ME Capstone

Case Studies & Insights into Sustainable Design

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Feb 19, 2024

Outline:
Case Studies and Insights into Sustainable Design

- UN SDGs
- A Cup of Tea?
- Comparing Unlike Energy Sources?
- Are EVs Emissions Free?

UN Sustainable Development Goals

https://sdgs.un.org/goals

UN SDGs

- The Sustainable Development Goals (SDGs), were adopted by the United Nations in 2015 as a universal call to action to end poverty, protect the planet, and ensure that by 2030 all people enjoy peace and prosperity.
- The 17 SDGs are integrated—they recognize that action in one area will affect outcomes in others, and that development must balance social, economic and environmental sustainability.
- Countries have committed to prioritize progress for those who're furthest behind. The SDGs are designed to end poverty, hunger, AIDS, and discrimination against women and girls.
- The creativity, knowhow, technology and financial resources from all of society is necessary to achieve the SDGs in every context.

https://www.undp.org/sustainable-development-goals

- Trending News…

Georgia Tech Named Top-Ranked Public University in Energy

FEB 07, 2024 -- ATLANTA, GA

U.S. News and World Report

U.S. News & World Report has ranked the Georgia Institute of Technology as the top public university and No. 3 nationally in energy and fuels research. This is the first year the category has been included in the annual rankings, and Georgia Tech's dominance reflects the dynamic research and expertise of the Institute.

"I'm thrilled to see Georgia Tech recognized for our leading-edge approach to creating sustainable energy solutions," said Executive Vice President for Research Chaouki Abdallah. "This achievement reflects the unwavering commitment of our faculty and researchers to conducting groundbreaking research

https://research.gatech.edu/georgia-tech-named-top-ranked-public-university-energy also,

- GT Sustainability Showcase during SDG Week…

Sustainability Showcase

SDG Week | March 4 - 8, 2024

Georgia Tech
Brook Byers Institute
for Sustainable Systems

Office of
Sustainability

- Lightning Talks
- Panel Discussions
- Posters
- Art on Display

For details and updates, visit:
sustainable.gatech.edu/showcase

SUSTAINABLE DEVELOPMENT GOALS

Learn about all the SDG Week events at:

sustain.gatech.edu/sdg-week

March 6-7, 8:30-4pm, in the John Lewis Student Center’s Atlantic Theater.

Poll Question 1

- Suggest a method for boiling a cup of water

Some Methods for Boiling Water

Microwave

Gas Stovetop

Electric Kettle

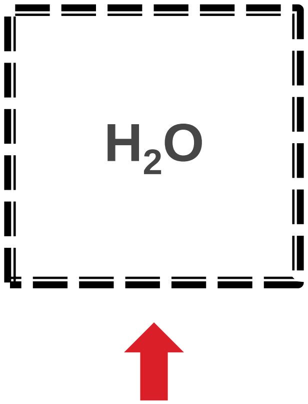
Concentrated Solar*

*Source: Contemporary Energy Solar Kettle & Amazon

Wood Fire
(Open Flame)

Poll Question 2

- Suggest an equation for estimating the energy required to boil a cup of water



H_2O

Unknown **Q_{in}**

$$Q_{in} = m \cdot c_p \cdot \Delta T$$

Knowns and Assumptions

Substance = Water

$m=8.0$ fl. oz. (1 cup)

$m=0.227$ kg

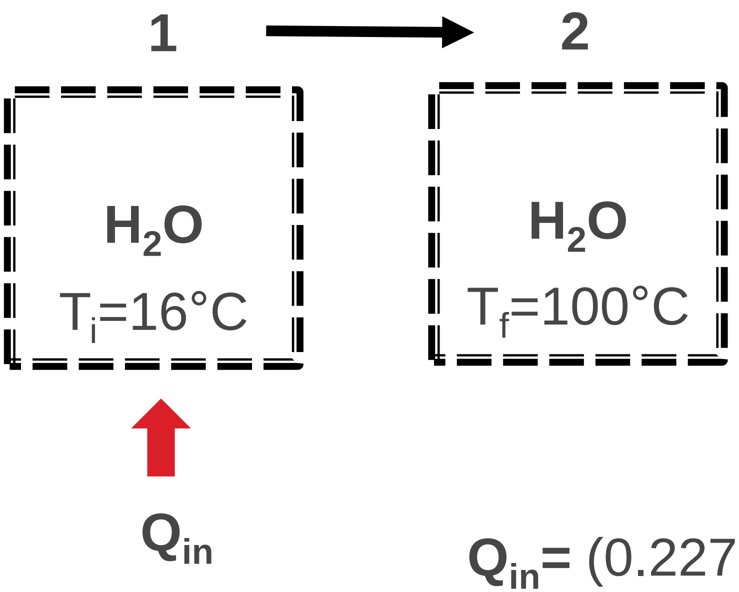
$c_p=4.184$ kJ/kg°C

$T_i=16°C$

$T_f=100°C$

R. Simmons, Strategic Energy Institute, Georgia Institute of Technology, 2021

Theoretical Energy Input



1

2

H_2O

T_i=16°C

H_2O

T_f=100°C

Q_{in}

Q_{in}= m ·c_p ·ΔT

Q_{in}= (0.227kg) ·(4.184kJ/kg°C)·(100-16°C)

Q_{in}= 79.7 kJ

Conversion: 1 kJ = 0.2777 Wh

Q_{in}= 22.1 Wh

How much energy is this?

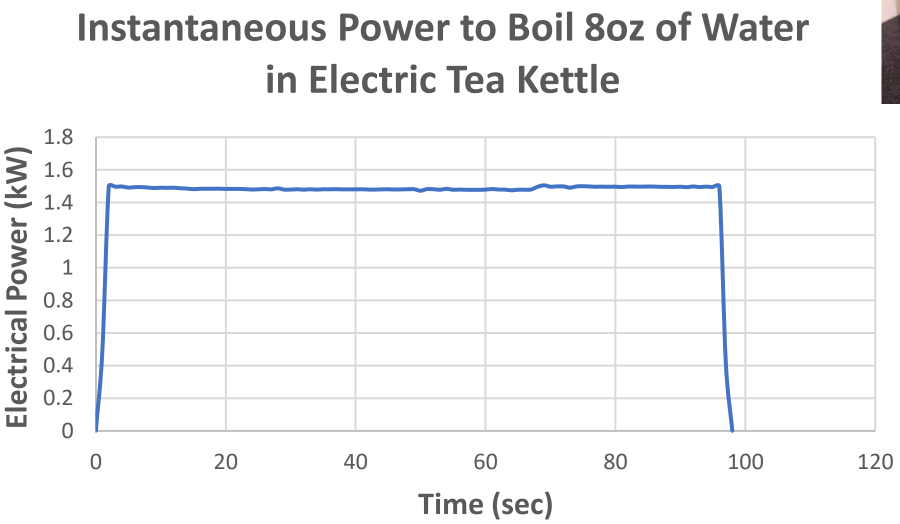
REF: W_{elec} = 10 W·h (to charge a smart phone)

REF: W_{elec} = 37,000 W·h (to charge a Nissan Leaf)

R. Simmons, Strategic Energy Institute, Georgia Institute of Technology, 2021

Boiling Water in an Electric Tea Kettle

Tea Kettle Experiment



$W_{elec} = P \cdot \Delta t$

$W_{elec} \approx (1500\ \text{W}) \cdot (96\ \text{sec})$

$W_{elec} \approx 142{,}000\ \text{W} \cdot \text{s}$

$\mathbf{W_{elec} \approx 39.4\ W{\cdot}h}$

$\mathbf{W_{elec} \approx 39.4\ Wh}$

$\mathbf{Q_{min,\ theor} = 22.1\ Wh}$

$\eta = E_{min}/E_{actual}$

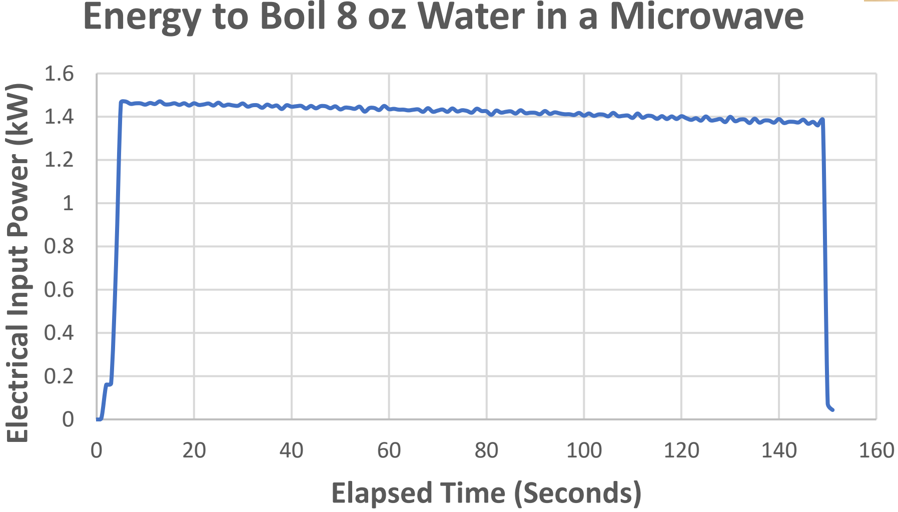
$\eta_{elec\_kettle} \approx 39.4\text{Wh}/57.5\text{Wh}$

$\mathbf{\eta_{elec\_kettle} \approx 0.56\ \ (56\%)}$

R. Simmons, Strategic Energy Institute, Georgia Institute of Technology, 2021

Boiling Water in a Microwave

Microwave Experiment



MONTHLY PEAK 15 MIN DEMAND 0.509 kilowatts

FEBRUARY USAGE 1.11 kWh

7:25:45 PM RATE 1431 Watts

$$W_{elec} = P \cdot \Delta t$$

$$W_{elec} \approx (1380\ \mathrm{W}) \cdot (150\ \mathrm{sec})$$

$$W_{elec} \approx 207{,}000\ \mathrm{W} \cdot \mathrm{s}$$

$$\mathbf{W_{elec} \approx 57.5\ W{\cdot}h}$$

$$\mathbf{W_{elec} \approx 57.5\ Wh}$$

$$\mathbf{Q_{min,\ theor} = 22.1\ Wh}$$

$$\eta = E_{min}/E_{actual}$$

$$\eta_{microwave} \approx 22.1\mathrm{Wh}/57.5\mathrm{Wh}$$

$$\mathbf{\eta_{microwave} \approx 0.38\ \ (38\%)}$$

R. Simmons, Strategic Energy Institute, Georgia Institute of Technology, 2021

Boiling Water on a Gas Burner

Gas Burner Experiments

Open Pot
5000 BTU/hr (1466 W)
Time to boil ≈ 390 s (0.108h)

$$\mathbf{W_{gas,low,open} = \dot{Q}_{in} \cdot \Delta t}$$

$$W_{gas,low,open} \approx (1466\ W) \cdot (390s)$$

$$W_{gas,low,open} \approx 572{,}000\ W \cdot s$$

$$\mathbf{W_{gas,low,open} \approx 159\ W \cdot h}$$

$$\boldsymbol{\eta_{gas,low,open} \approx 0.14\ \ (14\%)}$$

Closed Pot
9500 BTU/hr (2786 W)
Time to boil ≈ 120 s (0.033h)

$$\mathbf{W_{gas,high,closed} = \dot{Q}_{in} \cdot \Delta t}$$

$$W_{gas,high,closed} \approx (2786\ W) \cdot (120s)$$

$$W_{gas,high,closed} \approx 334{,}000\ W \cdot s$$

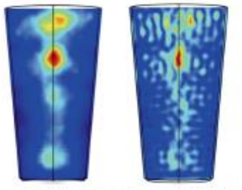
$$\mathbf{W_{gas,high,closed} \approx 93\ W \cdot h}$$

$$\boldsymbol{\eta_{gas,high,closed} \approx 0.24\ \ (24\%)}$$

R. Simmons, Strategic Energy Institute, Georgia Institute of Technology, 2022

Summary

Electricity



**

$W_{elec} \approx 57.5\ W\cdot h$

$\eta_{microwave} \approx 0.38$ (38%)

$W_{elec} \approx 39.4\ W\cdot h$

$\eta_{elec\_kettle} \approx 0.56$ (56%)

Natural Gas

$W_{gas,low,open} \approx 159\ W\cdot h$

$\eta_{gas,low,open} \approx 0.14$ (14%)

$W_{gas,high,closed} \approx 93\ W\cdot h$

$\eta_{gas,high,closed} \approx 0.24$ (24%)

** Nature Reviews Physics| https://doi.org/10.1038/s42254-020-0233-1 | Published online 13 August 2020

Engineering 101:
System Boundary is Key

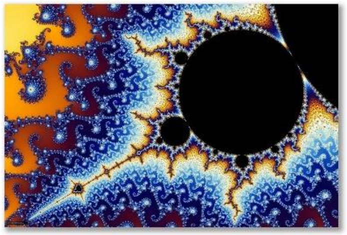
LOCAL ENERGY INPUTS

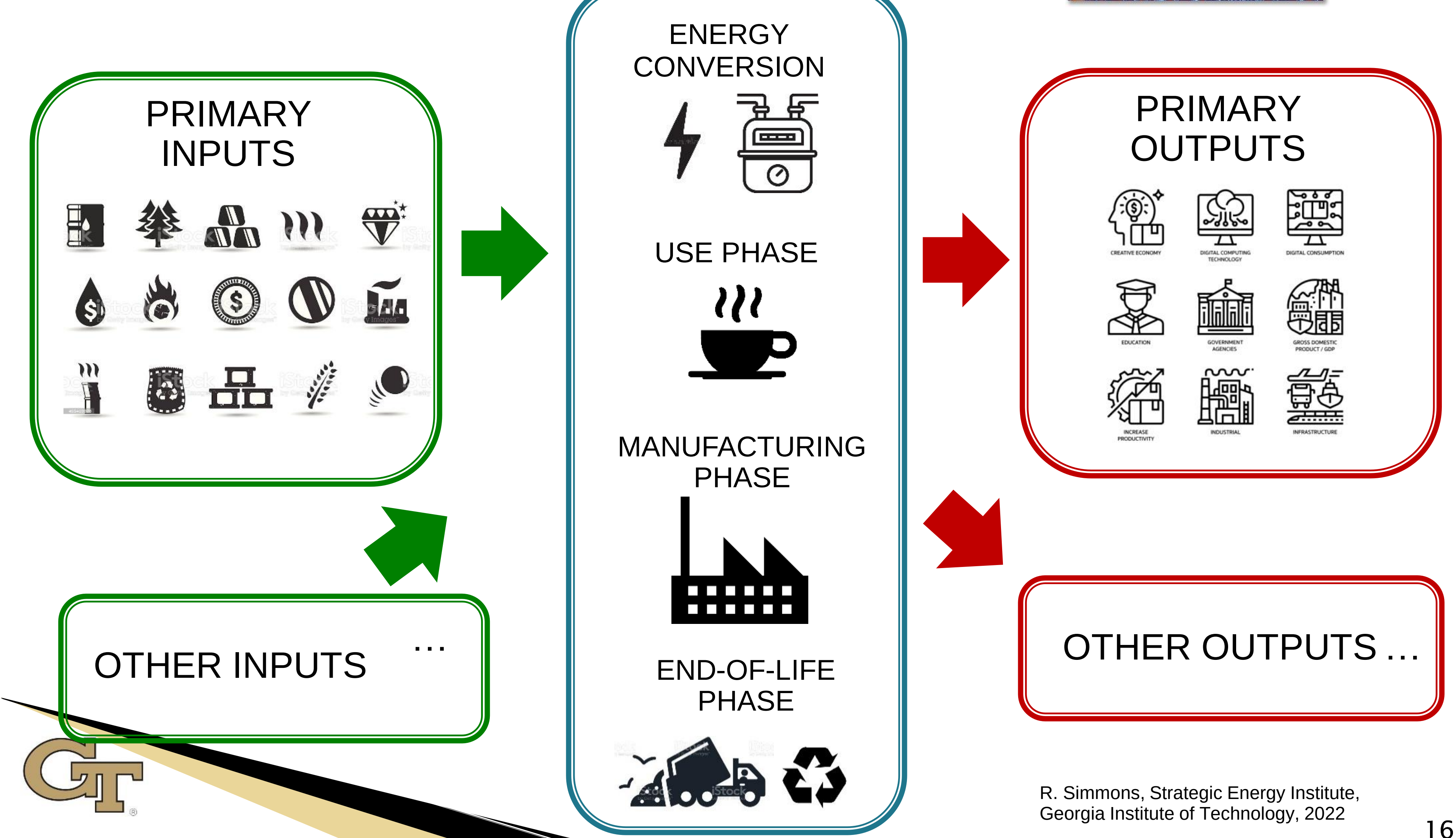
Boil a Cup of Water via Different Pathways

