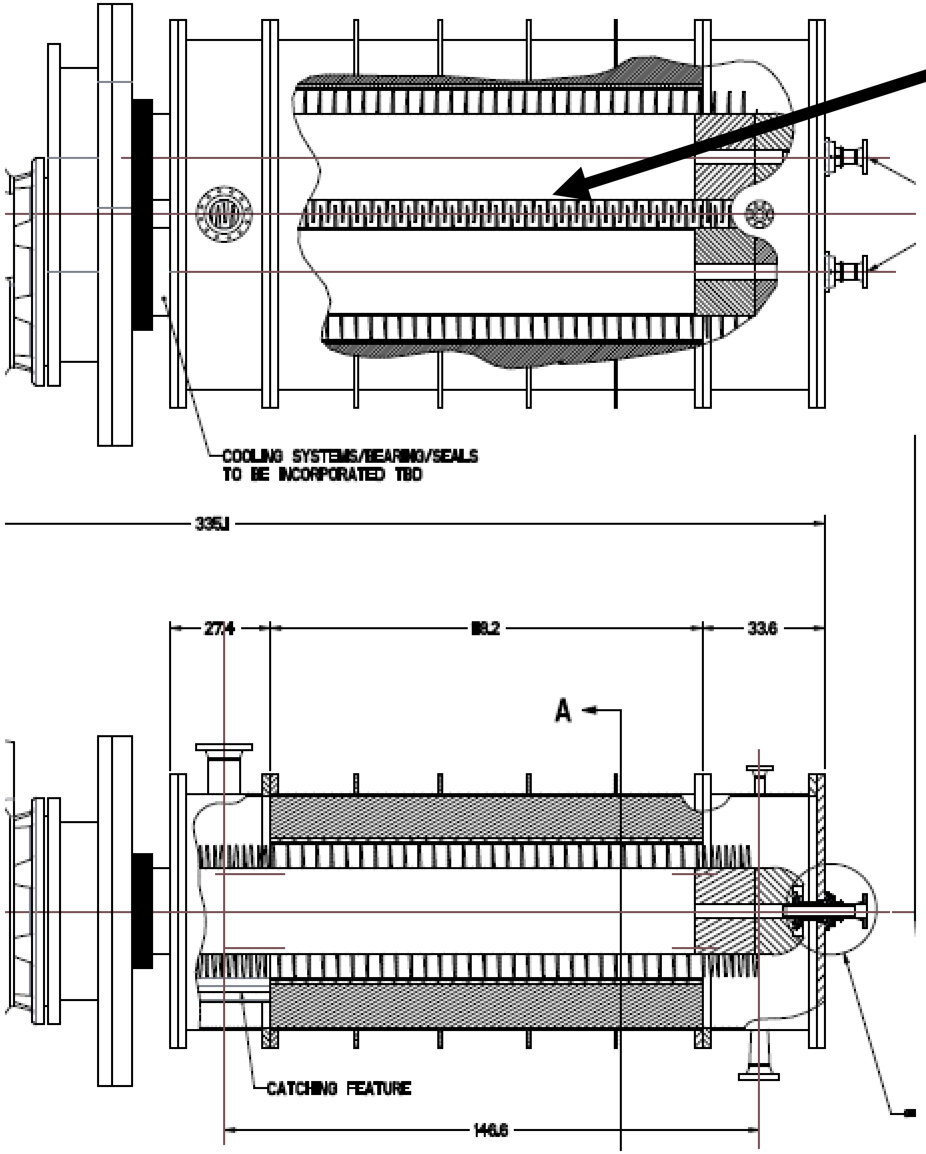
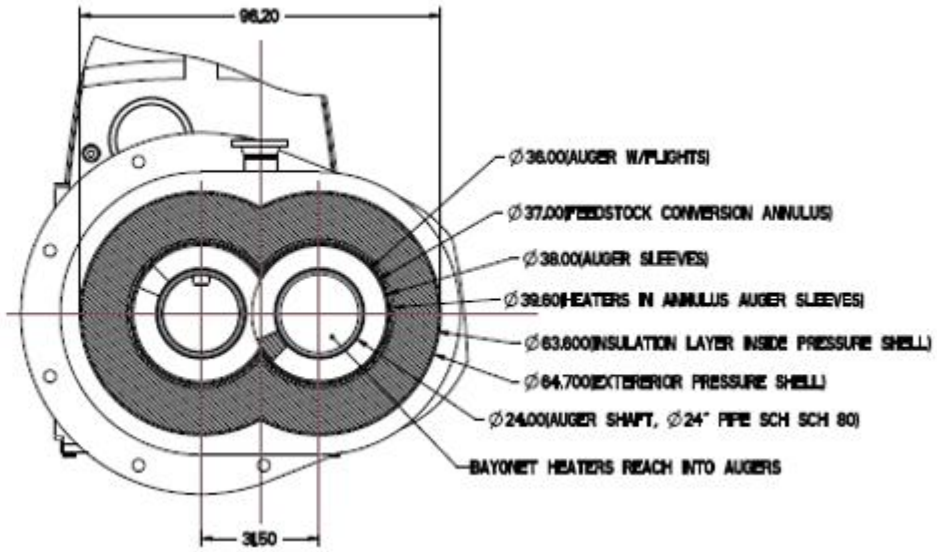
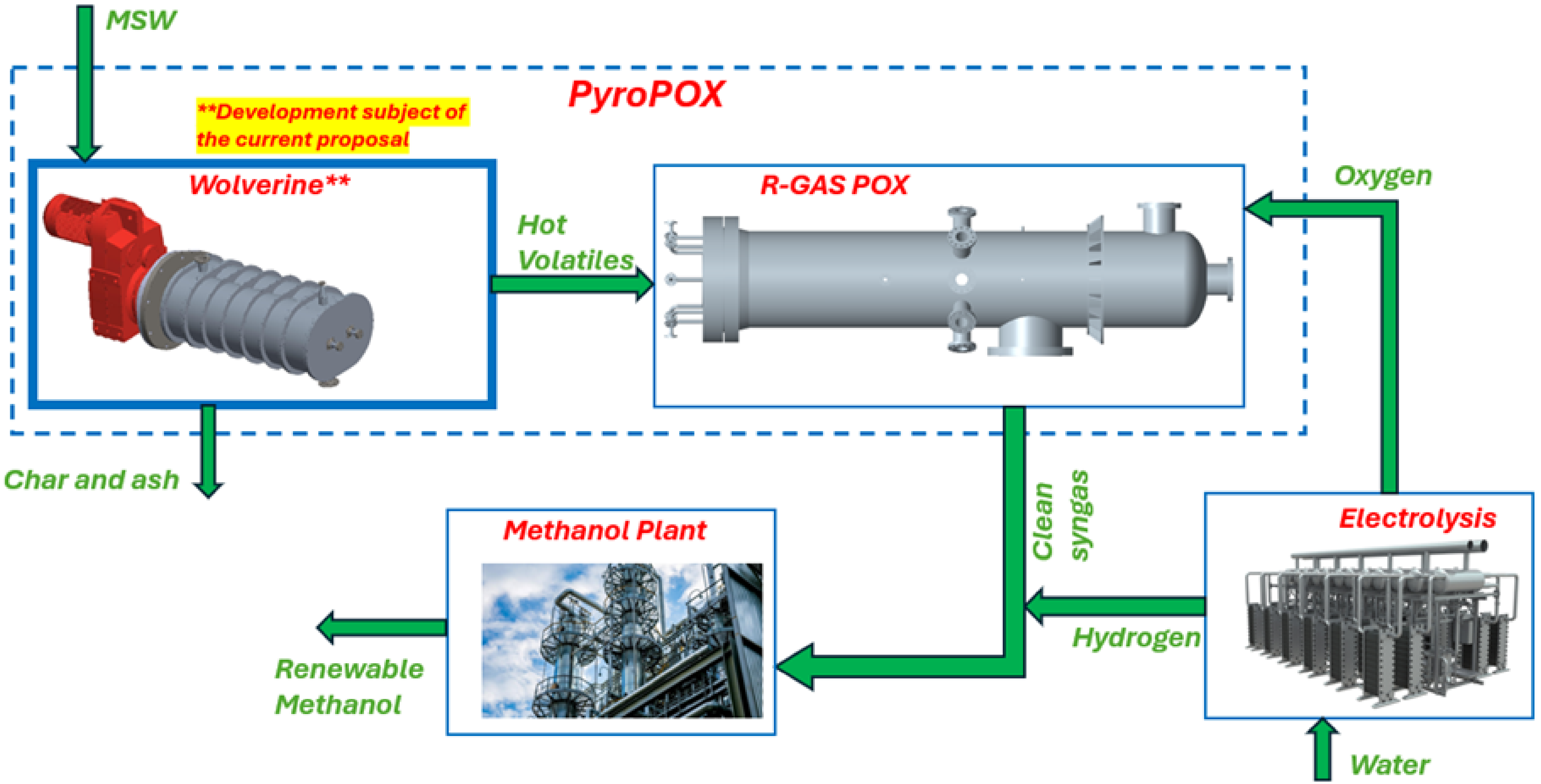


