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# THE ENERGY CRISIS FROM AN ENGINEERING PERSPECTIVE

EPEP2015

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# Course Description

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Currently proposed solutions to perceived energy problems of today's global community too often focus on specific technologies and address only a small portion of the overall problem. The tendency to "silo-ize" these issues tends to produce revolutionary solutions to minor problems and to foster neglect of larger issues. The "energy problem" is not a single problem but is an interconnected web of problems that has significant impact on the global environment and on the global economy. It actually can be seen as various disconnects between societal needs and the current energy infrastructure for meeting those needs. This presentation attempts to deconstruct the "energy problem" into component parts to facilitate evaluation of proposed solutions and technologies in the larger context.



# Learning Objectives

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*At the end of the this course, participants will be able to:*

1. Recognize the differences among curtailment, functional efficiency and systemic conservation in the pursuit of greenhouse gas reduction..
2. Recognize energy sources and understand the overhead required for their utilization.
3. Understand the importance energy storage for both stationary and mobile applications.
4. Evaluate the effectiveness of energy conservation strategies from a holistic systems perspective.



# The Energy Problem

- Interconnected web of problems not a single problem
- Aggregated effect of multiple measures rather than silver bullets
- Why do we need energy
- Curtailment vs. Functional Efficiency vs. Systemic Efficiency
- Four issues should be evaluated for each proposed solution
  - Conversion efficiency
  - Sourcing overhead
  - Energy transport
  - Energy storage

# Why Do We Need Energy?

Not energy but –

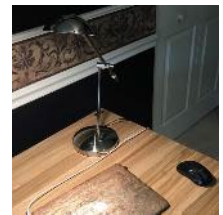
- Light
- Warmth
- Cooling
- Transport
- Food preparation and handling
- Data Processing
- Communication
- Fabrication
- Entertainment
- Force
- Velocity



# Curtailment vs. Functional Conservation

Reducing activity vs.  
improving process efficiency

- Drive less vs. get a hybrid electric vehicle
- Wear a sweater vs. re-insulate the house
- Sick building syndrome vs. heat recovery ventilators
- Work in the dark vs. retrofit LED lamps
- Watch less TV vs. get an LED flat screen



# Systemic Conservation

## Re-thinking the system to achieve the same ends

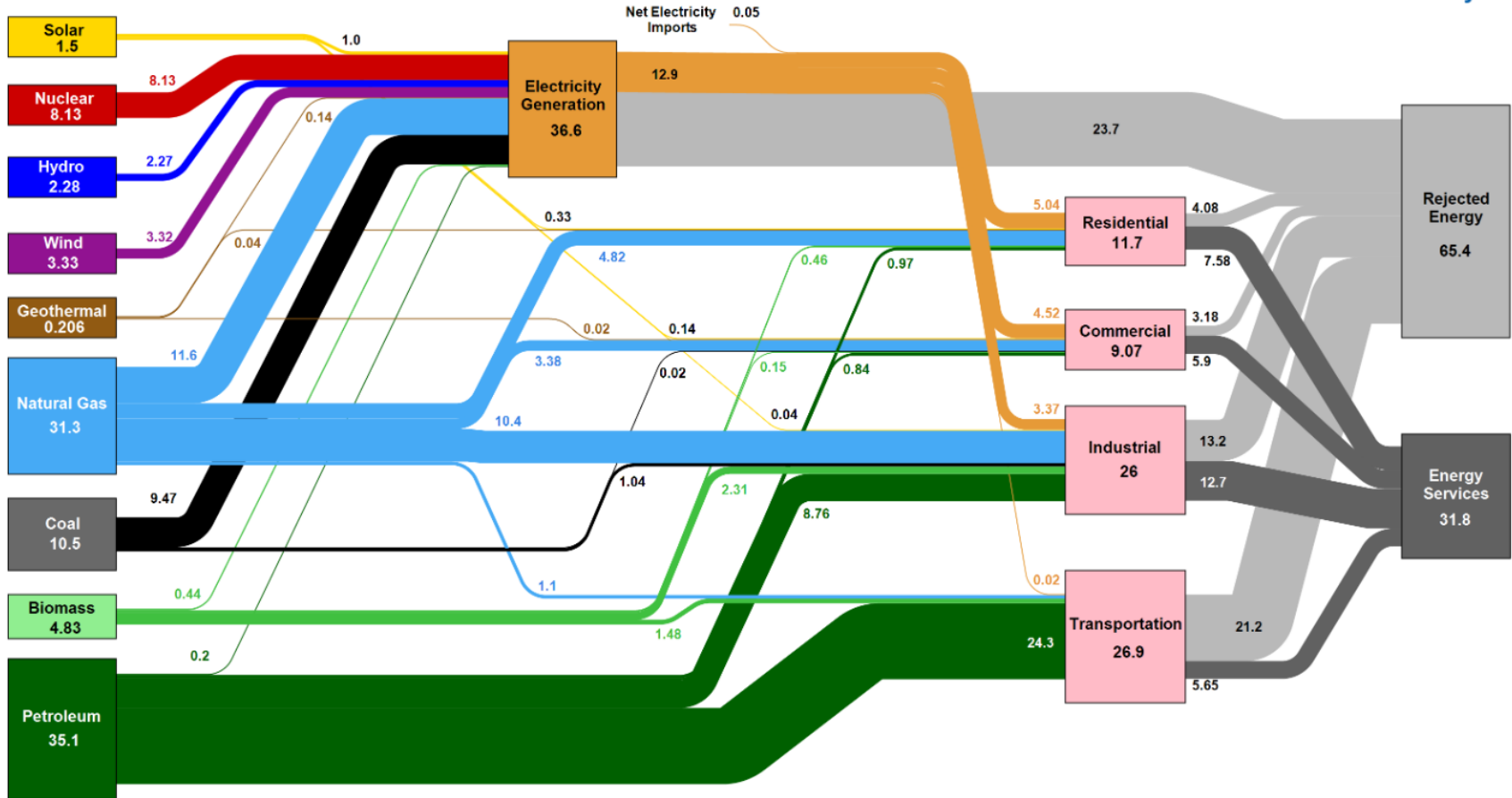
- Zoning incentives to encourage development around transit nodes
- Mixed use zoning and pedestrian circulation requirements to create walkable communities
- Locate data centers in cold climates with big data pipes
- Use tele-presence for business interaction instead of personal travel
- Use task-ambient lighting system design instead of uniform lighting levels
- Use demand-controlled ventilation
- Harvest internal heat gains to meet low-grade heat needs in buildings