KEY DECISIONS

…

Engineering 101: System Boundary is Key





PRIMARY INPUTS

OTHER INPUTS …

ENERGY CONVERSION

USE PHASE

MANUFACTURING PHASE

END-OF-LIFE PHASE

PRIMARY OUTPUTS

OTHER OUTPUTS …

R. Simmons, Strategic Energy Institute,
Georgia Institute of Technology, 2022

Consider the Boundary & Upstream Impacts

$W_{elec} \approx 39.4\ \text{W}\cdot\text{h}$

$\eta_{elec\_kettle} \approx 0.56$ (56%)

Electricity_home

Electricity_Distribution

$\eta_d \approx 0.98$ (98%)

Electricity_Transmission

$\eta_T \approx 0.94$ (94%)

Electricity_Generation

$\eta_G \approx 0.10$ to 0.95 (~40%)

$\eta_{elec\_kettle,net,sys} \approx \eta_{elec\_kettle}\ \eta_d\ \eta_T\ \eta_G \approx 0.20$ (20%)

Authors assumptions based on public sources, DOE, EIA, EPA

R. Simmons, Strategic Energy Institute, Georgia Institute of Technology, 2022

Consider the Boundary & Upstream Impacts

$W_{gas,high,closed} \approx 93\ W\cdot h$

$\eta_{gas,high,closed} \approx 0.24\ \ (24\%)$

NaturalGas_home

NG_Distribution $\eta_d \approx 0.99\ \ (99\%)$

NG_Refining

$\eta_R \approx 0.93\ (\sim 93\%)$

$$\eta_{gas,high,closed,net,sys} \approx \eta_{gas,high,closed}\ \eta_d\ \eta_R \approx 0.22\ \ (22\%)$$

Authors assumptions based on public sources, DOE, EIA, IGS

R. Simmons, Strategic Energy Institute, Georgia Institute of Technology, 2022

Poll Question 3

- What materials are used in an electric tea kettle?

Electric Kettle Raw Materials

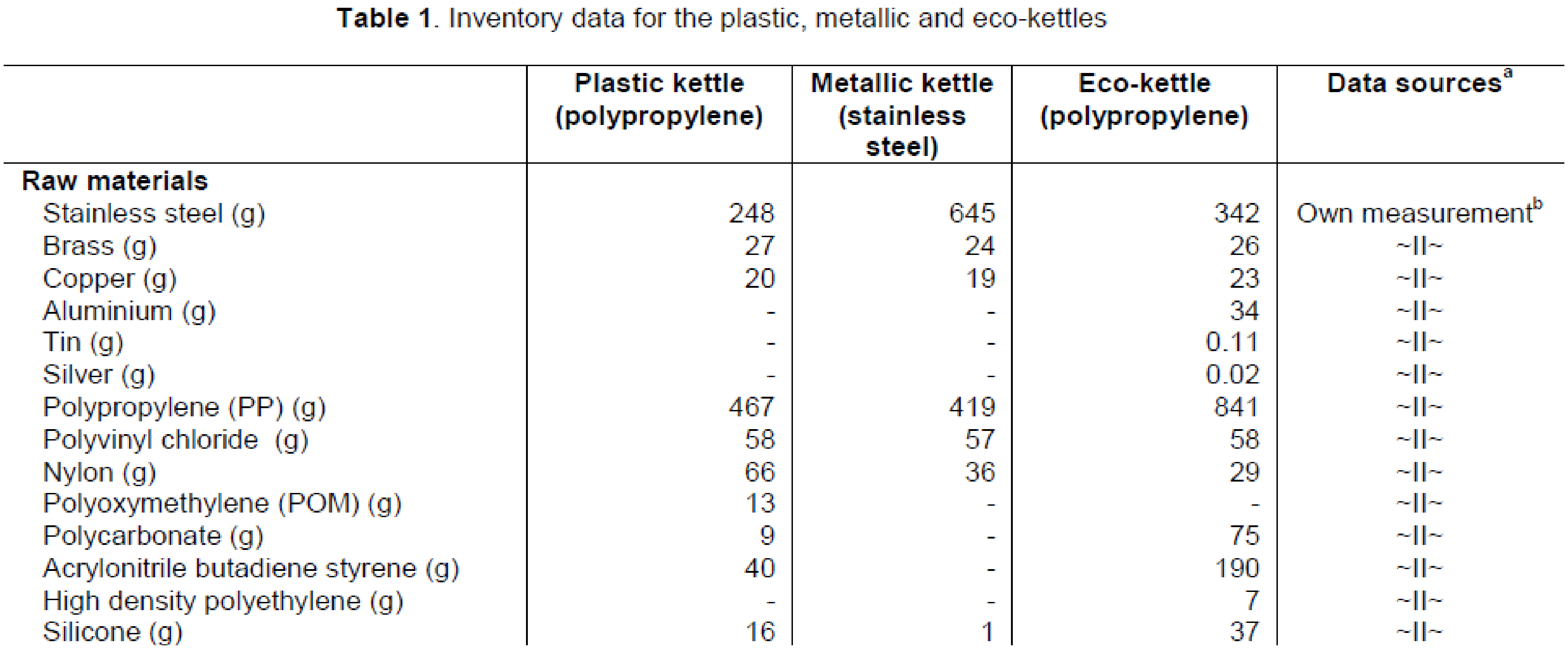
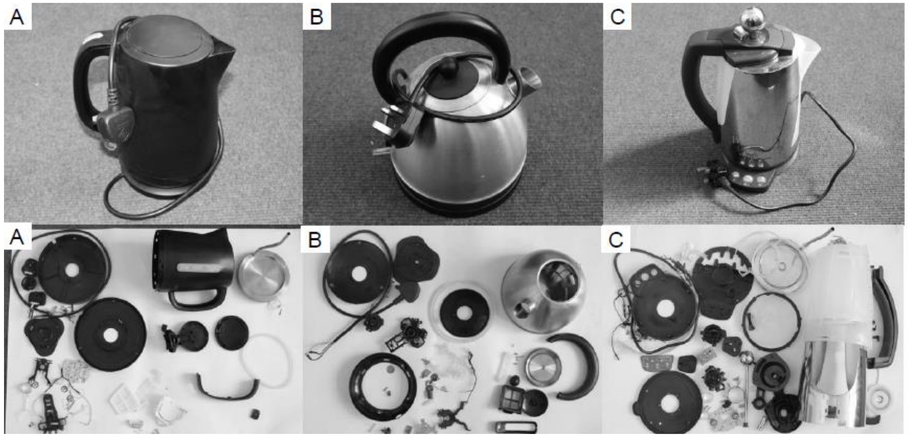


Table 1. Inventory data for the plastic, metallic and eco-kettles

	Plastic kettle (polypropylene)	Metallic kettle (stainless steel)	Eco-kettle (polypropylene)	Data sources[a]
Raw materials				
Stainless steel (g)	248	645	342	Own measurement[b]
Brass (g)	27	24	26	~II~
Copper (g)	20	19	23	~II~
Aluminium (g)	-	-	34	~II~
Tin (g)	-	-	0.11	~II~
Silver (g)	-	-	0.02	~II~
Polypropylene (PP) (g)	467	419	841	~II~
Polyvinyl chloride (g)	58	57	58	~II~
Nylon (g)	66	36	29	~II~
Polyoxymethylene (POM) (g)	13	-	-	~II~
Polycarbonate (g)	9	-	75	~II~
Acrylonitrile butadiene styrene (g)	40	-	190	~II~
High density polyethylene (g)	-	-	7	~II~
Silicone (g)	16	1	37	~II~



Gallego Schmid, Alejandro, Life cycle environmental evaluation of kettles: Recommendations for the development of eco-design regulations in the European Union, The Science of the total environment, 2017

LCA –Approach

- Electric tea kettle LCA

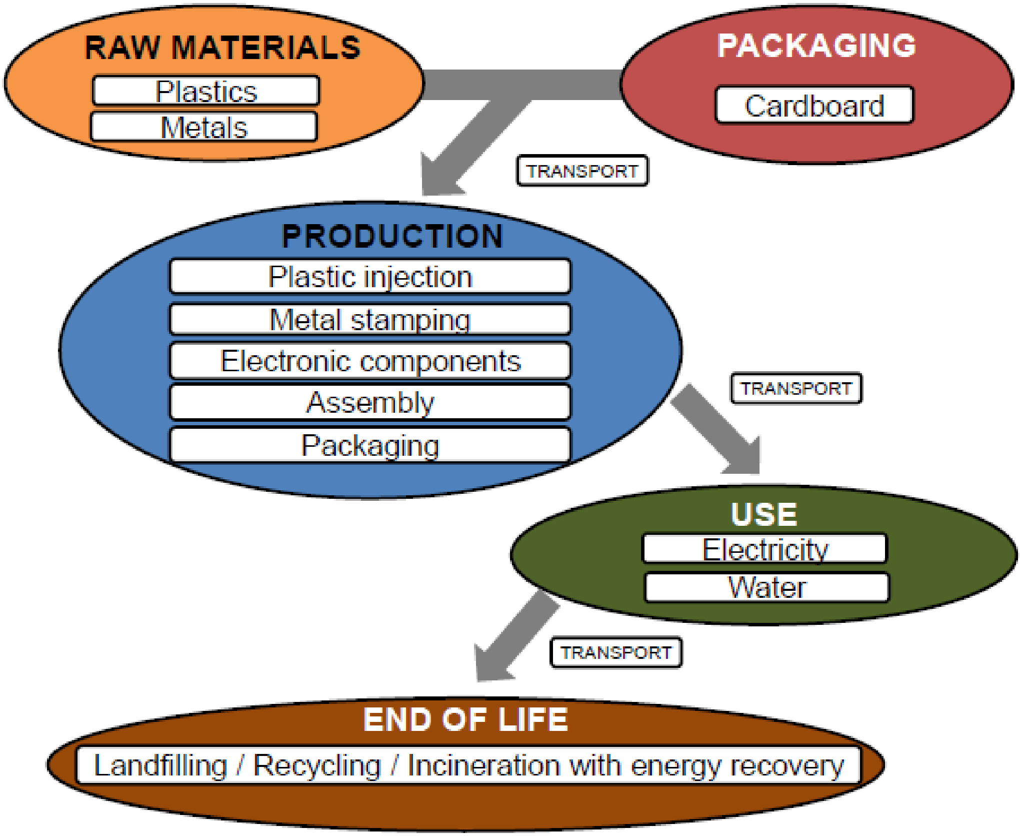
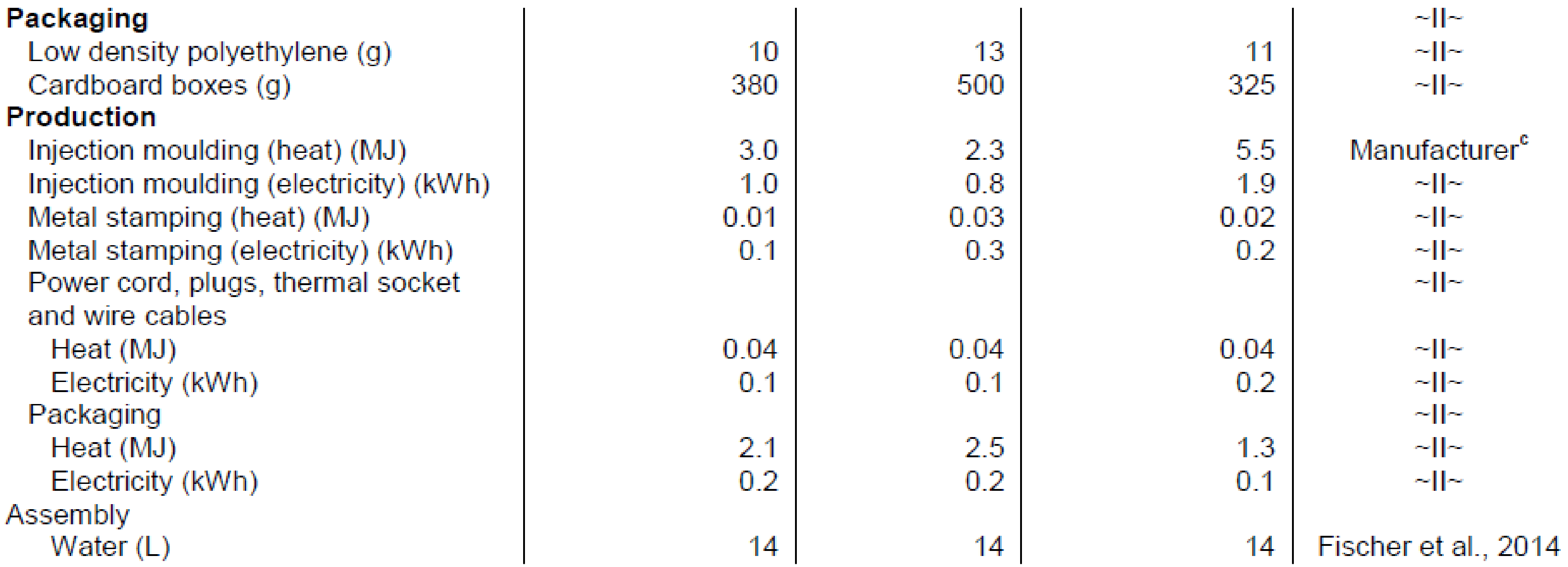


