Life-Cycle Analysis of Hydrogen On-Board Storage Options

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Project ID: an034

Project Overview

Timeline

- Start: Oct. 2012
- End: Oct. 2013
- % complete: 70%

Barriers to Address

- Evaluate impact of H_2 storage technologies on energy and emissions
- Overcome inconsistent data, assumptions, and guidelines
- Develop models and tools
- Conduct unplanned studies and analyses

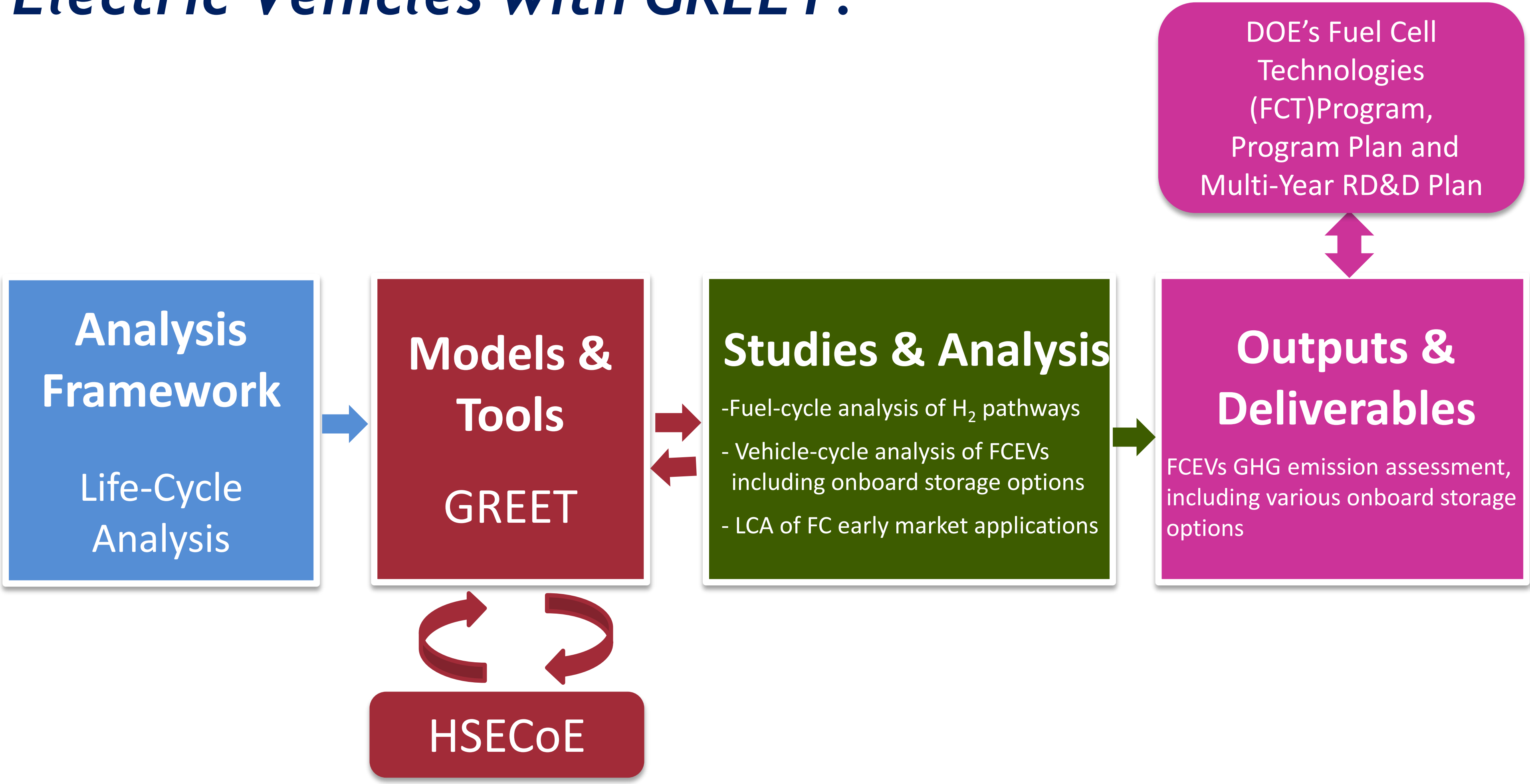
Budget

- Funding received in FY12: $0K
- Funding for FY13: $100K

Partners/Collaborators

- SNL and Univ. of Michigan (HSECoE partners)
- Industry stakeholders

LCA of Energy and Emission Effects of H2 Fuel Cell Electric Vehicles with GREET:



DOE's Fuel Cell Technologies (FCT)Program, Program Plan and Multi-Year RD&D Plan

Analysis Framework

Life-Cycle Analysis

Models & Tools

GREET

Studies & Analysis

-Fuel-cycle analysis of H_2 pathways

- Vehicle-cycle analysis of FCEVs including onboard storage options

- LCA of FC early market applications

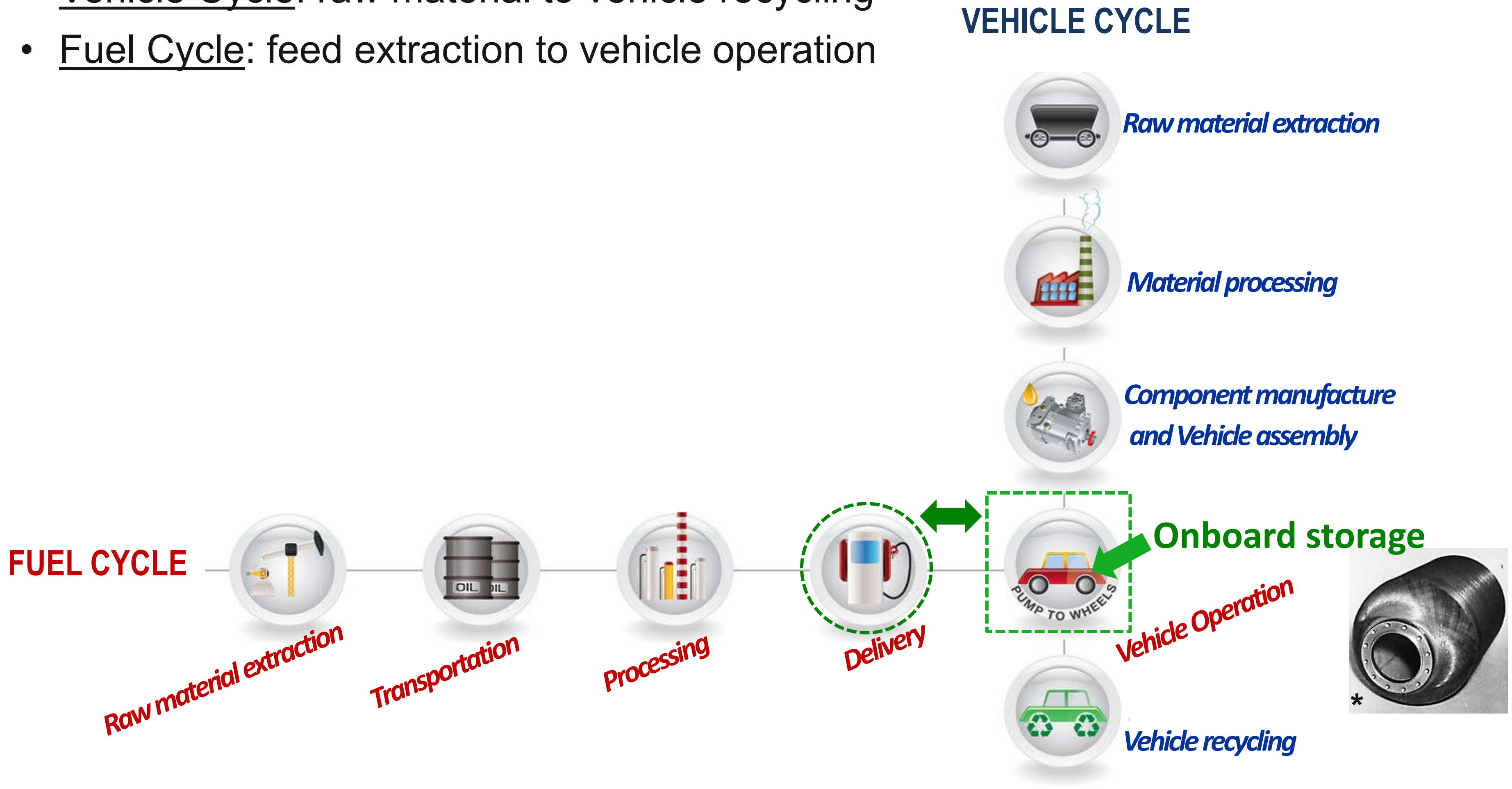
Outputs & Deliverables

FCEVs GHG emission assessment, including various onboard storage options

HSECoE

System Boundary:

- Vehicle Cycle: raw material to vehicle recycling
- Fuel Cycle: feed extraction to vehicle operation



VEHICLE CYCLE

Raw material extraction

Material processing

Component manufacture and Vehicle assembly

Onboard storage

Vehicle Operation

Vehicle recycling

FUEL CYCLE

Raw material extraction

Transportation

Processing

Delivery

*http://www.adoptech.com/pressure-vessels/main.htm

Approach and Data Sources

- ☐ Approach: build LCA modeling capacity with the GREET model
  - Continue to expand and update GREET to serve the LCA community
  - Address emerging LCA issues related to H_2 and FC systems
  - Maintain openness and transparency of LCAs
- ☐ Data Sources
  - Data for FCEVs onboard storage systems
    - Open literature
    - Simulation results from other researchers
    - HSTT
  - Data for FCEV manufacturing and operation
    - Open literature
    - Simulation results with models such as Autonomie
    - Auto makers and FC system producers
  - Data for H_2 production and delivery pathways
    - Open literature
    - Simulation results with models such as H2A
    - H_2 producers and technology developers

Key Milestones

- ☐ Evaluate LCA of FCEV onboard storage options
  - 350 bar compressed gas
  - 700 bar compressed gas
  - Cryo-compressed (CcH2)
  - MOF-5 sorption
- ☐ Evaluate FCEV manufacturing cycle
  - Components (powertrain, transmission, chassis, traction motor, generator, electronic controller, fuel cell auxiliaries, <u>storage</u> and body)
  - Batteries (startup/accessories, motive)
  - Fluids (engine oil, power steering fluid, brake fluid, transmission fluid, powertrain coolant, windshield fluid, adhesives)
  - Vehicle assembly, disposal, and recycling
- ☐ Evaluate FCEV fuel cycle (Well-To-Wheels)
  - Hydrogen production
  - Hydrogen compression/cooling/liquefaction
  - Hydrogen delivery
  - Hydrogen consumption by FCEV

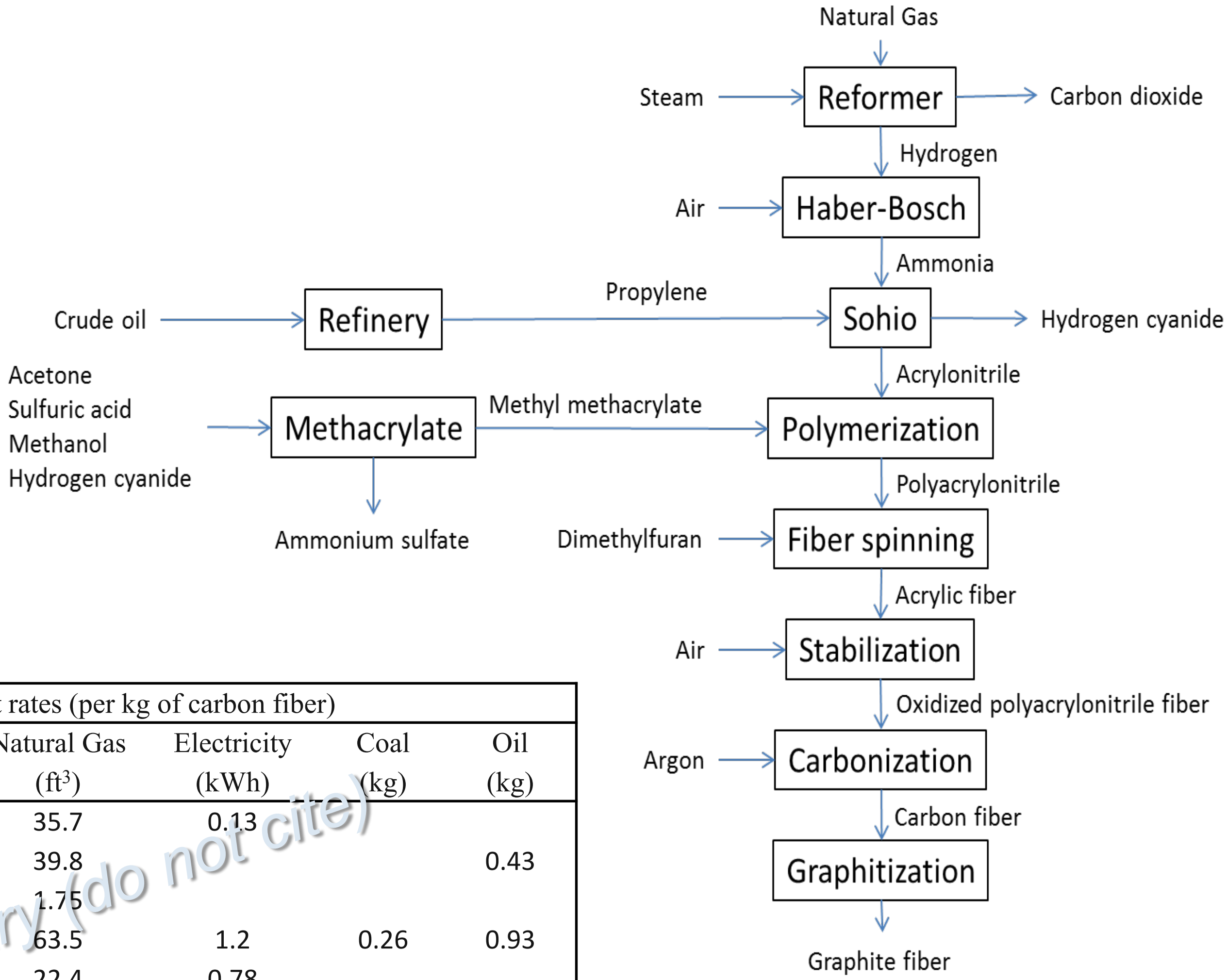
Onboard Storage and Vehicle Manufacturing Cycle