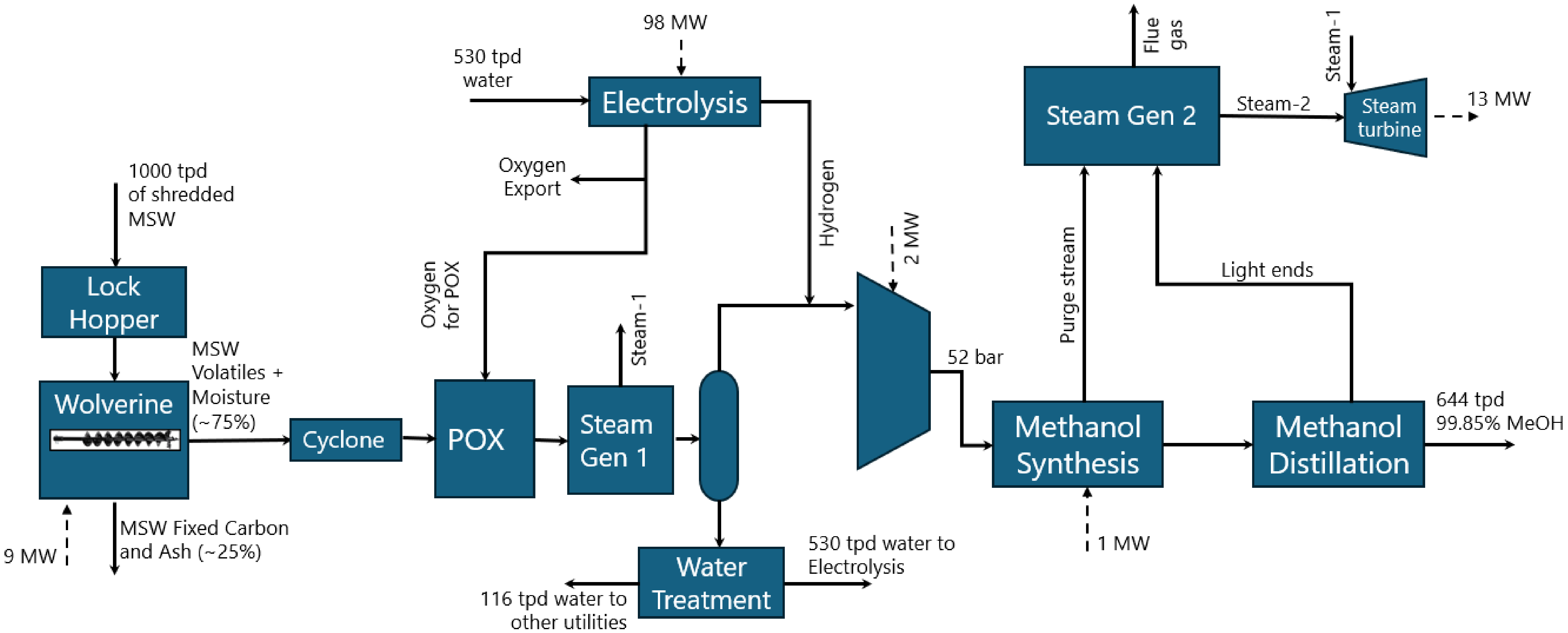
- Augers and flights – adds to high specific surface area for heat transfer from heating elements to feedstock.
- Very compact system geometry
- High degree of process intensification
- Highly effective integration of renewable energy in robust, flexible devolatilization approach.