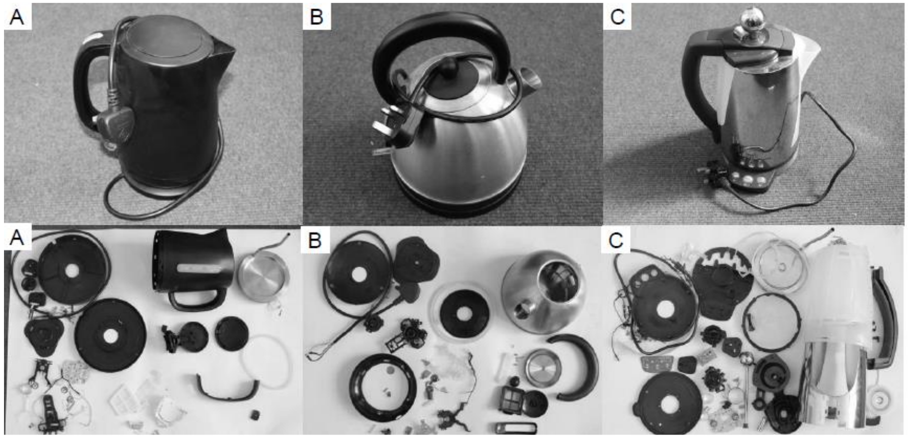
Fig. 1. System boundaries for the kettles considered in the study

Gallego Schmid, Alejandro, Life cycle environmental evaluation of kettles: Recommendations for the development of eco-design regulations in the European Union, The Science of the total environment, 2017

Electric Kettle Energy/Process Inputs



Packaging				~II~
Low density polyethylene (g)	10	13	11	~II~
Cardboard boxes (g)	380	500	325	~II~
Production				
Injection moulding (heat) (MJ)	3.0	2.3	5.5	Manufacturer[c]
Injection moulding (electricity) (kWh)	1.0	0.8	1.9	~II~
Metal stamping (heat) (MJ)	0.01	0.03	0.02	~II~
Metal stamping (electricity) (kWh)	0.1	0.3	0.2	~II~
Power cord, plugs, thermal socket and wire cables				~II~
Heat (MJ)	0.04	0.04	0.04	~II~
Electricity (kWh)	0.1	0.1	0.2	~II~
Packaging				~II~
Heat (MJ)	2.1	2.5	1.3	~II~
Electricity (kWh)	0.2	0.2	0.1	~II~
Assembly				
Water (L)	14	14	14	Fischer et al., 2014



Gallego Schmid, Alejandro, Life cycle environmental evaluation of kettles: Recommendations for the development of eco-design regulations in the European Union, The Science of the total environment, 2017

Electric Kettle Dist/Use/E-o-L

Distribution				
Raw materials: to factory (t·km)	0.1	0.2	0.2	Own assumption[d]
Packaging: to factory (t·km)	0.1	0.1	0.1	~II~
Kettle: factory to Shanghai (t·km)	0.2	0.3	0.3	~II~
Kettle: Shanghai Rotterdam (t·km)	28.4	36.0	42.0	Sea distance (2017)
Kettle: Rotherham to Munich (t·km)	1.1	1.4	1.7	Via Michellin (2017)
Kettle: distribution centre (Munich) to retailer (t·km)	0.2	0.3	0.3	Own assumption[d]
End of life: to treatment facility (t·km)	0.1	0.2	0.2	Own assumption[e]
Use				
Electricity (kWh)	829	829	532	Own measurements[b,f]
Water (L)	1542	1542	1028	Fischer et al. (2014)
End of life				
Recycling (plastics) (g)	243	191	447	Eurostat (2016b)
Recycling (metals) (g)	281	654	404	Kemna et al. (2011)
Recycling (cardboard) (g)	322	424	275	Eurostat (2016b)
Incineration with energy recovery (plastics) (g)	205	161	377	~II~
Incineration with energy recovery (cardboard) (g)	31	41	27	~II~
Landfilling (plastics) (g)	230	174	424	~II~
Landfilling (metals) (g)	15	34	21	Kemna et al. (2011)
Landfilling (cardboard) (g)	25	36	23	Eurostat (2016b)

Gallego Schmid, Alejandro, Life cycle environmental evaluation of kettles: Recommendations for the development of eco-design regulations in the European Union, The Science of the total environment, 2017

Electric Kettle LCA

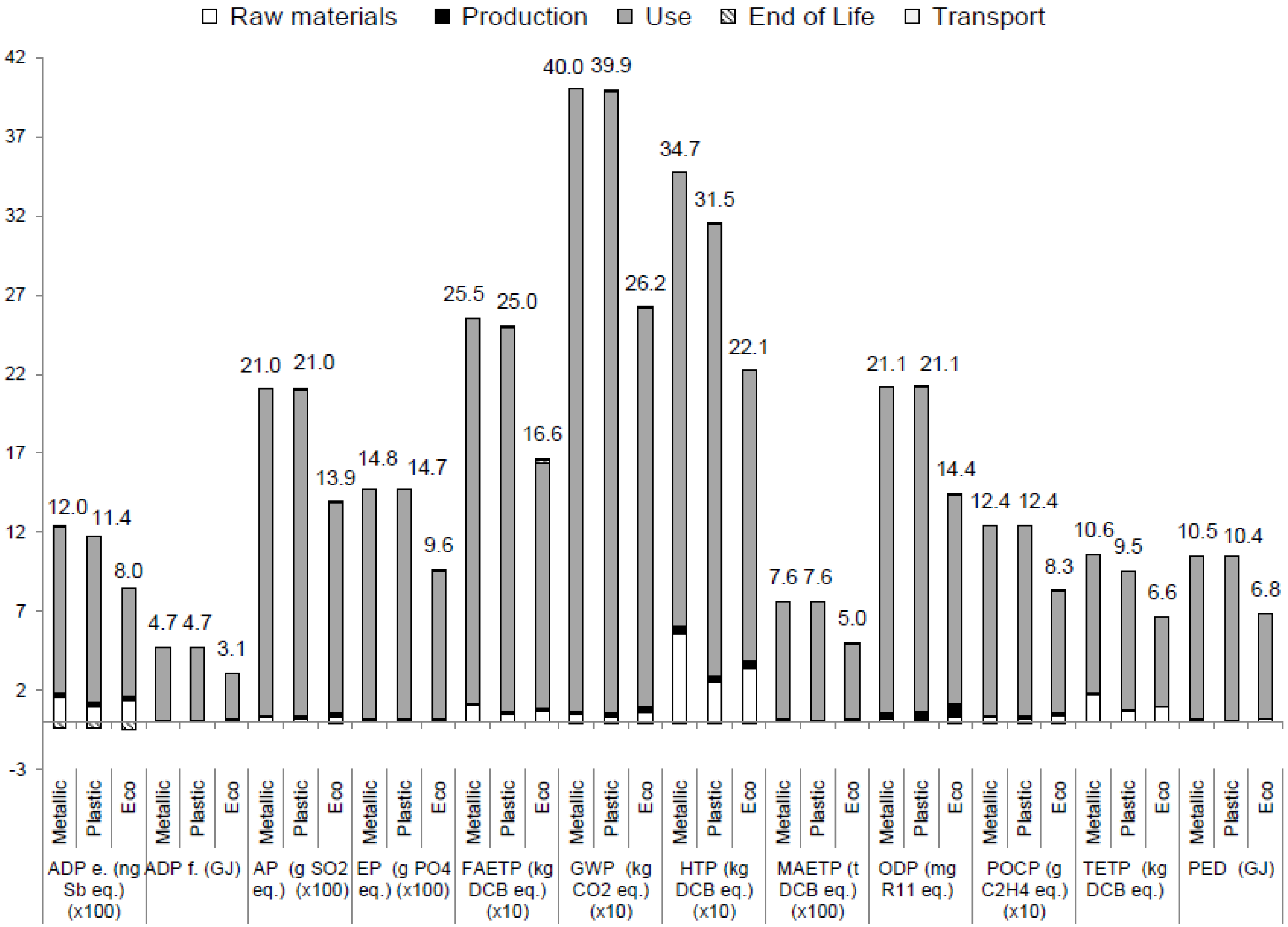


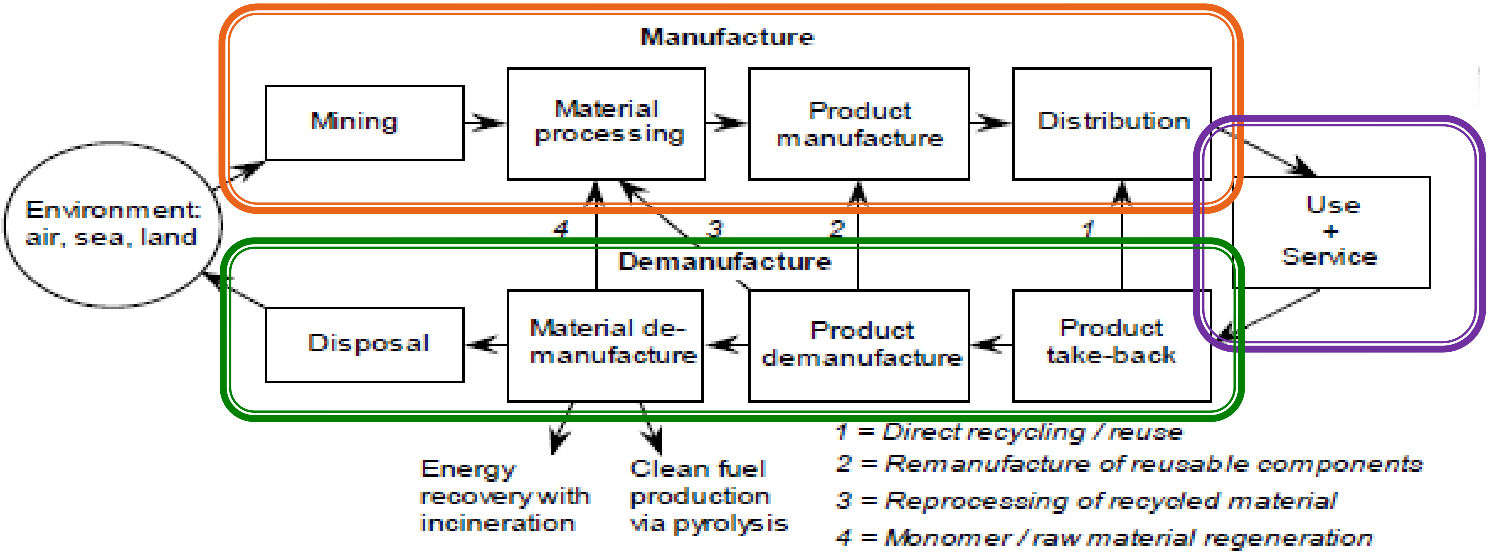
Fig. 3. Life cycle environmental impacts of plastic, metallic and eco-kettles over their average useful lifetime (4.4 years).

Gallego Schmid, Alejandro, Life cycle environmental evaluation of kettles: Recommendations for the development of eco-design regulations in the European Union, The Science of the total environment, 2017

Poll Question 4

What share of total energy is typically used by a Plug-In EV during Use-Phase?

- Resource Extraction & Manufacturing (M)
- Use-Phase (U)
- End-of-Life Phase (EoL)



1 = Direct recycling / reuse
2 = Remanufacture of reusable components
3 = Reprocessing of recycled material
4 = Monomer / raw material regeneration

Flowchart source: Bras, B. “Sustainable Design and Manufacturing Including Environmental and Social Considerations,” www.sdm.gatech.edu

Compiled by: R. Simmons, Strategic Energy Institute, Georgia Institute of Technology, 2021

LCA- Car Example

Typical breakdown for a plug-in hybrid EV

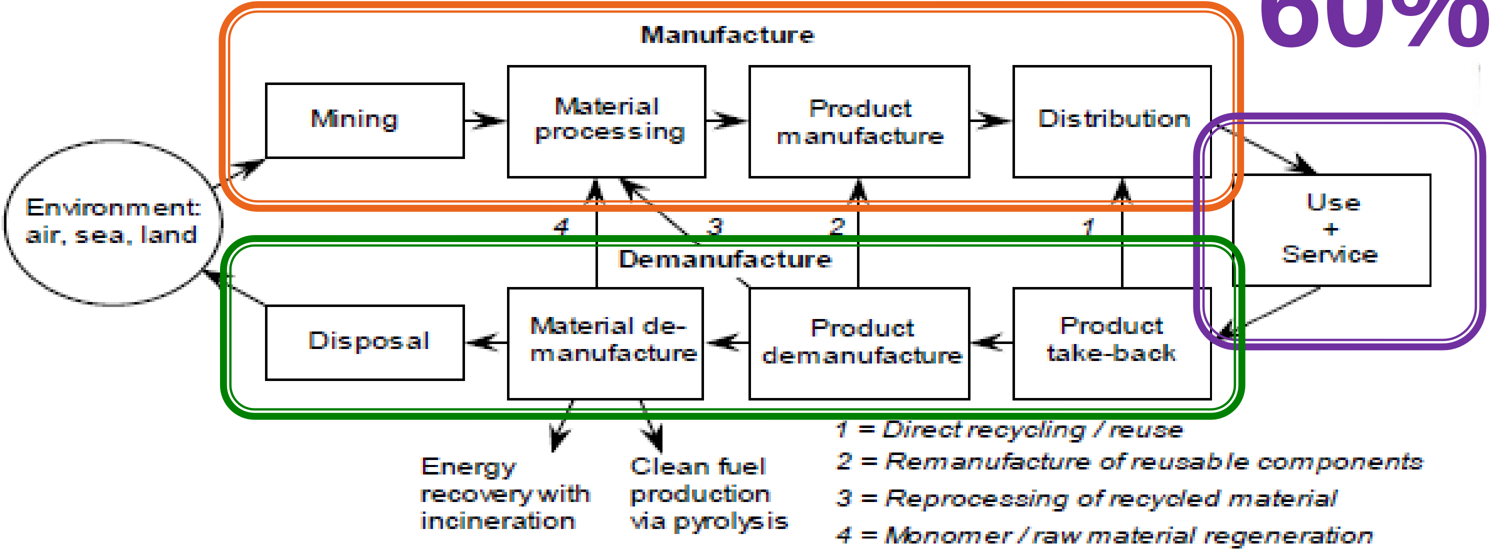
- Resource Extraction & Manufacturing

+ **40%**

- End-of-Life Phase

- Use-Phase

60%



Flowchart source: Bras, B. “Sustainable Design and Manufacturing Including Environmental and Social Considerations,” www.sdm.gatech.edu

Compiled by: R. Simmons, Strategic Energy Institute, Georgia Institute of Technology, 2021