On-Board physical storage material composition*

Component	350 bar (258 L, 6 kg$_{H2}$)		700bar (149 L, 5.8 kg$_{H2}$)		CcH$_2$ (81 L, 5.7 kg$_{H2}$)	
	Type IV Tank				LLNL Gen3, 4000 psi Tank (scaled to 5.7 kg$_{H2}$)	
	Weight (kg)	Material	Weight (kg)	Material	Weight (kg)	Material
Liner	11.4	HDPE	8.0	HDPE	25.7	Al
Carbon Fiber	53.0	CF/Epoxy	67.4	CF/Epoxy	12.4	CF/Epoxy
Glass Fiber	6.1	GF/Epoxy	4.6	GF/Epoxy	--	--
Boss	0.4	SS	0.9	SS	0.4	SS
Plug	0.2	SS	0.1	SS	0.3	SS
Insulation	5.2	Foam	4.0	Foam	1.2	PET
Vacuum Shell	--	--	--	--	32.9	SS
Supporting brackets	5.2	carbon steel	4.0	carbon steel	6.5	carbon steel
Balance Of Plant						
Electronics and Controls	1.0	Si	1.0	Si	2.4	Si
Valves	3.4	carbon steel	3.4	carbon steel	6.9	carbon steel
Instruments	3.3	SS	3.3	SS	1.1	SS
Heat Exchanger	--	--	--	--	1.8	Al
Piping/fittings	4.0	SS	4.0	SS	4.0	SS
Miscellaneous	2.0	carbon steel	2.0	carbon steel	--	--
Total	**95.2**	**kg**	**102.7**	**kg**	**95.6**	**kg**

*Argonne assessment of H2 storage tank systems by Ahluwalia et al. (2010) and Hua et al. (2011)

*Calculation of carbon fiber energy and emissions intensity**



Natural Gas → Reformer

Steam → Reformer

Reformer → Carbon dioxide

Reformer → Hydrogen → Haber-Bosch

Air → Haber-Bosch

Haber-Bosch → Ammonia → Sohio

Crude oil → Refinery → Propylene → Sohio

Sohio → Hydrogen cyanide

Sohio → Acrylonitrile → Polymerization

Acetone, Sulfuric acid, Methanol, Hydrogen cyanide → Methacrylate

Methacrylate → Methyl methacrylate → Polymerization

Methacrylate → Ammonium sulfate

Polymerization → Polyacrylonitrile → Fiber spinning

Dimethylfuran → Fiber spinning

Fiber spinning → Acrylic fiber → Stabilization

Air → Stabilization

Stabilization → Oxidized polyacrylonitrile fiber → Carbonization

Argon → Carbonization

Carbonization → Carbon fiber → Graphitization

Graphitization → Graphite fiber

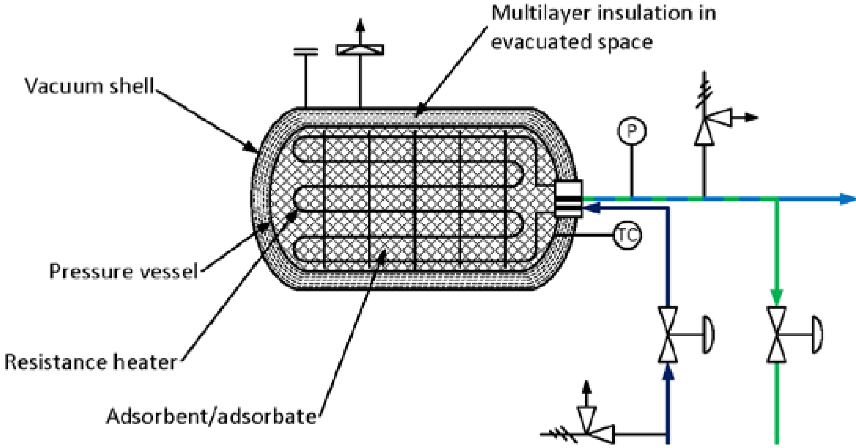
Input rates (per kg of carbon fiber)					
Component units	Input (kg)	Natural Gas (ft^3)	Electricity (kWh)	Coal (kg)	Oil (kg)
Ammonia	0.48	35.7	0.13		
Propylene	2.09	39.8			0.43
Acrylonitrile	1.9	1.75			
MMA	0.1	63.5	1.2	0.26	0.93
Acrylic fiber	2	22.4	0.78		
Carbon fiber	1	94.3	20		
Total		249	21.7	0.026	0.99
Total in Btus		245,000	74,000	650	37,000

*By Michael C. Johnson and John Sullivan, ANL

*On-Board MOF-5 storage material composition**

- 200 L, Type I tank
- 5.6 kg_{H2} useable (6.2 kg_{H2} total) @ 100 bar, 80K

Component	MOF-5	
	Weight (kg)	**Material**
Pressure Vessel	62.2	Al
Vacuum Shell	14.8	Al
Heat Exchanger	4.3	Al
Insulation	7.7	PET
Adsorbent	24.4	MOF-5
Balance Of Plant	17.4	SS
Total	**130.8**	**kg**



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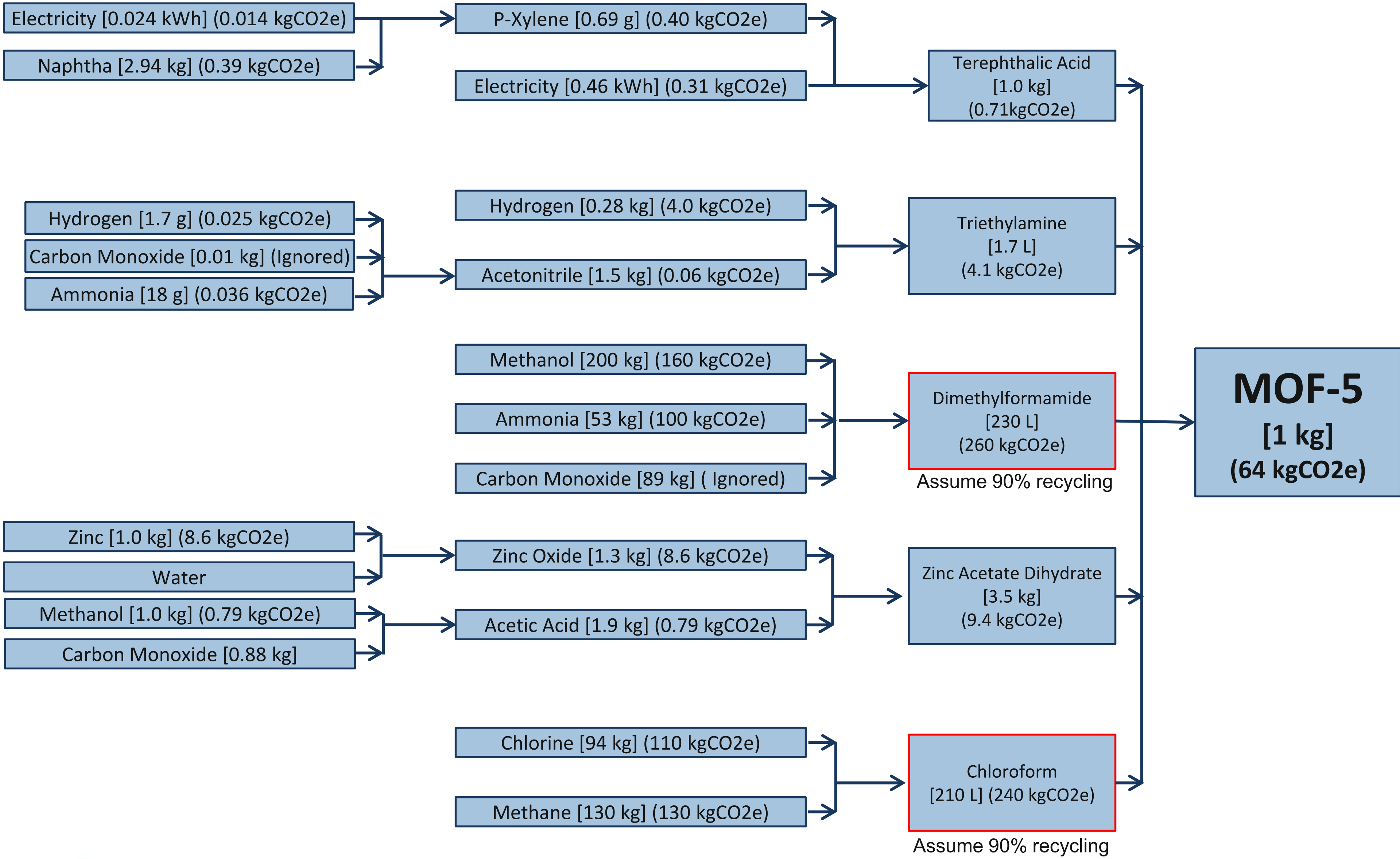
*Donald Siegel, University of Michigan