# Conversion Efficiency

- Only solar thermal and geothermal energy sources are used directly for end-use without conversion (space heating, domestic hot water and industrial heating)
- Multiple reasons for energy conversion
  - Control
  - Environmental isolation
  - Transport
  - Storage
  - End-use
- Many source to end-use streams involve multiple conversions
- Each conversion has 2<sup>nd</sup> law inefficiency

# Initial Conversion Efficiency

Estimated U.S. Energy Consumption in 2021: 97.3 Quads



# Distributed Generation “Prime Movers

	Diesel Engine	Nat. Gas Engine	Steam Turbine	Combustion Turbine	Phos. Acid Fuel Cells	Photo-voltaic	Small Wind Turbine	Micro-Turbines	High Temperature Fuel Cells	Stirling Engines	
Electric efficiency (LHV)	28-50%	23-45%	15-40%	20-40%	30-40%	5-20% c	20-46% d	25-35%	40-70%	20-40%	Electric Efficiency (LHV)
Part load performance or efficiency	Good	OK	OK	Poor	Very good	Very good	N/A	OK	Very Good	OK	Part Load
Size (MW)	0.05-5	0.05-5	0.06-1,000	3-200	0.2-2	0.0001-7	.004-0.05	0.025-0.25	0.2-2	0.001-0.1	Size (MW)
Footprint (sqft/kW)	0.22-0.70	0.15-0.31	<0.1	0.02-0.61	0.6-4	50-100e	1000-1200	0.15-1.5	0.6-4	2-Jan	Footprint (sqft/kW)
Installed cost (\$USD/kW) <sup>f</sup>	500-1000	600-1200	>800	650-900	>3000	>5000	1200-1300	300-500	>3000	>1000	Installed Cost d (\$/kW)
O&M cost (\$USD/kWh)	0.005-0.0010	0.007-0.015	0.004	0.003-0.008	0.005-0.010	Neg.	.002-.005	0.002-0.01	0.003-0.015	0.002-0.008	O&M Cost (\$/kWh)
Capacity	90-95%	92-97%	Near 100%	90-98%	>95%	30%	30%	90-98%	>95%	Near 100%	Capacity
Fuels	Diesel and residual oil	Natural gas, biogas, propane	All	Natural gas, biogas, propane, oil	H2, natural gas, propane	None	N/A	Natural gas, biogas, propane, oil	H2, natural gas, propane	All	Fuels
Noise	High	High	High	Moderate	Low	None	Low	Moderate	Low	Low	Noise
NOx (lb/MW <sub>hr</sub> )	Mar-33	2.2-28	1.8i	0.3-4	<0.02	None	None	0.4-2.2	<0.02	<0.2	NOx (lb/MW <sub>hr</sub> )
Uses for heat recovery	Hot water, LP steam	Hot water, LP steam	LP-HP steam,	Heat, hot water, LP-HP steam	Hot water, LP-HP steam	Warm water in niche	N/A	Heat, hot water, LP steam	Hot water, LP-HP steam	Heat, hot water, LP steam	Uses for Heat Recovery