LCA- Car Example

Typical energy breakdown for a conventional ICE car

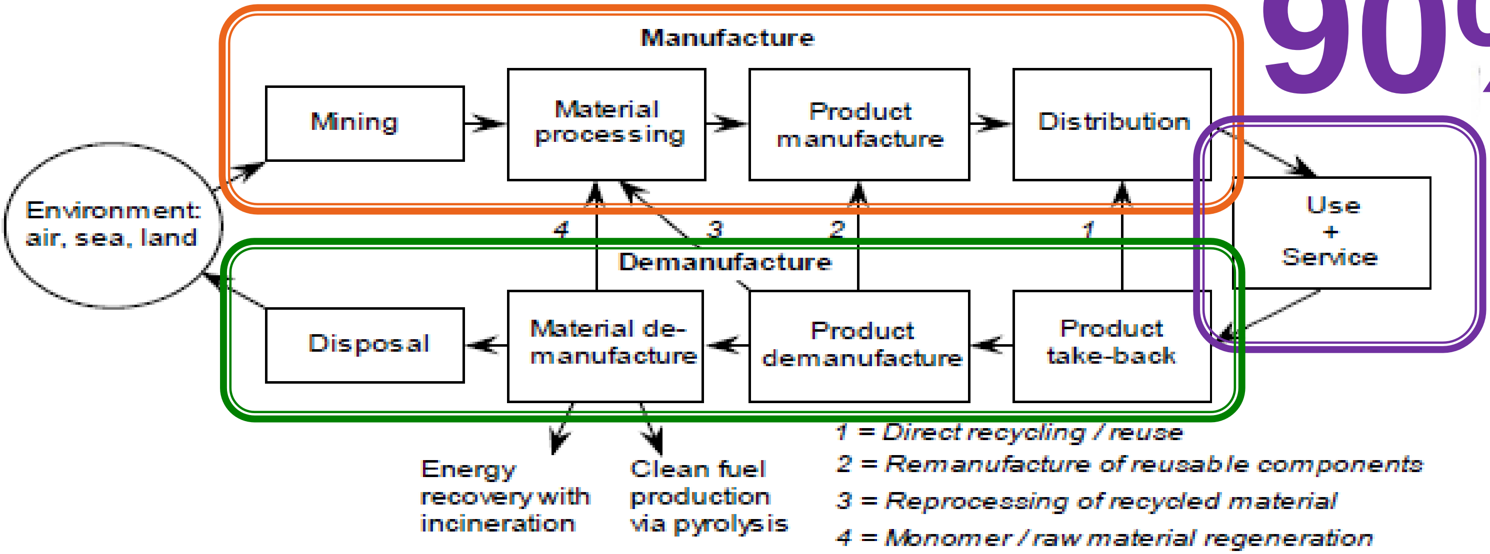
- Resource Extraction & Manufacturing

  \+ **10%**

- End-of-Life Phase

- Use-Phase

90%



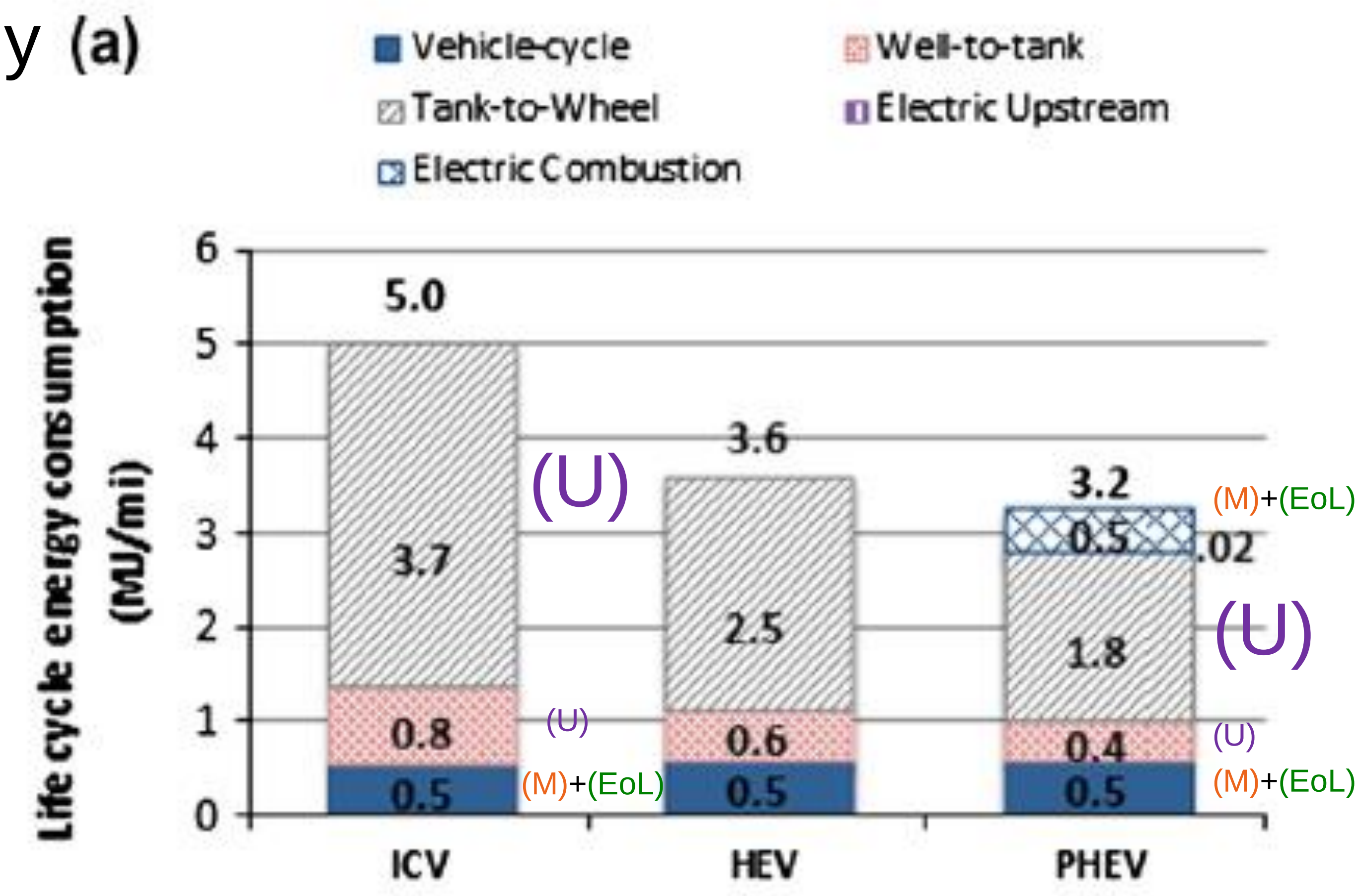
Flowchart source: Bras, B. "Sustainable Design and Manufacturing Including Environmental and Social Considerations," www.sdm.gatech.edu

Compiled by: R. Simmons, Strategic Energy Institute, Georgia Institute of Technology, 2021

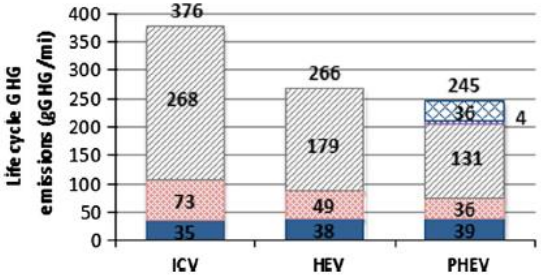
Energy/Emissions LCA for cars

LCA Energy

(M) Mfg
(U) Use
(EoL) End of Life



LCA Emissions



Lewis, AM, Jarod CK, & Keoleian, GK. "Vehicle lightweighting vs. electrification: life cycle energy and GHG emissions results for diverse powertrain vehicles." *Applied Energy* 126 (2014): 13-20.

Surprising Fact

- 99.3% of Lead Acid Batteries are recycled in the US
- 5% of Lithium Ion Batteries are recycled in the US

Sources: DOE. 2019 and wastedive.com

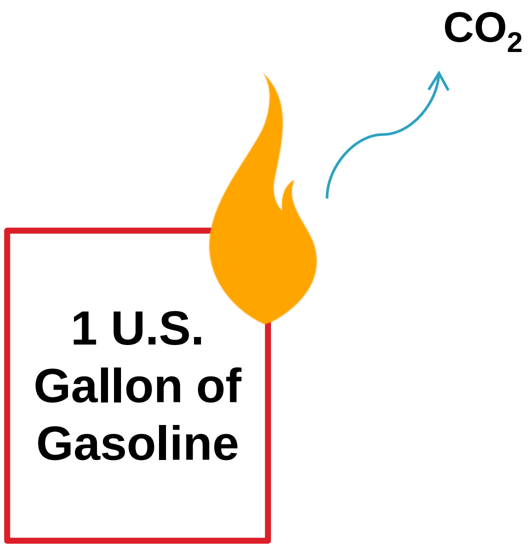
https://www.energy.gov/sites/prod/files/2019/07/f64/112306-battery-recycling-brochure-June-2019%202-web150.pdf

https://www.wastedive.com/news/lithium-ion-battery-recycling-ev-li-cycle-retriev/608778/#:~:text=The%20industry%20is%20familiar%20with,recycled%2C%20according%20to%20the%20DOE.

Poll Question 5

How much CO_2 is emitted from the combustion of 1 gallon of gasoline?

Note: 1 gallon of gasoline weighs about 6.3 lbs.



CO_2

1 U.S. Gallon of Gasoline

A. Less than 3 lbs

B. Between 3 and 7 lbs

C. Between 7 and 16 lbs

D. More than 16 lbs

Calculating the CO_2 released by 1 gallon of gasoline

Consider the combustion reaction of octane, a primary constituent of gasoline:

$$C_8H_{18} + 12.5(O_2 + 3.76\ N_2) \rightarrow 8CO_2 + 9H_2O + 47N_2$$

1 mol $C_8H_{18} \approx 114$ g/gmol

1 gallon ≈ 6.3 lbs = 2860 g

Thus, we have 2860/114 mols of fuel = 25.1 mols fuel

1 mol $CO_2 \approx 44$ g/gmol

The reaction produces → 8 mols CO_2 for every mol of fuel

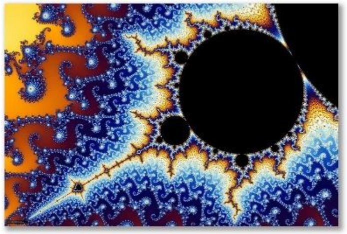
This equals 8*25.1 = 200.8 mols CO_2

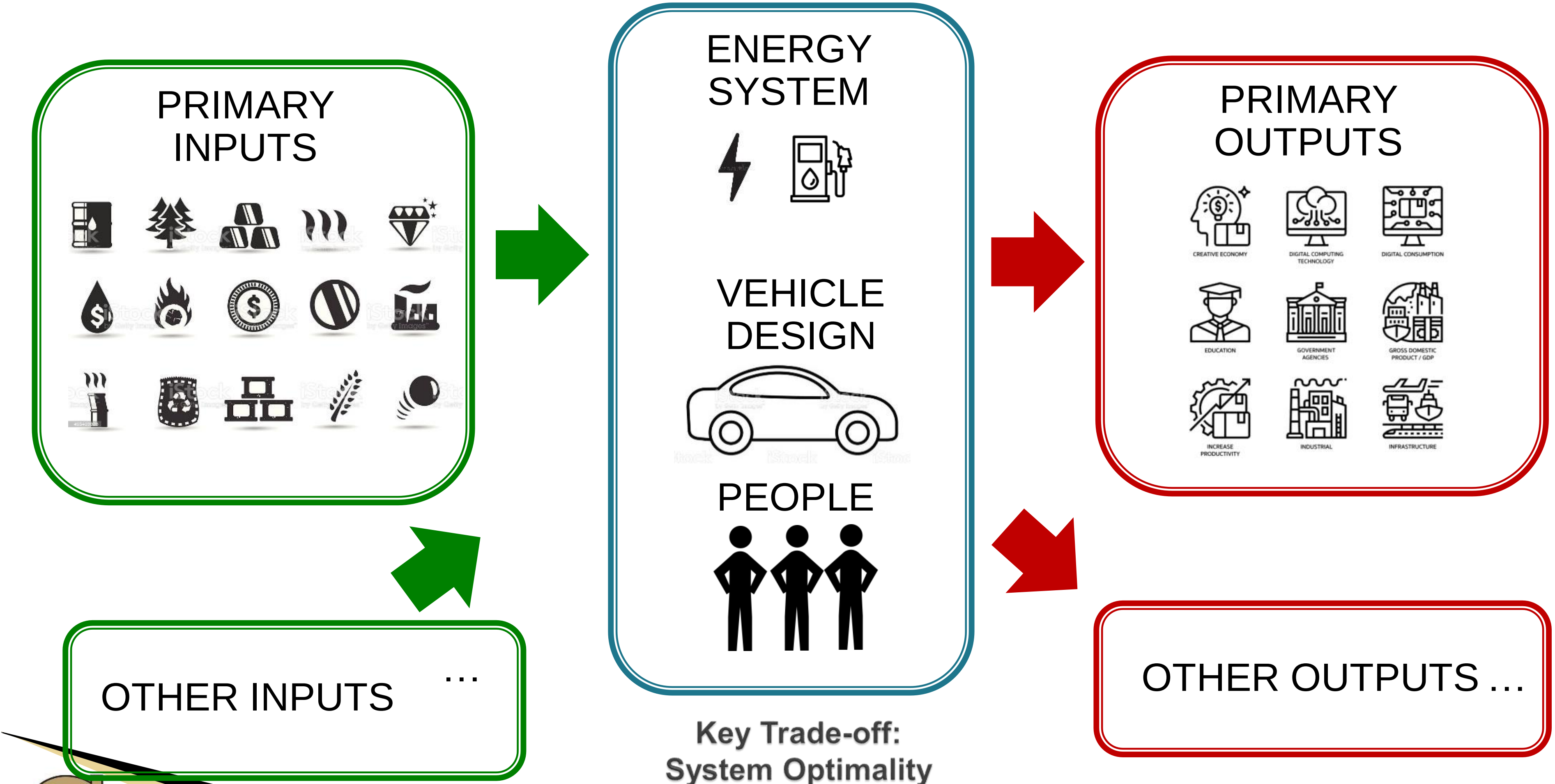
→ 200.8 mols * 44g/gmol ≈ 8835 g ≈ **19.4 lbs**

CO_2 Tailpipe Emissions Fuel Type	CO_2 Emissions Kg CO_2/Liter of Fuel	CO_2 Emissions Lbs CO_2/gallon of fuel
Gasoline	2.3 kg/L	19.4 lbs/gal
Liquid Petroleum Gas (LPG)	1.6 kg/L	12.7 lbs/gal
Diesel	2.7 kg/L	22.2 lbs/gal