MOF-5 synthesis carbon intensity



Electricity [0.024 kWh] (0.014 kgCO2e)

Naphtha [2.94 kg] (0.39 kgCO2e)

P-Xylene [0.69 g] (0.40 kgCO2e)

Electricity [0.46 kWh] (0.31 kgCO2e)

Terephthalic Acid
[1.0 kg]
(0.71kgCO2e)

Hydrogen [1.7 g] (0.025 kgCO2e)

Carbon Monoxide [0.01 kg] (Ignored)

Ammonia [18 g] (0.036 kgCO2e)

Hydrogen [0.28 kg] (4.0 kgCO2e)

Acetonitrile [1.5 kg] (0.06 kgCO2e)

Triethylamine
[1.7 L]
(4.1 kgCO2e)

Methanol [200 kg] (160 kgCO2e)

Ammonia [53 kg] (100 kgCO2e)

Carbon Monoxide [89 kg] (Ignored)

Dimethylformamide
[230 L]
(260 kgCO2e)

Assume 90% recycling

Zinc [1.0 kg] (8.6 kgCO2e)

Water

Methanol [1.0 kg] (0.79 kgCO2e)

Carbon Monoxide [0.88 kg]

Zinc Oxide [1.3 kg] (8.6 kgCO2e)

Acetic Acid [1.9 kg] (0.79 kgCO2e)

Zinc Acetate Dihydrate
[3.5 kg]
(9.4 kgCO2e)

Chlorine [94 kg] (110 kgCO2e)

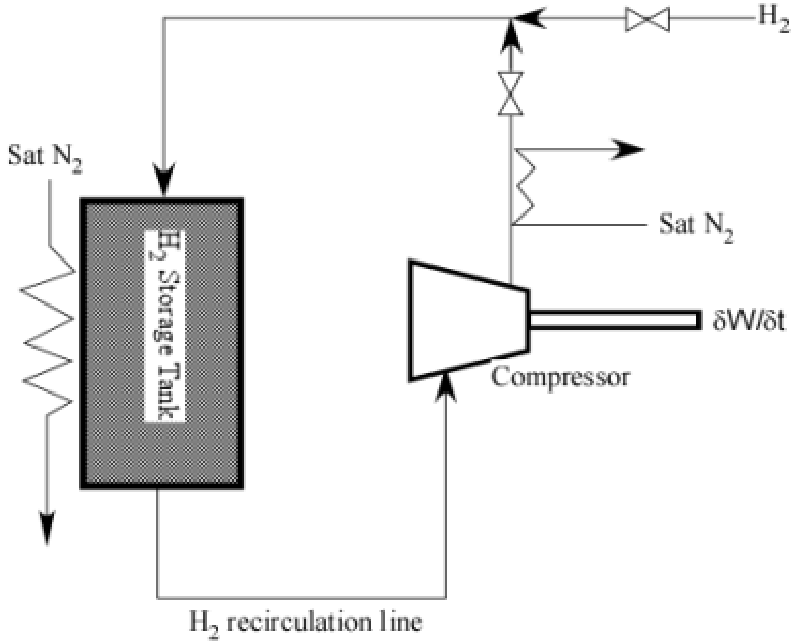
Methane [130 kg] (130 kgCO2e)

Chloroform
[210 L] (240 kgCO2e)

Assume 90% recycling

MOF-5
[1 kg]
(64 kgCO2e)

On-Board MOF-5 storage adsorption/desorption energy



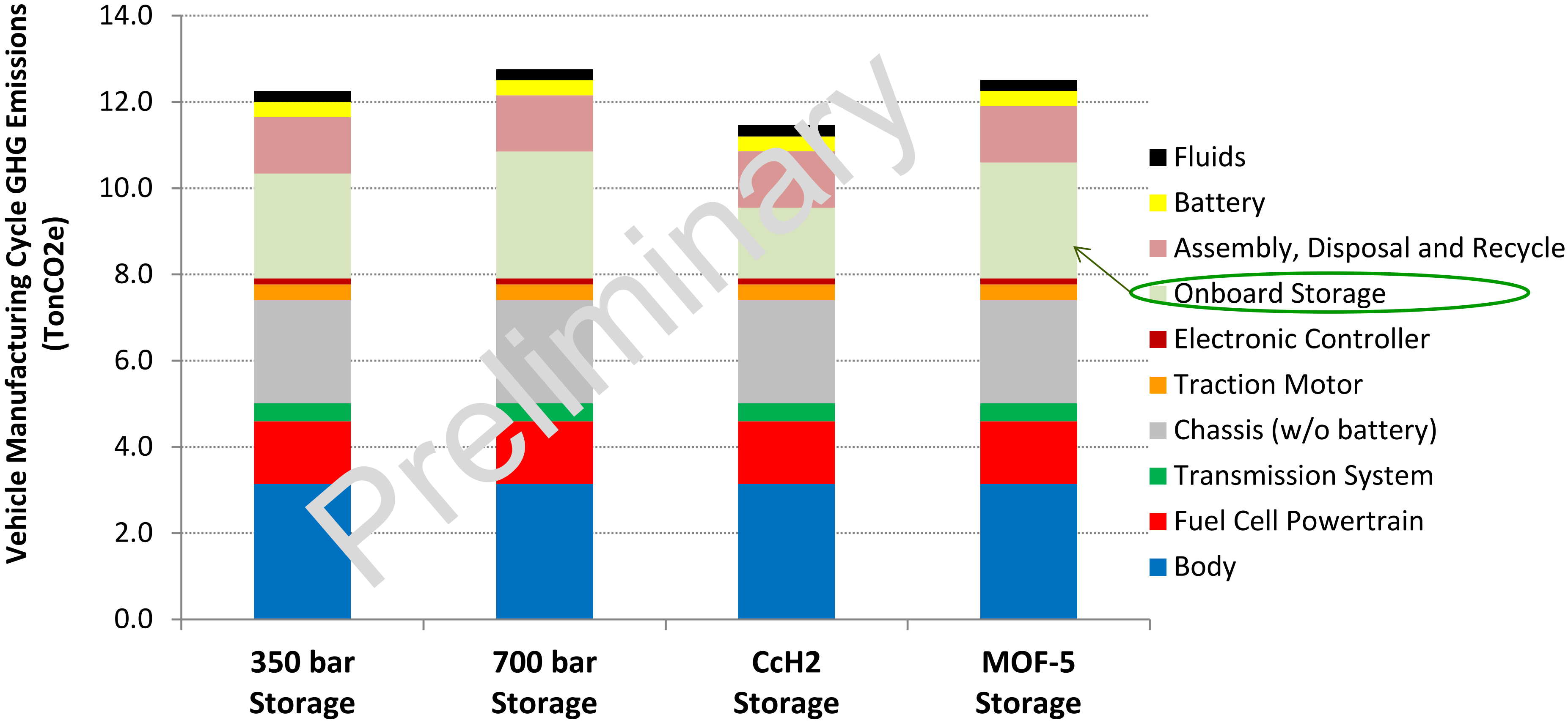
- Cooling to remove adsorption energy
  - ✓ 4 kJ/mol (2.2-7.4 kJ/mol reported)
  - ✓ 56 kg liquid N2 is required
- Cooling of tank from 180 K to 80 K
  - ✓ 25 kg liquid N2 is required
- Heat of desorption
  - ✓ 1.546 kW for 5600 seconds to desorb 5.6 kg_{H2}
  - ✓ 4.8 kWh_{H2} assuming 50% efficiency for H2→electricity
- Compressor recirculation energy
  - ✓ 940 kJ/kg_{H2}, 4.5 kg_{H2} recirculated
  - ✓ 1.8 kWhe for recirculation