Application: PyroPOX – MSW to Renewable Methanol



Application: PyroPOX – MSW to Renewable Methanol



Application: PyroPOX – MSW to Renewable Methanol

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Objectives	Metrics	Assessed PyroPOX Performance	Baseline Performance
>50% lifecycle GHG intensity	% lifecycle carbon intensity change as measured by kg CO_{2e}/tonne MeOH.	**~71% reduction** when compared to baseline. Initial lifecycle evaluation led to a carbon intensity of 511.5 kg CO_{2e}/tonne MeOH, assuming a 50% MSW biogenic content.	Case 3 in DOE/NETL-341/101514 – natural gas auto-thermal reforming process without carbon capture and sequestration (CCS): Carbon intensity of 1771.2 kg CO_{2e}/tonne MeOH.
Reduce energy consumption associated with production	% of energy consumption change in GJ/tonne MeOH.	**~59% reduction** when compared to baseline. Initial process evaluation led to an energy consumption of 13.2 GJ/tonne MeOH, considering that MSW is a "waste" feedstock without any inherent energy.	Case 3 in DOE/NETL-341/101514 – natural gas auto-thermal reforming process without CCS: Energy consumption of 32.1 GJ/tonne MeOH.
Reduce cost	2024 levelized cost of MeOH.	**~12% reduction** when compared to baseline. Initial techno-economic evaluation led to an estimated levelized cost of $509/tonne MeOH.	North America pricing of $575/tonne MeOH as published by Methanex.

Results and Conclusions

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- The GTI "Wolverine™" has the potential to enable cost-effective conversion of economically-advantaged waste feedstocks like MSW
- Process intensification is the key – leveraging cost-effective renewable electricity and eliminating CAPEX and OPEX requirements (sorting, drying, hammer-mills, etc.)
- Enables PyroPOX conversion concept when integrated with GTI's very compact, flexible, and robust R-Gas technology.
- Integration with H2 production via electrolysis has the potential to enable further synergies and process intensification.
- Case Study: Renewable MeOH from MSW:
  - 71% reduction in carbon intensity
  - 59% reduction in energy intensity
  - 12% reduction in production cost vs MeOH from fossil feedstocks

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solutions that transform

GTI Energy develops innovative solutions that transform lives, economies, and the environment