R. Simmons, Strategic Energy Institute, Georgia Institute of Technology, 2021

Engineering 101:
System Boundary is Key





PRIMARY INPUTS

OTHER INPUTS …

ENERGY SYSTEM

VEHICLE DESIGN

PEOPLE

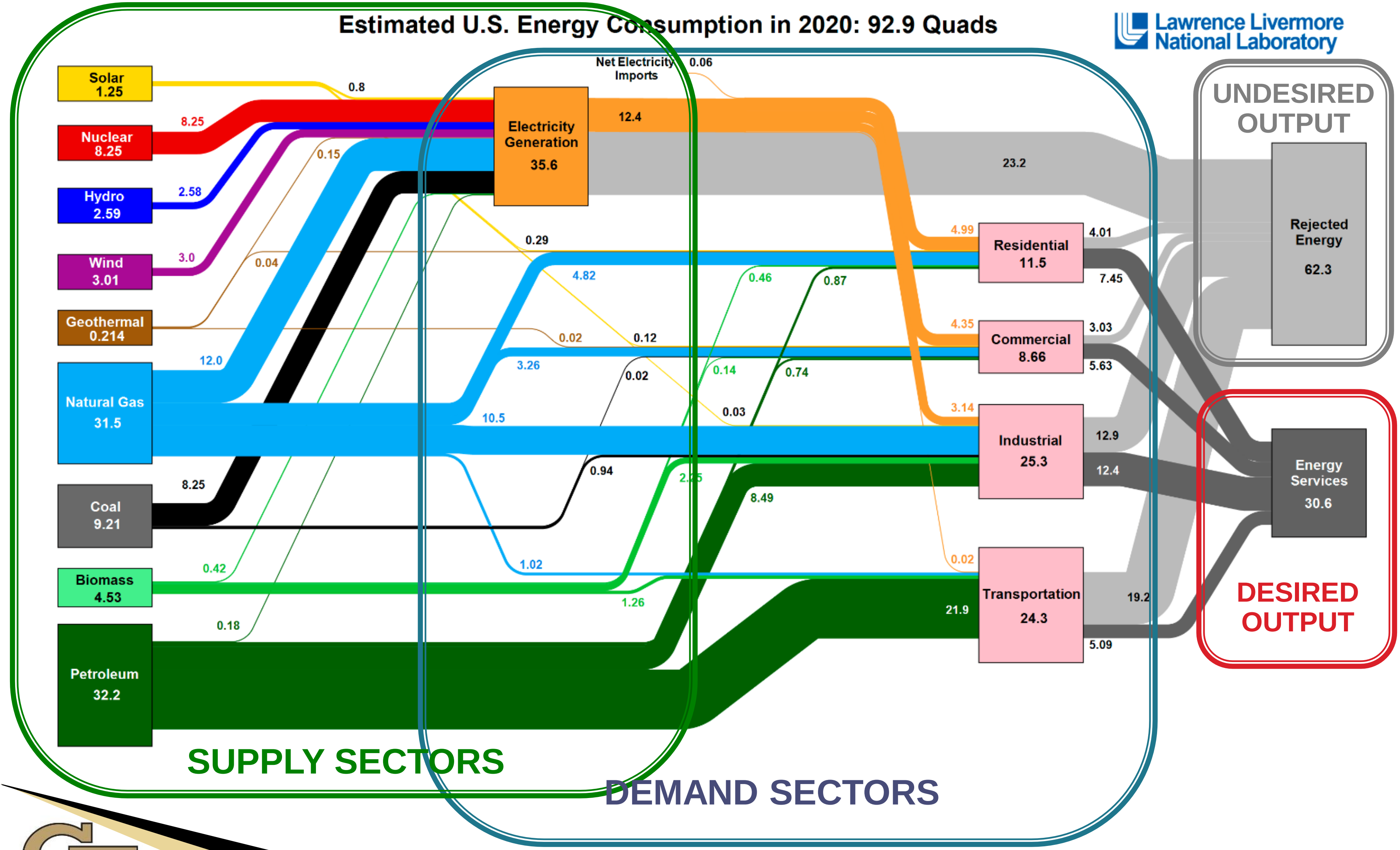
PRIMARY OUTPUTS

OTHER OUTPUTS …

Key Trade-off:
System Optimality
AND
Complexity/Cost

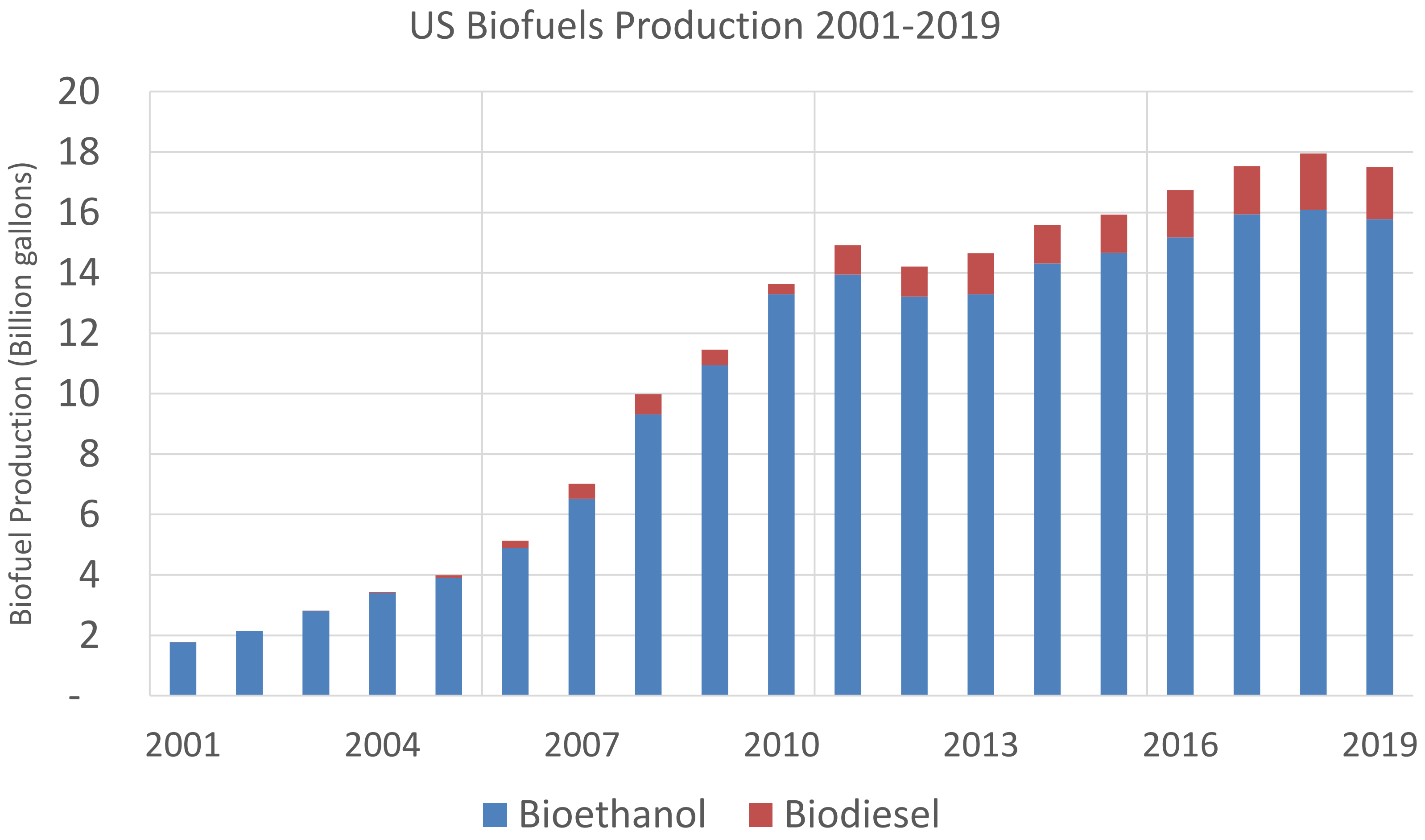
R. Simmons, Strategic Energy Institute,
Georgia Institute of Technology, 2022

System Boundary: US Economy



Compiled by R. Simmons, Strategic Energy Institute, Georgia Institute of Technology, 2021

U.S. Biofuels Production



Bioethanol: 15.8 BGPY
Biodiesel: 1.8 BGPY
All U.S. Ground Fuels:215 BGPY
Share that is Biofuels: 8%

Source: USDA Economic Research Service, U.S. Bioenergy Statistics, 2021
https://www.ers.usda.gov/data-products/us-bioenergy-statistics/

Advanced Biofuels

Major 2nd Generation Biofuel Conversion Pathways:

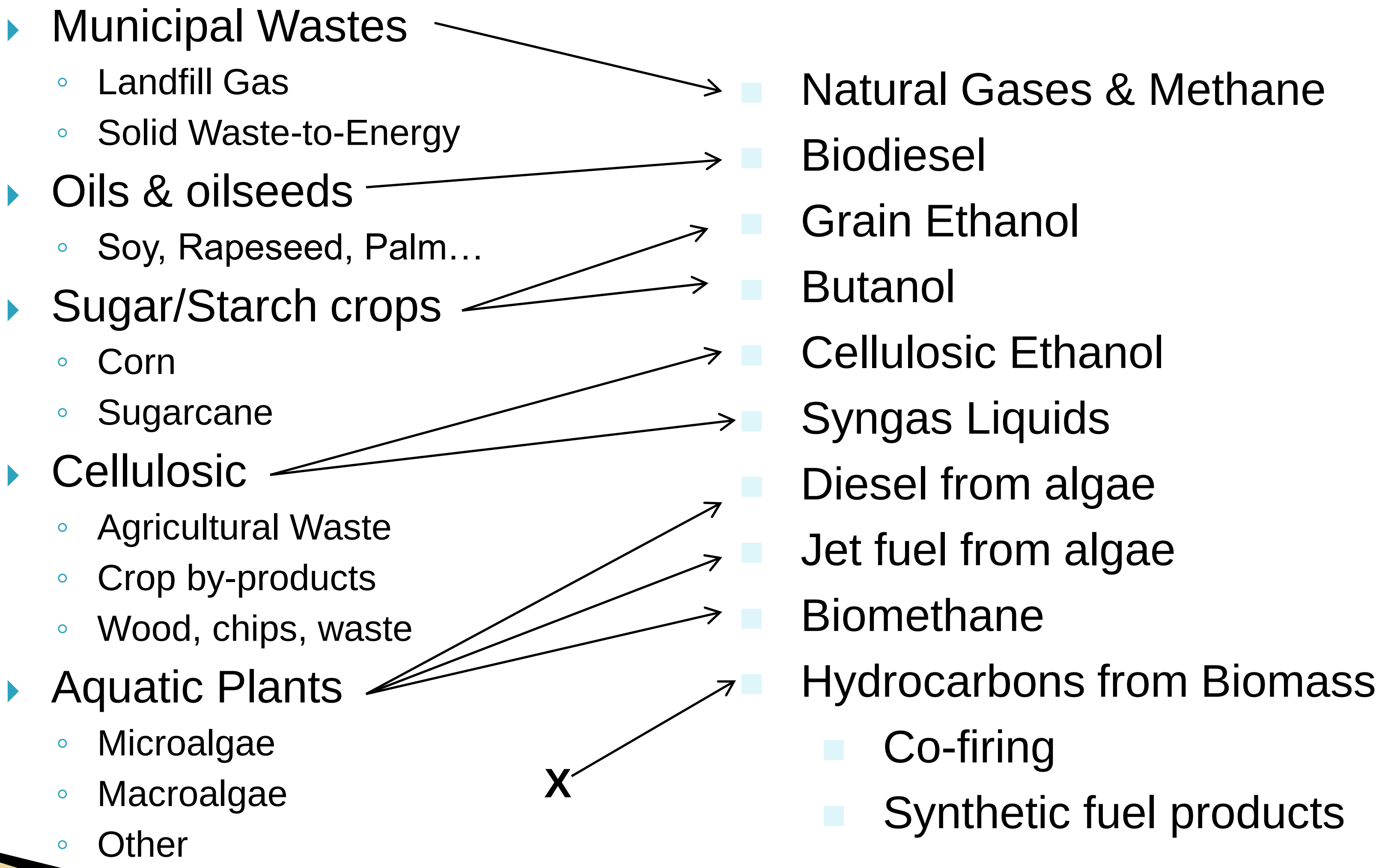
- Biochemical
  - Pre-treatment of biomass into cellulose, hemicellulose & lignin
  - Enzymatic hydrolysis
  - Biological conversion of sugars to alcohol via fermentation

- Thermochemical
  - Heating in the absence of air/oxygen
  - Extraction of hydrocarbons into liquid (pyrolysis) or gas (syngas)
  - Reformation, purification & production of synthetic hydrocarbons

Source: “Understanding the Global Energy Crisis,” Coyle & Simmons, Purdue University Press, 2014.

https://docs.lib.purdue.edu/purduepress_ebooks/29/

Some 2nd Generation Biomass Feedstocks & Their Common Fuels



- Municipal Wastes
  - Landfill Gas
  - Solid Waste-to-Energy
- Oils & oilseeds
  - Soy, Rapeseed, Palm…
- Sugar/Starch crops
  - Corn
  - Sugarcane
- Cellulosic
  - Agricultural Waste
  - Crop by-products
  - Wood, chips, waste
- Aquatic Plants
  - Microalgae
  - Macroalgae
  - Other

- Natural Gases & Methane
- Biodiesel
- Grain Ethanol
- Butanol
- Cellulosic Ethanol
- Syngas Liquids
- Diesel from algae
- Jet fuel from algae
- Biomethane
- Hydrocarbons from Biomass
  - Co-firing
  - Synthetic fuel products

More info at source: NREL website, http://www.nrel.gov/biomass/pdfs/39436.pdf

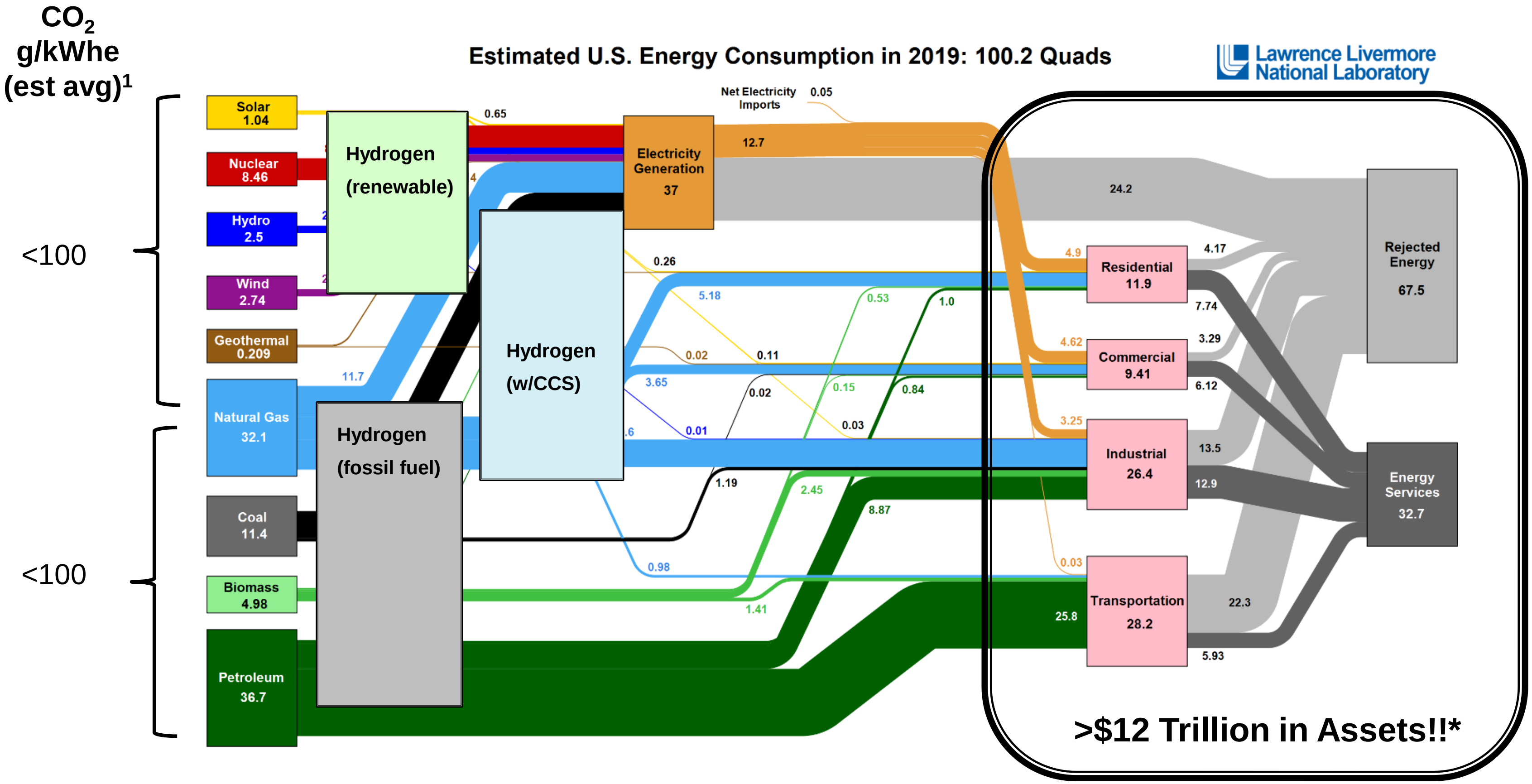
Common biofuels & their benefits…

Biofuel & Feedstock	**Energy Balance**	**GHG reduction**
Ethanol from Corn	1.4	20%
Ethanol from Sugarcane	8.0	60%
Cellulosic Ethanol	*6 - *14	*70-*90%
Biodiesel from Rapeseed	2.5	40%
Biodiesel from Soy	3.2	40%

Average Values from Published Literature,
*Cellulosic Ethanol Figures are estimates

R. Simmons, Strategic Energy Institute, Georgia Institute of Technology, 2022

Why is Hydrogen so enticing?