Summary of materials' life-cycle GHG emissions intensity

Material	Carbon Intensity ($kg_{CO2e}/kg_{material}$)
Carbon Fiber Resin	34
MOF-5	64
Aluminum	10
HDPE	3.5
Stamped Steel Parts	4.2
Stainless Steel Parts	2.5
Glass Fiber	5.9
Foam	3.4

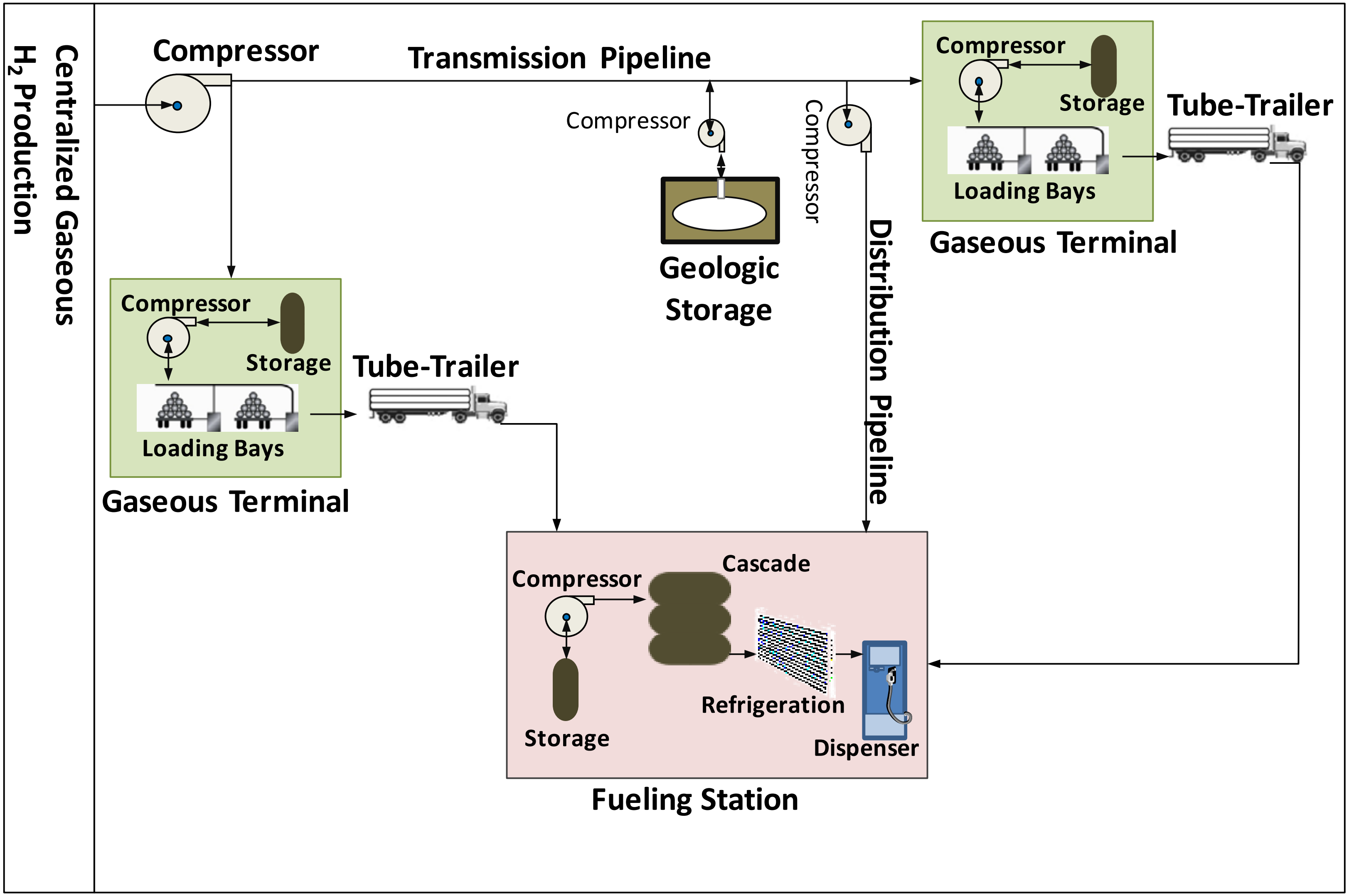
- 350 bar storage → 2210 kg_{CO2e}
- 700 bar storage → 2670 kg_{CO2e}
- CcH2 storage → 1490 kg_{CO2e}
- MOF-5 storage → 2440 kg_{CO2e}