Estimated U.S. Energy Consumption in 2019: 100.2 Quads

>$12 Trillion in Assets!!*

- Hydrogen can be an energy carrier or converted directly into electricity
- Hydrogen can be combusted directly in Gas Turbines
- Hydrogen can be combined with Carbon and synthesized into renewable fuels
- Hydrogen can help attain net zero CO2 emissions

Source: Estimated Energy Use, US DOE, Lawrence Livermore National Lab, 2019 https://flowcharts.llnl.gov/

Source*: Simmons and Metz, Georgia Tech Strategic Energy Institute, 2019

Why is Hydrogen so enticing?

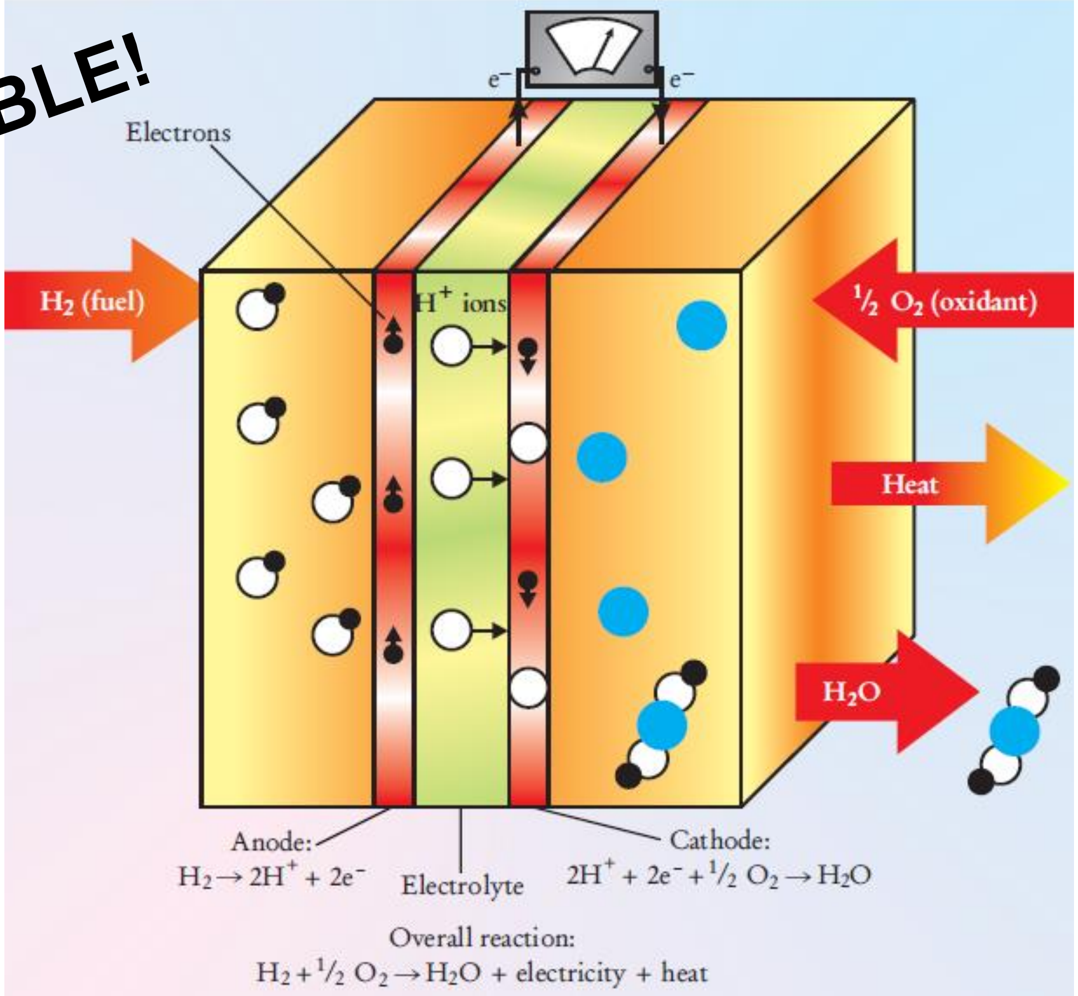
REVERSIBLE!

$\eta_{12} \approx 0.65$

(FC stack generating electricity)

$\eta_{21} \approx 0.90$

(Electrolysis of water to produce H_2)



- **Fuel Cells (FCs) enable bi-directional conversion between hydrogen and electricity**

SourceHydrogen: Fuel of the Future? Joan Ogden, Physics Today 55, 4, 69 (2002)

H_2: So what's the catch?

- Technical Challenges
  - Conversion
  - Storage
  - Safety
  - Distribution
  - Combustion characteristics
  - Diffusion rate
  - Fungibility (i.e., "drop-in")
  - …
- Economic Challenges
  - Capital cost
  - Feedstock cost
  - Storage cost & Leakage Loss
  - Delivery cost
  - Infrastructure implications
  - …
- Environmental Challenges
  - Net Energy & CO_2 impact
  - LifeCycle Assessment (LCA)
  - Human Health
  - Ecosystem Quality
  - Resource Depletion
  - Full Cost Accounting is complex

Hydrogen: Fuel of the Future? Joan Ogden, Physics Today 55, 4, 69 (2002)

https://h2tools.org/bestpractices/hydrogen-compared-other-fuels

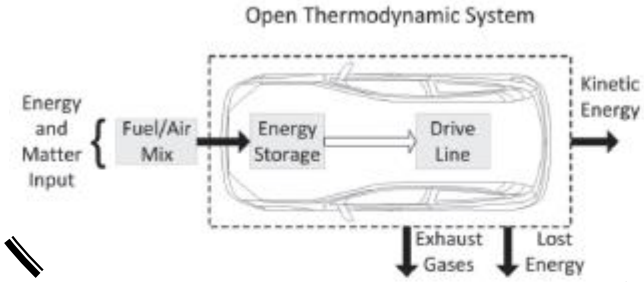
How Green are Electric Cars?

Comparing vehicles using dissimilar energy sources

LARGELY INDEPENDENT OF LOCALITY

Ext

INTERNAL COMBUSTION ENGINE VEHICLE



W_{out}

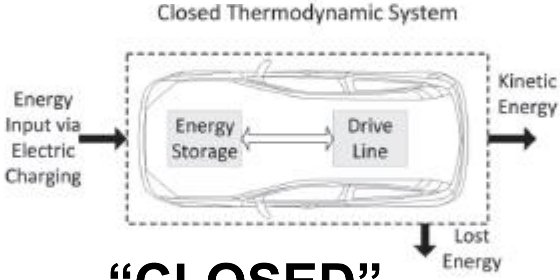
“OPEN”

Again- Consider the system boundary!
MPG ≠ MPGe

HIGHLY DEPENDENT ON LOCALITY

Extent of C

ELECTRIC VEHICLE



W_{out}

“CLOSED”

Comparison of Energy Use by Vehicle Type

VEHICLE TYPE DRIVING CYCLE TEMPERATURE

Modeling is based upon representative vehicles

- Conventional
- **ICE-SI** (Toyota Corolla, Honda Civic, Ford Focus)
- **ICE-CI** (Volkswagen Jetta)

- Hybrid
- **HEV** (Toyota Prius)

- Plug-in hybrid
- **PHEV40** (Chevrolet Volt)

- Electric Vehicle
- **EV** (Nissan Leaf)

R. Simmons, Georgia Tech Strategic Energy Institute, 2022

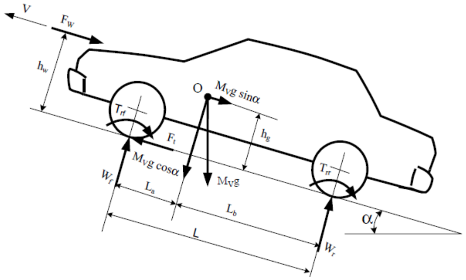
Model Inputs

VEHICLE TYPE DRIVING CYCLE TEMPERATURE

Specifications	Vehicle Type:	ICE-SI[7]	ICE-CI[8]	HEV-PS[9]	PHEV-40[10]	EV-PAC[11]
	Source:	[8a,b,c]	[8d]	[8a]	[8e]	[8f]
Vehicle Attribute						
Vehicle mass[1] [kg]		1438	1595	1519	1857	1610
Drag coefficient		0.29	0.30	0.25	0.29	0.28
Frontal area [m^2]		2.12	2.10	2.17	2.16	2.31
Engine power[2] [kW]		108	104	73	63	-
Electric motor power[2] [kW]		-	-	60	111	80
Total vehicle power[2] [kW]		108	104	100	111	80
Battery mass[3] [kg]		-	-	45	198	294
Battery capacity[3] [kWh]		-	-	1.3	16.5	24.0
Fuel economy[4] [US[5]mpg]		31.4	34.0	50.0	37.0	-
Fuel consumption[4] [L/100km]		7.5	6.9	4.7	6.4	-
Elec. consumption[6] [Wh/km]		-	-	-	214	184
Equiv. fuel econ.[6] [mpge]		-	-	-	98	114
All electric range [km(mi)]		-	-	-	64(40)	134(84)

Simmons, Richard A. "A techno-economic investigation of advanced vehicle technologies and their impacts on fuel economy, emissions, and the future fleet." PhD diss., Purdue University, 2015.

Propulsion model



General dynamic force balance:

$$F_{tractive} = F_{rolling\_resistance} + F_{aero\_drag} + F_{hill\_climb} + F_{acceleration} \quad \text{Eq. (9)}$$

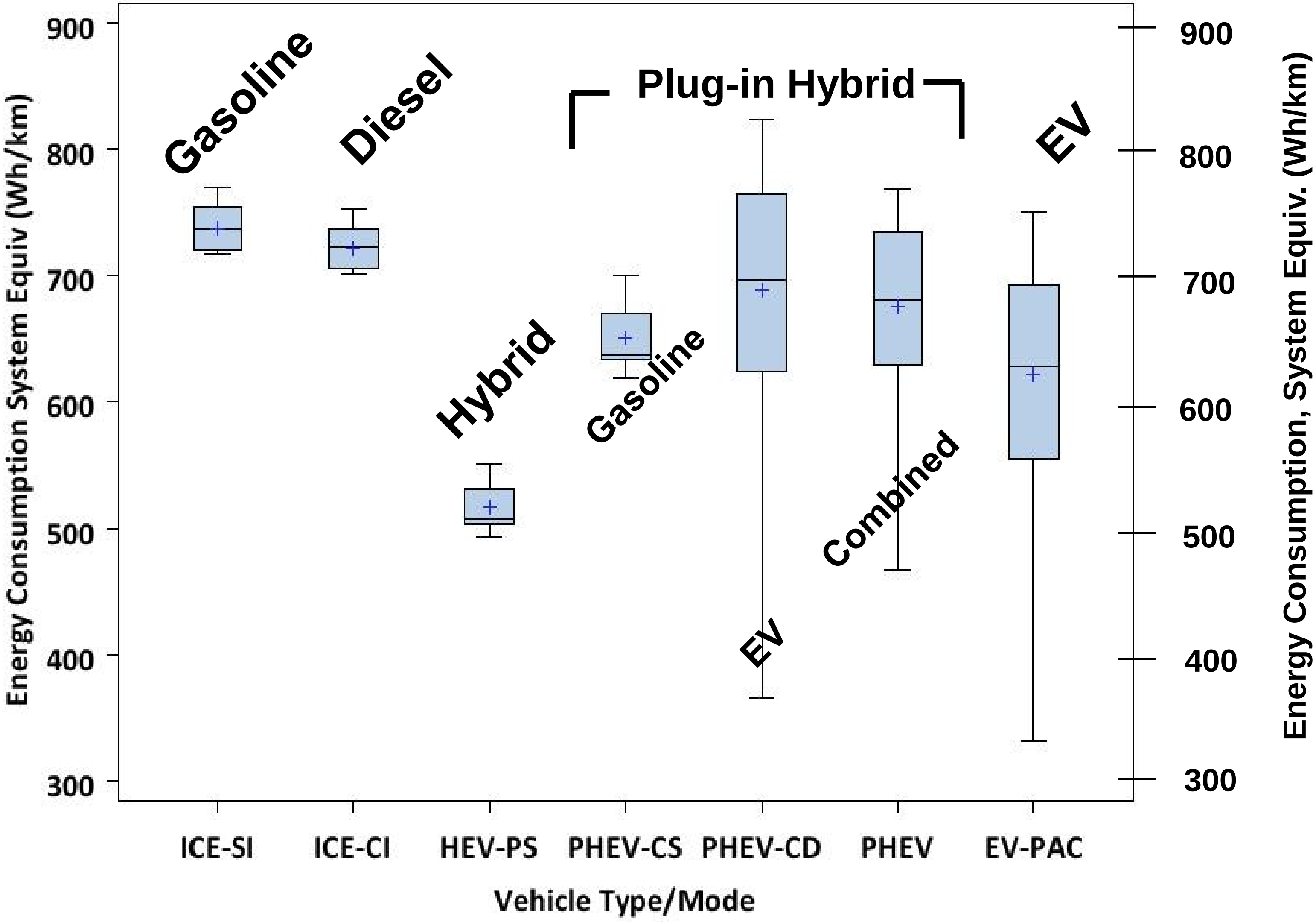
$$F_{tractive} = m_{veh} \cdot g(C_0 + C_1 v_{veh}) + 0.5\rho_{air} C_{Drag} A_F v_{veh}^2 + m_{veh} g \cdot sin\theta_{grade} + m_{veh} \cdot a_{veh}$$

Eq. (10)

$$P_{tractive} = F_{tractive} \cdot v_{veh}(t) \quad \text{Eq. (11)}$$

Simmons, Richard A. "A techno-economic investigation of advanced vehicle technologies and their impacts on fuel economy, emissions, and the future fleet." PhD diss., Purdue University, 2015.

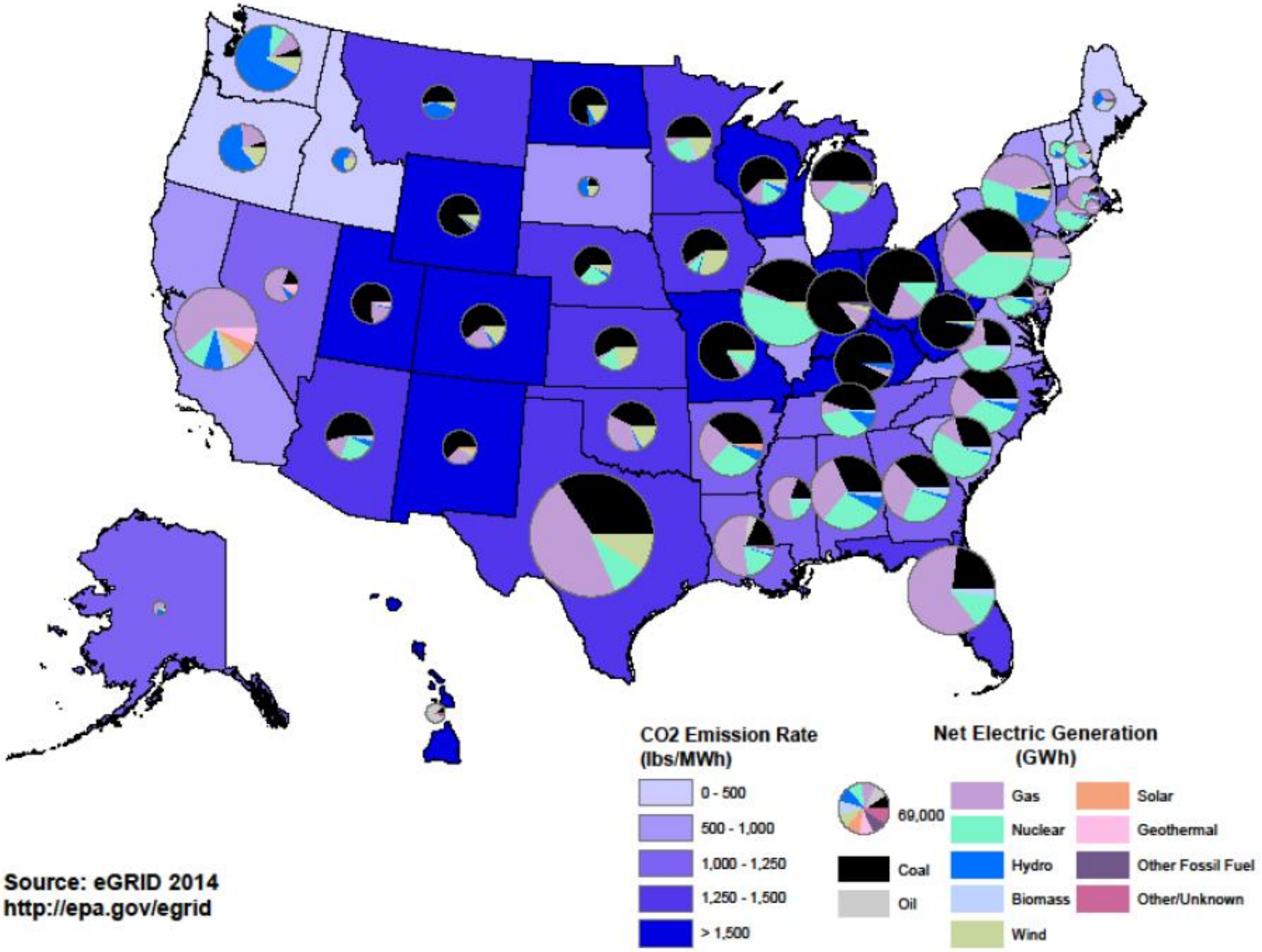
Energy use depends on vehicle type and locality



Simmons, Richard A. "A techno-economic investigation of advanced vehicle technologies and their impacts on fuel economy, emissions, and the future fleet." PhD diss., Purdue University, 2015.

State-by-state generation by source 2014

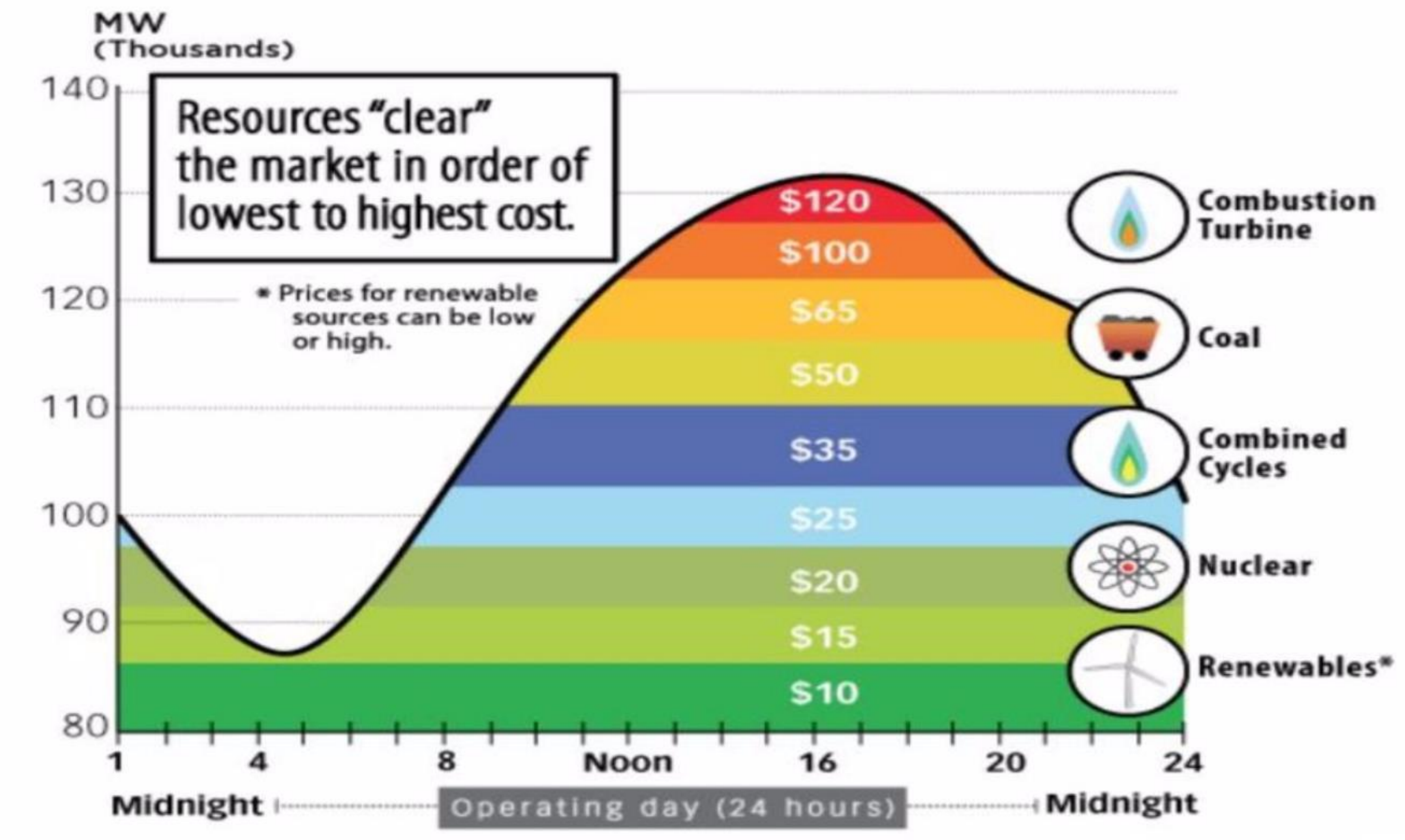
12. Generation by Fuel Type and CO_2 Emission Rates (eGRID2014v2)



Source: eGRID 2014
http://epa.gov/egrid

(illustrative)

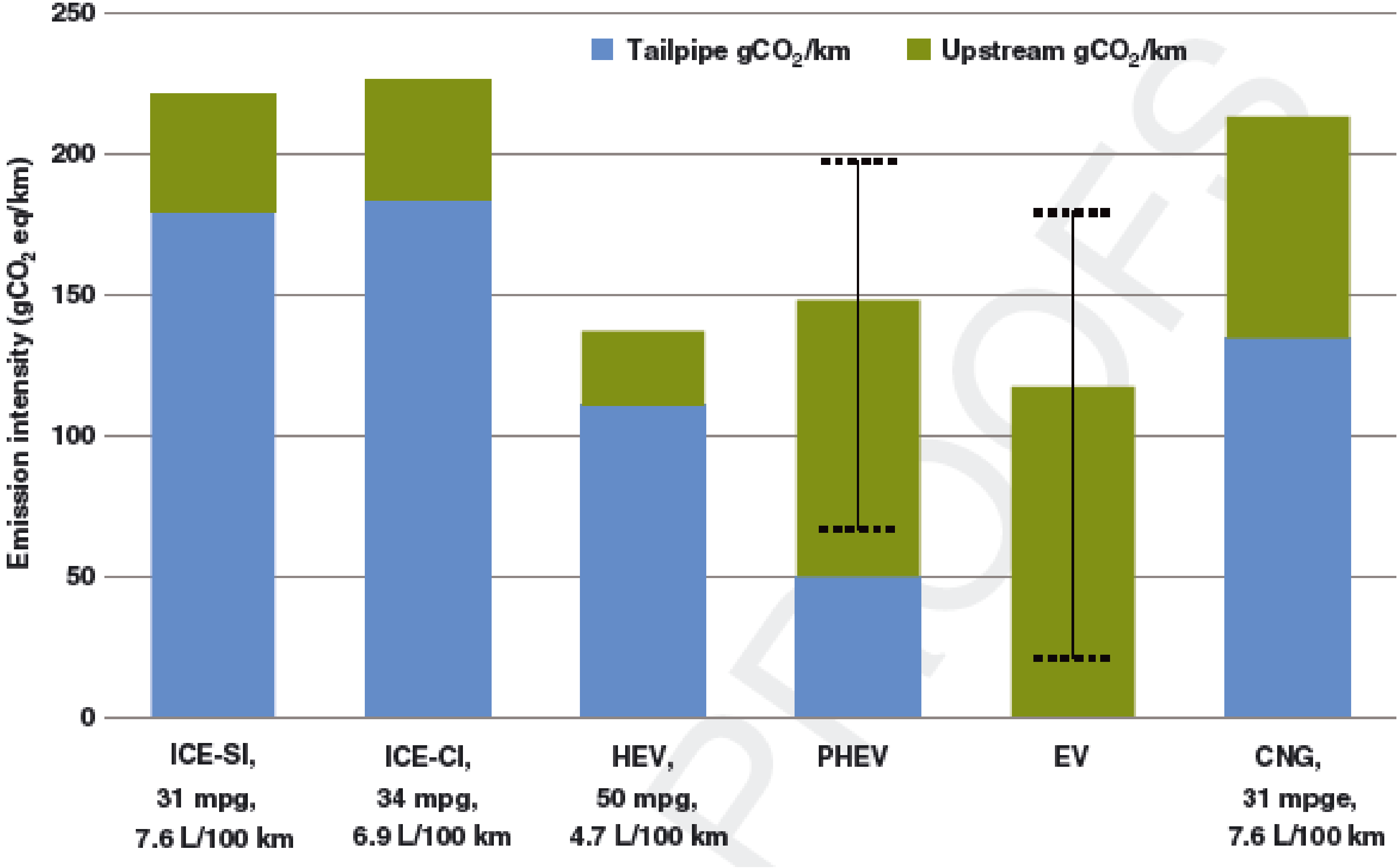
Example Grid Dispatch Curve



Important Note: This is MARGINAL cost per unit (i.e., doesn't consider capex), Not Levelized Cost, or LCOE

Graphic Source: Northbridge Energy Partners, P. Kelly-Detwiler

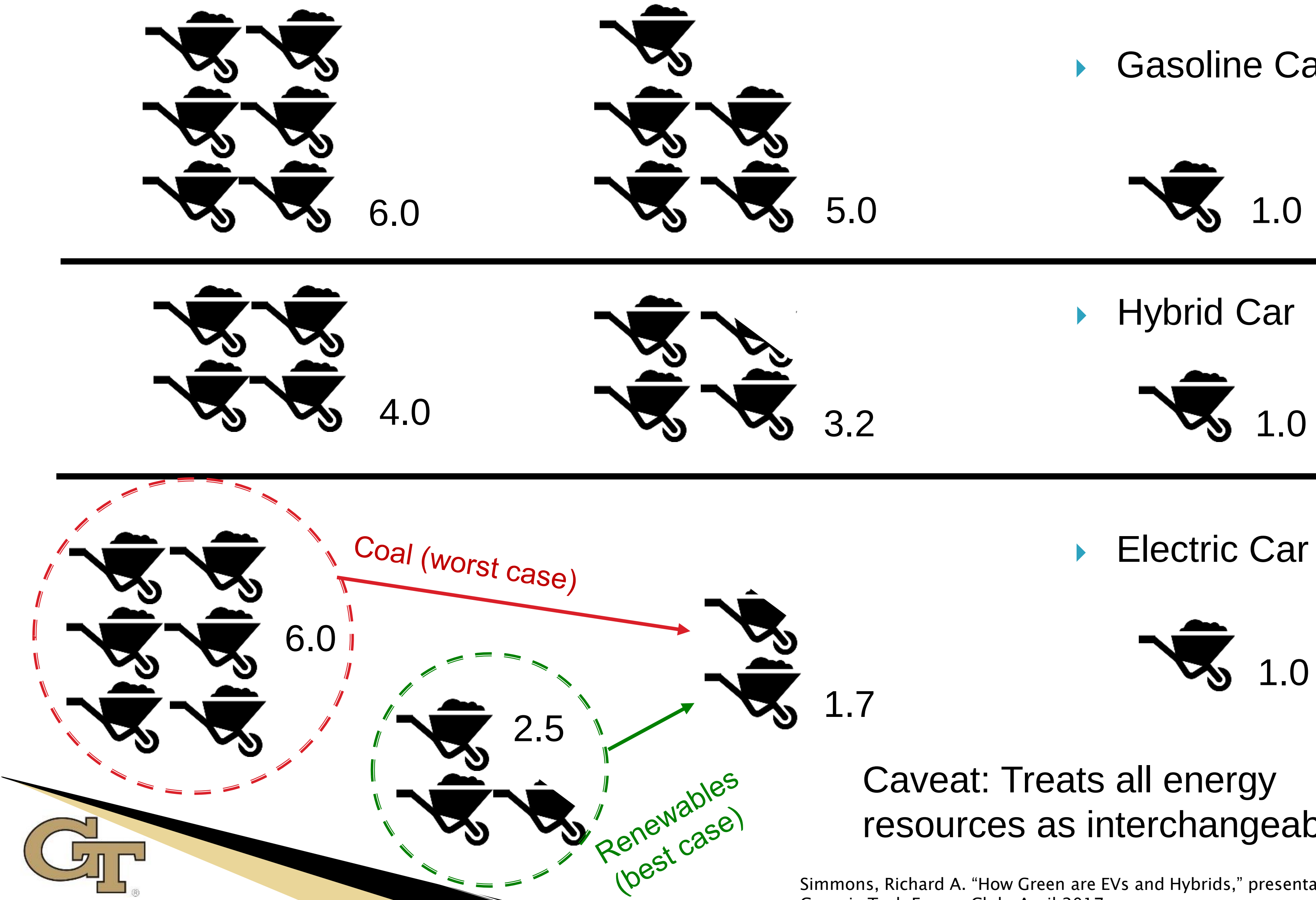
Use phase emissions depend on: vehicle type and locality



Wide variation for grid-recharged EVs

RA Simmons, SV Garimella. Electric, hybrid and advanced vehicles: finding a lane on the road ahead. In: Yan, J. ed. Handbook of Clean Energy Systems. 2015. John Wiley & Sons, pp. 2279-99.