Onboard H2 storage contributes 15-23% to the vehicle manufacturing cycle

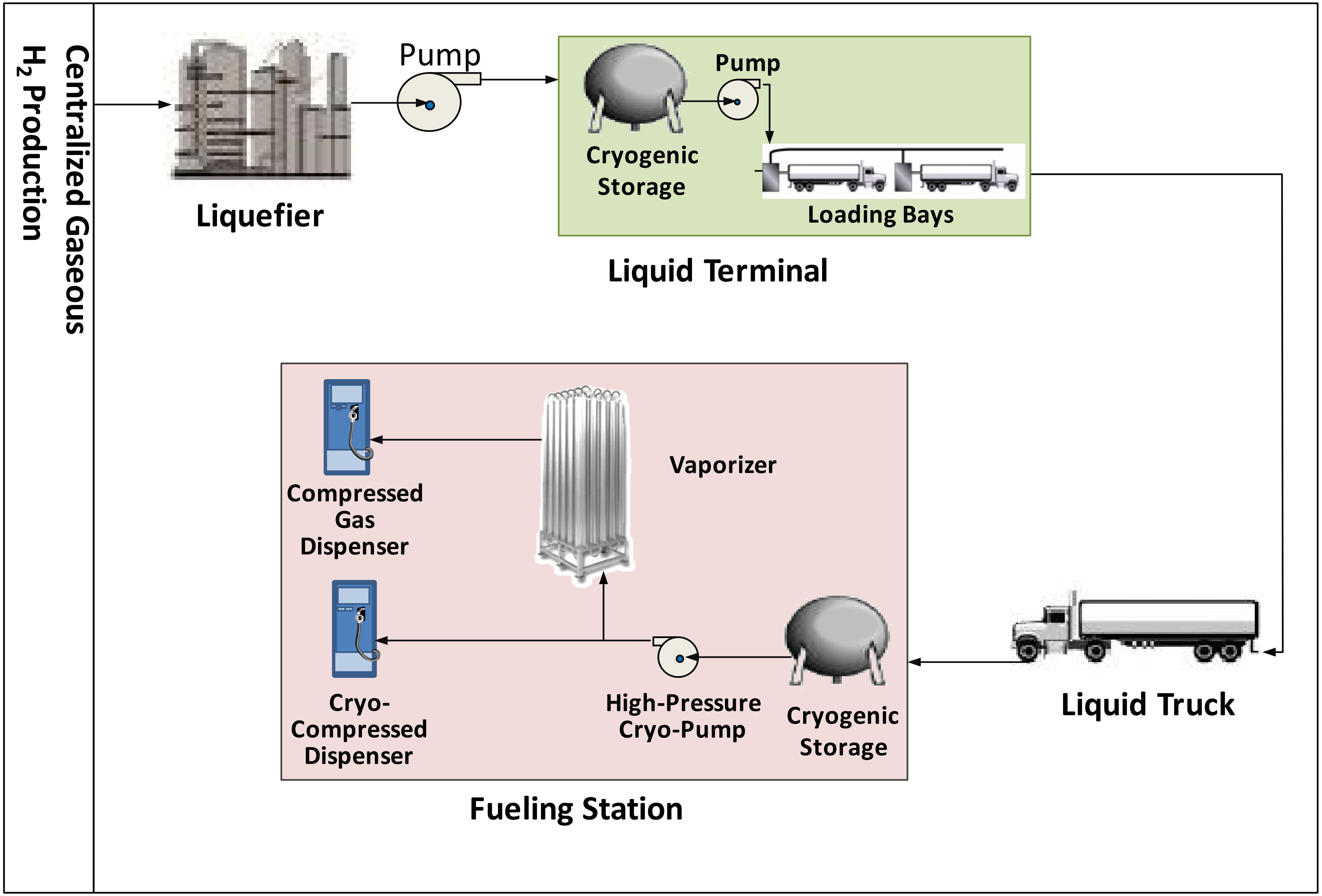


Fuel Cycle (WTW)

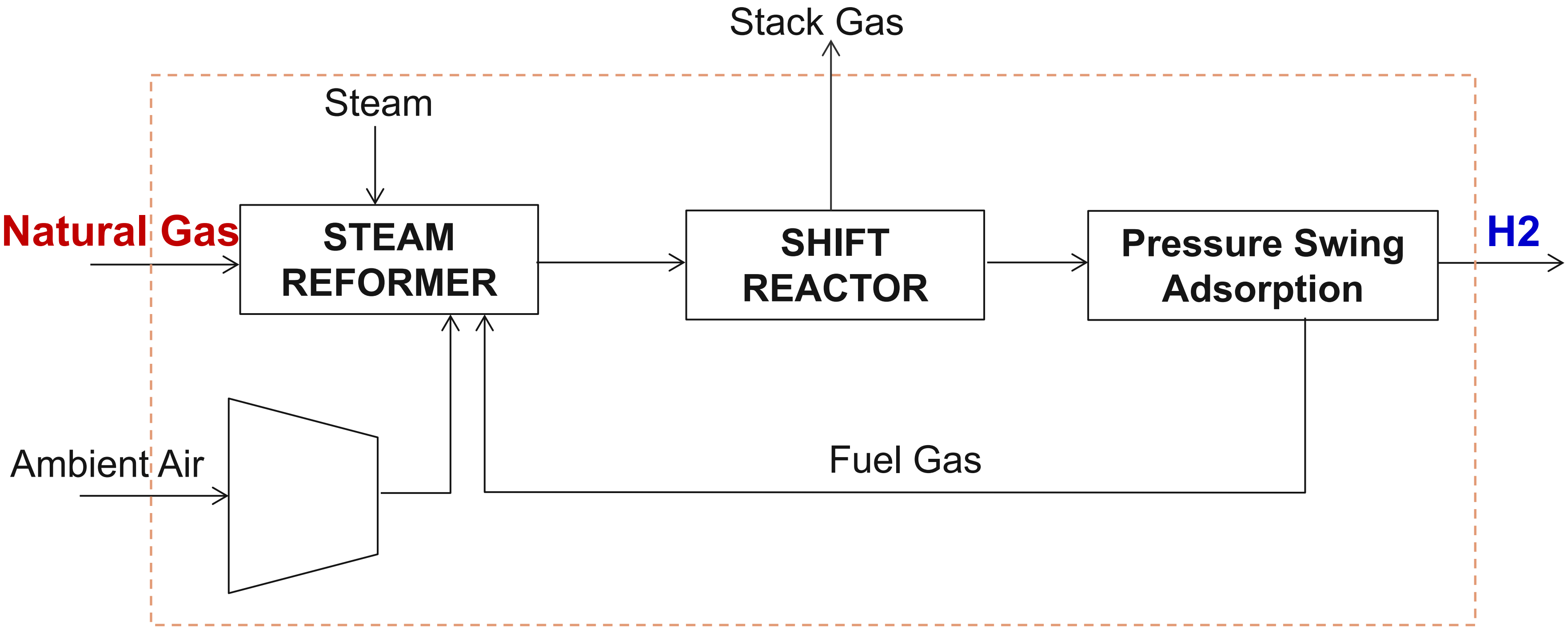
Fuel production and delivery pathways for compressed gaseous hydrogen



Fuel production and delivery pathways for cryo-compressed hydrogen



Hydrogen production today is mainly from SMR, but other low-carbon pathways exist today



At 72% NG to H2 energy efficiency

→ $\boxed{12\ \mathrm{kg}_{CO2e}/\mathrm{kg}_{H2}}$

Actual North America liquefaction plants GHG emissions are different from US average mix

Liquefaction GHG emissions today may be much less (~40% less) than based on US average mix

Region	GHG Emissions (g_{CO2e}/kWhe)	GHG Emissions (kg_{CO2e}/kg_{H2})*	Liquefaction Capacity (ton/day)
California	380	4.5	30
Louisiana	610	7.4	70
Indiana	1070	12.8	30
New York	330	4.0 or 0**	40
Alabama	580	7.0	30
Ontario	130	1.6	30
Quebec	20	0.20	27
Total			257
Weighted average		**5.7 or 5.0****	
If US mix	670	**8.0**	