Upstream energy impact



	Resource	On-board	Delivered Work
Gasoline Car	6.0	5.0	1.0
Hybrid Car	4.0	3.2	1.0
Electric Car	6.0 2.5	1.7	1.0

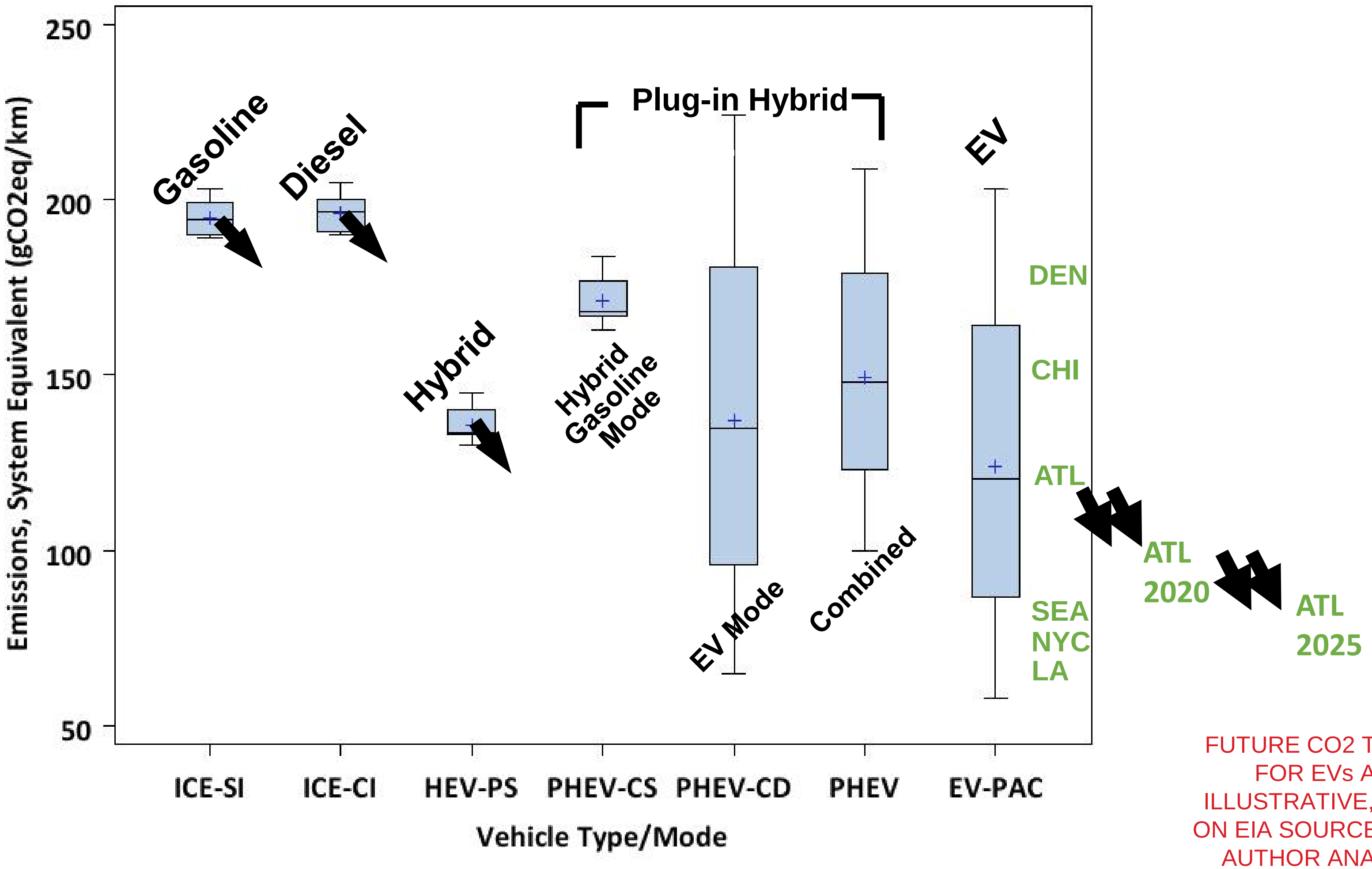
Coal (worst case)

Renewables (best case)

Caveat: Treats all energy resources as interchangeable

Simmons, Richard A. “How Green are EVs and Hybrids,” presentation, Georgia Tech Energy Club, April 2017

System-Equivalent CO_2 Emissions by Vehicle Type and Locality



FUTURE CO2 TRENDS FOR EVs ARE ILLUSTRATIVE, BASED ON EIA SOURCE DATA & AUTHOR ANALYSIS

- Total CO_{2eq} emissions from extracted resource thru use-phase consumption
- Does NOT include CO2 associated with vehicle manufacturing

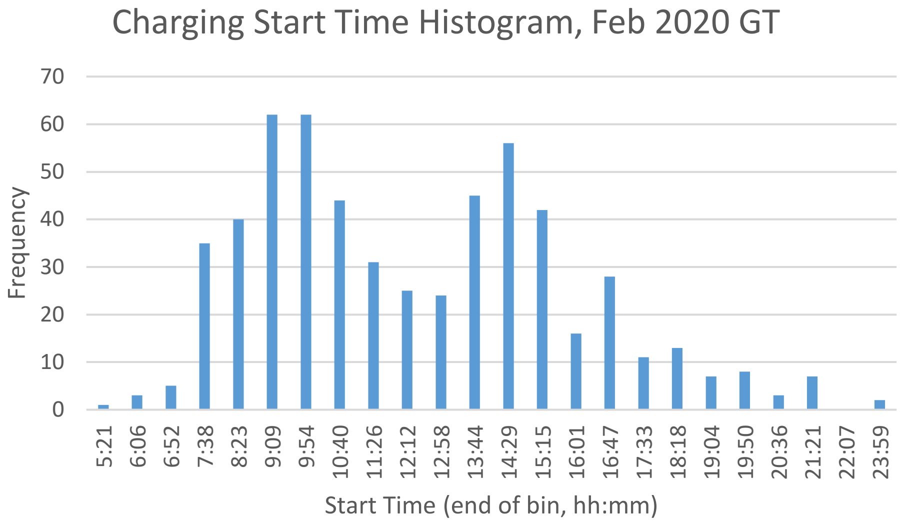
Notes: Grid data as of 2014.

Simmons, Richard A. "A techno-economic investigation of advanced vehicle technologies and their impacts on fuel economy, emissions, and the future fleet." PhD diss., Purdue University, 2015.

Additional Info, As of 2020: https://cepl.gatech.edu/projects/Drawdown-Georgia

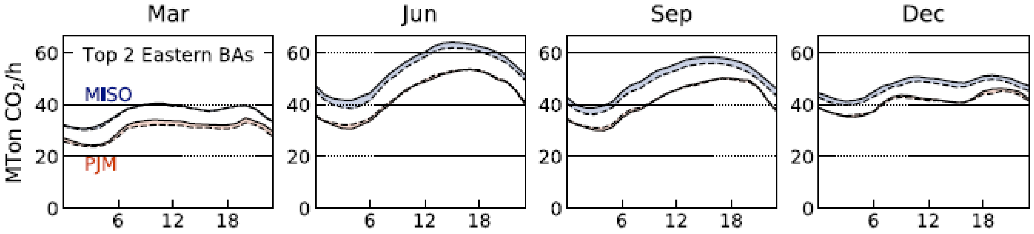
How Green are Electric Cars?

- EV Charging fn(time)
  - Sample Data
  - Georgia Tech Daytime Workplace Charging



R. Simmons, Strategic Energy Institute, Georgia Institute of Technology, 2022

- Emissions fn(time,location)
  - Top 2 Eastern Balancing Authorities
  - Typical Marginal CO2 emissions
  - Seasonal and Hourly



Tracking emissions in the US electricity system
Jacques A. de Chalendar, John Taggart, Sally M. Benson
Proceedings of the National Academy of Sciences Dec 2019, 116 (51) 25497-25502; DOI: 10.1073/pnas.1912950116

Resources of Interest

LCA examples

- e-Scooters
  - Hollingsworth, Joseph, Brenna Copeland, and Jeremiah X. Johnson. "Are e-scooters polluters? The environmental impacts of shared dockless electric scooters." *Environmental Research Letters* 14, no. 8 (2019): 084031.
- Reusable vs. Disposable Cups
  - Hocking, M. Reusable and disposable cups: An energy-based evaluation. Environmental Management (1994) 18(6):889-899.
  - Woods, L, Bakshi, B. Reusable vs. disposable cups revisited: guidance in life cycle comparisons addressing scenario, model, and parameter uncertainties for the US consumer. Int J Life Cycle Assess (2014) 19:931–940.
- Videoconferences vs. In-person meetings
  - Ong, Dennis, Tim Moors, and Vijay Sivaraman. "Comparison of the energy, carbon and time costs of videoconferencing and in-person meetings." *Computer communications* 50 (2014): 86-94.
- Locality impacts of EV efficiency and emissions
  - Tamayao, Mili-Ann M., Jeremy J. Michalek, Chris Hendrickson, and Inês ML Azevedo. "Regional variability and uncertainty of electric vehicle life cycle CO2 emissions across the United States." *Environmental science & technology* 49, no. 14 (2015): 8844-8855.

Resources of potential interest

https://epicenter.energy.gatech.edu/energy-101/

- Energy 101 SE
  - Open Access 8-part Video Short Course

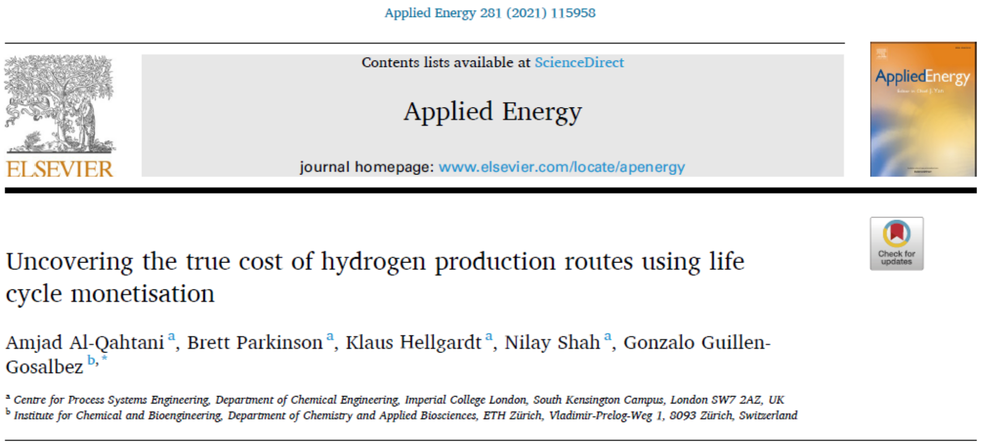
Energy 101 p1 Energy Generation - A Global Perspective

Dr. Rich Simmons

Director, Research and Studies for EPICenter

Resources of Interest

- Hydrogen Readings



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Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Uncovering the true cost of hydrogen production routes using life cycle monetisation

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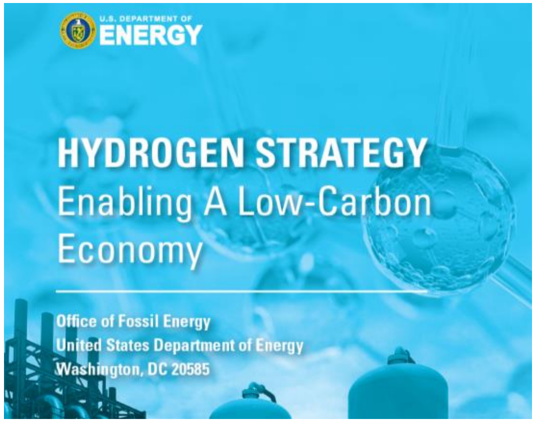
[b] *Institute for Chemical and Bioengineering, Department of Chemistry and Applied Biosciences, ETH Zürich, Vladimir-Prelog-Weg 1, 8093 Zürich, Switzerland*

Al-Qahtani, Amjad, et al. "Uncovering the true cost of hydrogen production routes using life cycle monetisation." *Applied Energy* 281 (2021): 115958.



U.S. DEPARTMENT OF ENERGY

HYDROGEN STRATEGY
Enabling A Low-Carbon Economy

Office of Fossil Energy
United States Department of Energy
Washington, DC 20585

US. DOE, Office of Fossil Energy "Hydrogen Strategy: Enabling a Low-Carbon Economy," Washington DC. June 2020

Blog on similar boiling water experiments and comparisons
http://insideenergy.org/2016/02/23/boiling-water-ieq/

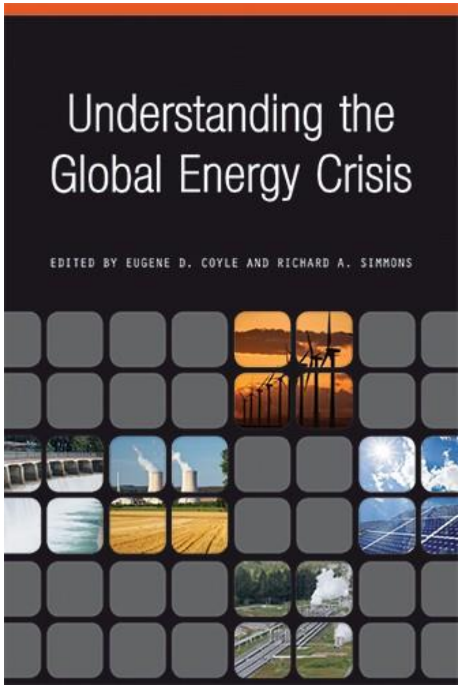
Resources of potential interest

“Understanding the Global Energy Crisis”

Edited by Coyle & Simmons
Published by Purdue University Press, 2014

Available for free download:

http://docs.lib.purdue.edu/purduepress_ebooks/29/



Understanding the Global Energy Crisis

EDITED BY EUGENE D. COYLE AND RICHARD A. SIMMONS

Thank you

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