*Assuming liquefaction energy of 12 kWhe/kg_H2

** Plant in NY uses hydro power

MOF adsorption/desorption GHG emissions

Material	Carbon Intensity (kg_{CO2e}/kg_{H2})
Adsorption cooling*	3.4
Tank cooling*	1.5
Desorption heat	0.3
Recirculation	0.2
Total	5.4

*0.5 kWhe/kg_LN2

GHG emissions of H2 compression are based on US average mix

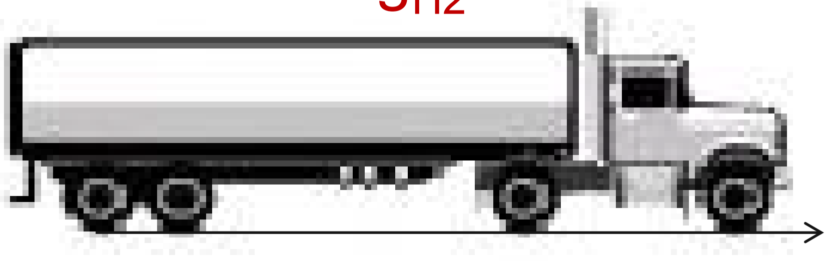
Compression process	Pressure lift (bar)	Compression Energy (kWhe/kg_{H2})	GHG Emissions (kg_{CO2e}/kg_{H2})*
Pipeline compression	20 → 70	0.6	**0.40**
350 bar dispensing	20 → 440	3	**2.0**
700 bar dispensing	20 → 900	4	**2.7**
-40°C pre-cooling	---	0.25	**0.17**
CcH2 station	2 → 350	0.3	**0.20**

*Assuming US average generation mix

GHG emissions of LH2 truck delivery is smaller than tube-trailer delivery due to higher payload

4000 kg_{H2}

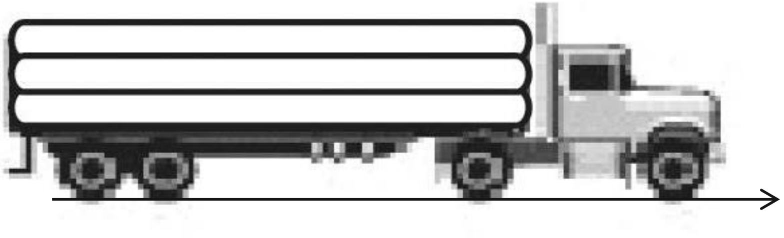
0.1 kg_{CO2e}/kg_{H2}



60 mi to city gate

250 bar, 550 kg_{H2}

0.7 kg_{CO2e}/kg_{H2}



60 mi to city gate

Fuel cycle GHG emissions of MOF-5, LH2 and compressed GH2 pathways

kg_{CO2e}/kg_{H2}

Pathway	Production	Transport	Compression/ liquefaction	Total
GH2 Pathway (350 bar)	12	0.7	2.0	**14.7**
GH2 Pathway (700 bar)	12	0.7	2.9	**15.6**
LH2 Pathway (CcH2)	12	0.1	5.2	**17.3** or **20.3‡**
MOF-5 Pathway	12	0.7	5.4	**18.1**

‡ Assuming US mix for H2 liquefaction

Onboard storage represents 3-5% of total LCA GHG emissions of compressed GH2, LH2 and MOF-5 pathways

g_{CO2e}/mi*

Pathway	Onboard Storage	Balance of Vehicle Cycle	Fuel Cycle	Total
GH2 Pathway (350 bar)	14	56	245	**315**
GH2 Pathway (700 bar)	17	56	257	**330**
LH2 Pathway (CcH2)	9	56	288	**350** **or 400‡**
MOF-5 pathway	15	56	302	**373**

*Assuming 60 mi/kg_{H2} fuel economy for FCEVs, and 160,000 lifetime VMT

‡ Assuming US mix for H2 liquefaction

Summary of Preliminary LCA Results

- Onboard H2 storage contributes 15-23% to the vehicle manufacturing cycle
  - Largest contribution from 700 bar and MOF-5 storage systems
- Onboard storage systems contribute 3-5% of the total LCA GHG emissions of compressed GH2, LH2 and MOF-5 pathways
- GHG emissions of H2 liquefaction overshadow the low GHG emissions of the CcH2 storage system

Future Work

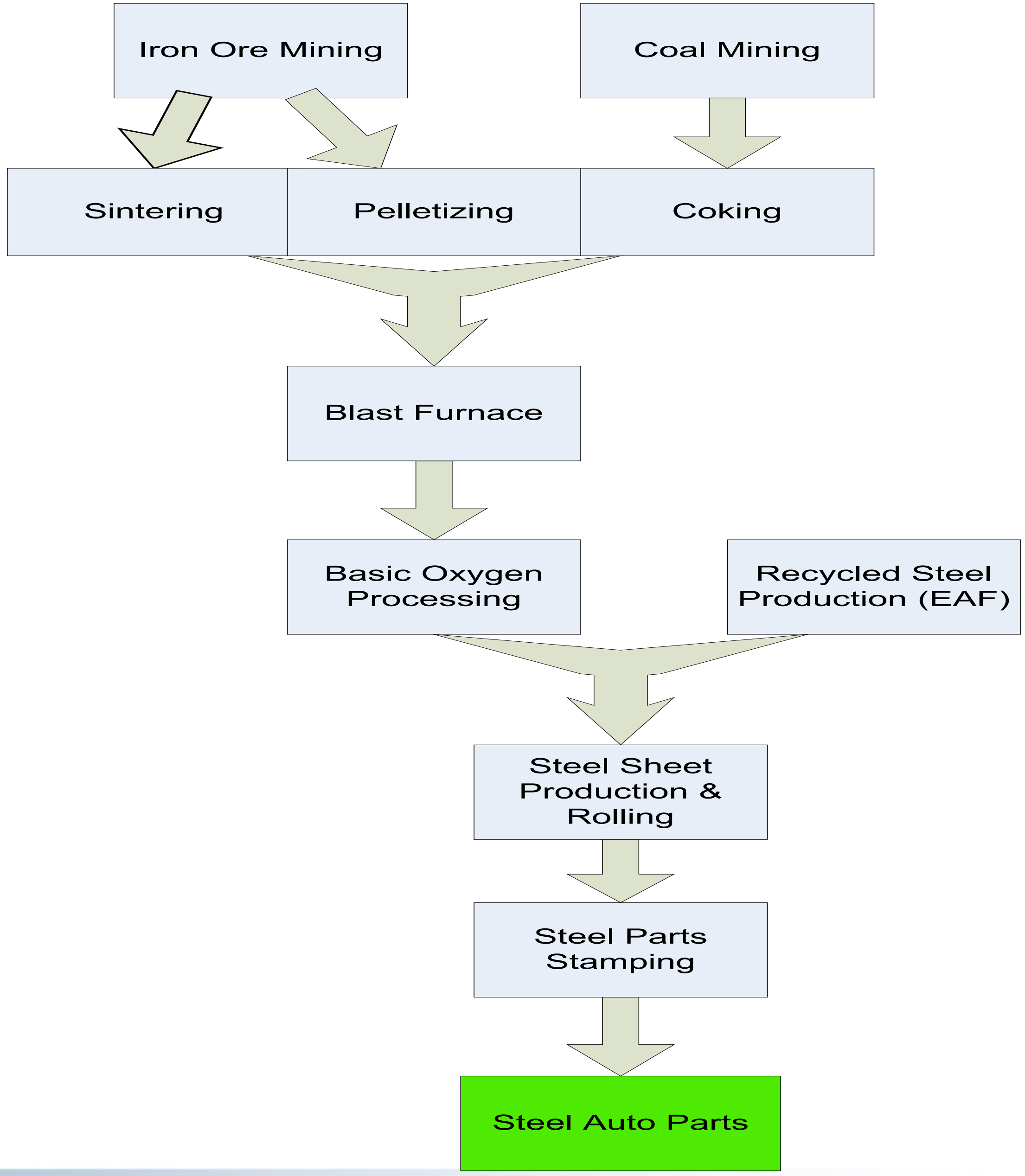
- ☐ Address outstanding issues related to CcH2 and sorption storage systems
- ☐ Update GREET model with new data and analysis
- ☐ Evaluate emerging hydrogen production, delivery and FCEV technologies
- ☐ Continue to provide LCA technical support to DOE FCT program and industry stakeholders

Acronyms

- Al: Aluminum
- ANL: Argonne National Laboratory
- CcH2: Cryo-compressed Hydrogen
- CF: Carbon Fiber
- CO2: Carbon Dioxide
- DOE: Department of Energy
- FC: Fuel Cell
- FCT: Fuel Cell Technologies
- FCEV: Fuel Cell Electric Vehicle
- GH2: Gaseous Hydrogen
- GHG: Greenhouse Gases
- GREET: Greenhouse gases, Emissions, and Energy use in Transportation
- H2: Hydrogen
- HDPE: High Density Polyethylene
- HSECoE: Hydrogen Storage Engineering Center of Excellence
- HSTT: Hydrogen Storage Tech Team
- LCA: Life Cycle Analysis
- LH2: Liquid Hydrogen
- LN2: Liquid Nitrogen
- mi: mile
- MOF: Metal Organic Framework
- MOF-5: $Zn_4O(BDC)_3$
- MMA: Methyl Methacrylate
- N2: Nitrogen
- NG: Natural Gas
- PET: Polyethylene Terephthalate
- RD&D: Research, Development, and Demonstration
- SMR: Steam Methane Reforming
- SNL: Sandia National Laboratory
- SS: Stainless Steel
- VMT: Vehicle Miles Traveled
- WTW: Well-To-Wheels

Backup Slides

Steel parts energy and emissions intensity



Iron Ore Mining

Coal Mining

Sintering

Pelletizing

Coking

Blast Furnace

Basic Oxygen Processing

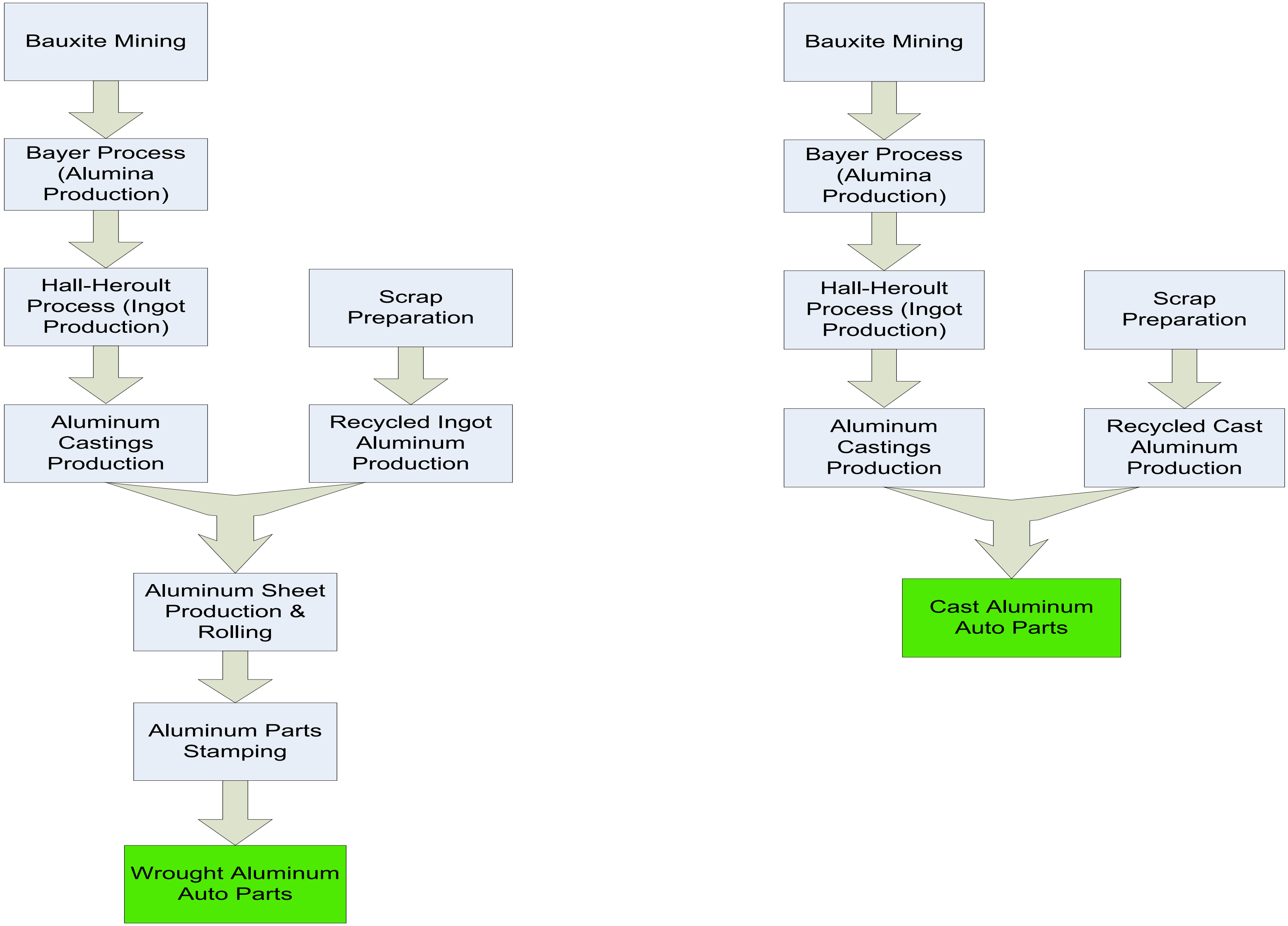
Recycled Steel Production (EAF)

Steel Sheet Production & Rolling

Steel Parts Stamping

Steel Auto Parts

Aluminum parts energy and emissions intensity



Bauxite Mining

Bayer Process (Alumina Production)

Hall-Heroult Process (Ingot Production)

Scrap Preparation

Aluminum Castings Production

Recycled Ingot Aluminum Production

Aluminum Sheet Production & Rolling

Aluminum Parts Stamping

Wrought Aluminum Auto Parts

Bauxite Mining

Bayer Process (Alumina Production)

Hall-Heroult Process (Ingot Production)

Scrap Preparation

Aluminum Castings Production

Recycled Cast Aluminum Production

Cast Aluminum Auto Parts