# Typical Energy Conversion Path



Fossil Fuel



Heat Flow



80%



Kinetic Energy



45%



Electric Generation



93%

Electricity  
Transmission



-20%  
Transport



Heat Flow



200%

"Big Bend Power Station" by Wknight94 talk - Own work. Licensed under CC BY-SA 3.0 via Wikimedia Commons -

# Conversion to End-Use

## Local infrastructure requirements

- Supervision
- Heat rejection

## Conversion overhead

- Emissions
- Upstream impact of efficiency upgrade

## Flexibility of second to last energy form for conversion to multiple end uses

- #6 fuel oil fired iPhones???
- Complexity of distribution network

# First Law vs. Second Law Efficiency

- Energy calculation vs. entropy calculation
  - All Btu's are not equal
  - The world has an entropy problem not an energy problem
- How much end-use benefit could you produce with an ideal thermodynamic cycle.
  - Cogeneration
  - Heat pump cycles
  - High grade vs. low grade heat
  - Finding heat sources and sinks for refrigeration cycles

# Exergy Analysis

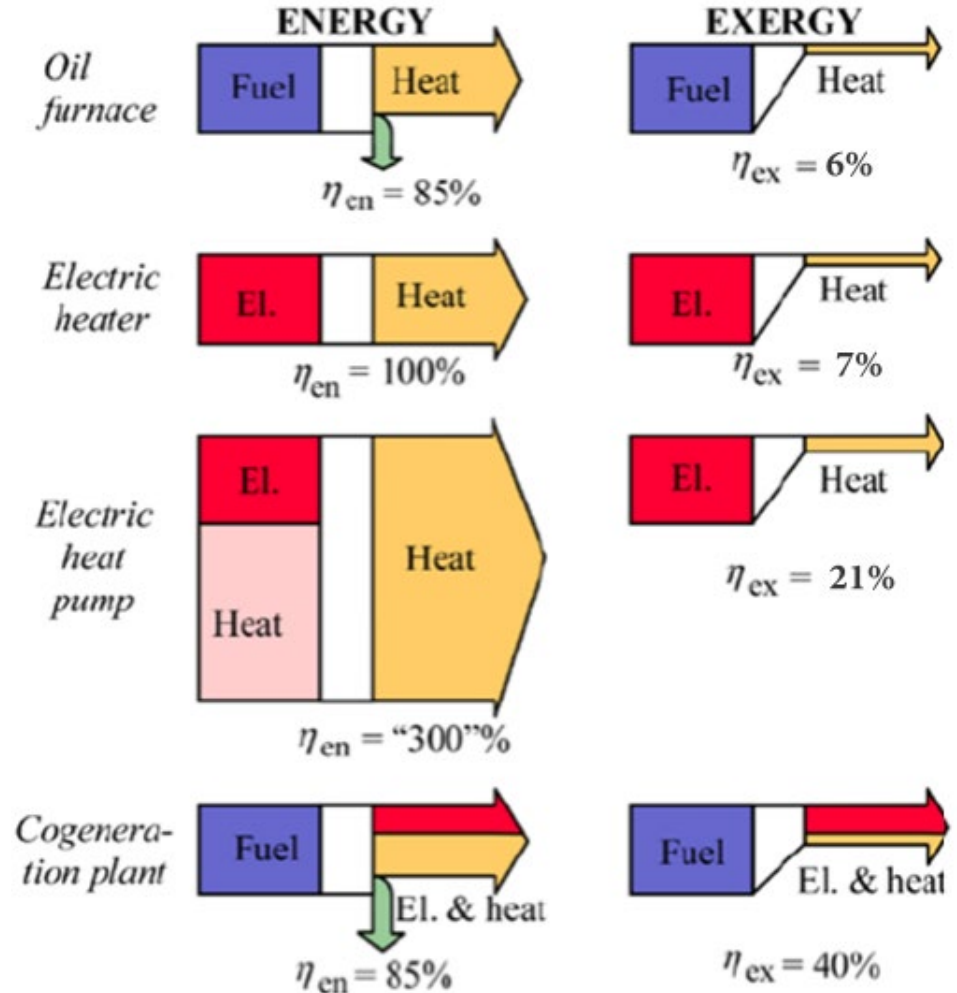
$W_{actual}$

*The actual useful work that is extracted from a system as it comes into equilibrium with its environment.*

$W_{max}$

*The maximum useful work which can be extracted from a system as it reversibly comes into equilibrium with its environment.*

$$\eta_{ex} = W_{actual} / W_{max}$$



# Exergy Analysis

## Electric Water Heater

$$T_{\text{hot}} = 333^{\circ}\text{K}$$

$$T_{\text{cold}} = 283^{\circ}\text{K}$$

$$\eta_{\text{en}} = 100\%$$

$$\eta_{\text{ex}} = 100\% * ((T_{\text{hot}} - T_{\text{cold}}) / T_{\text{hot}}) = 15.0\%$$



## Electric Arc Furnace

$$T_{\text{hot}} = 922^{\circ}\text{K}$$

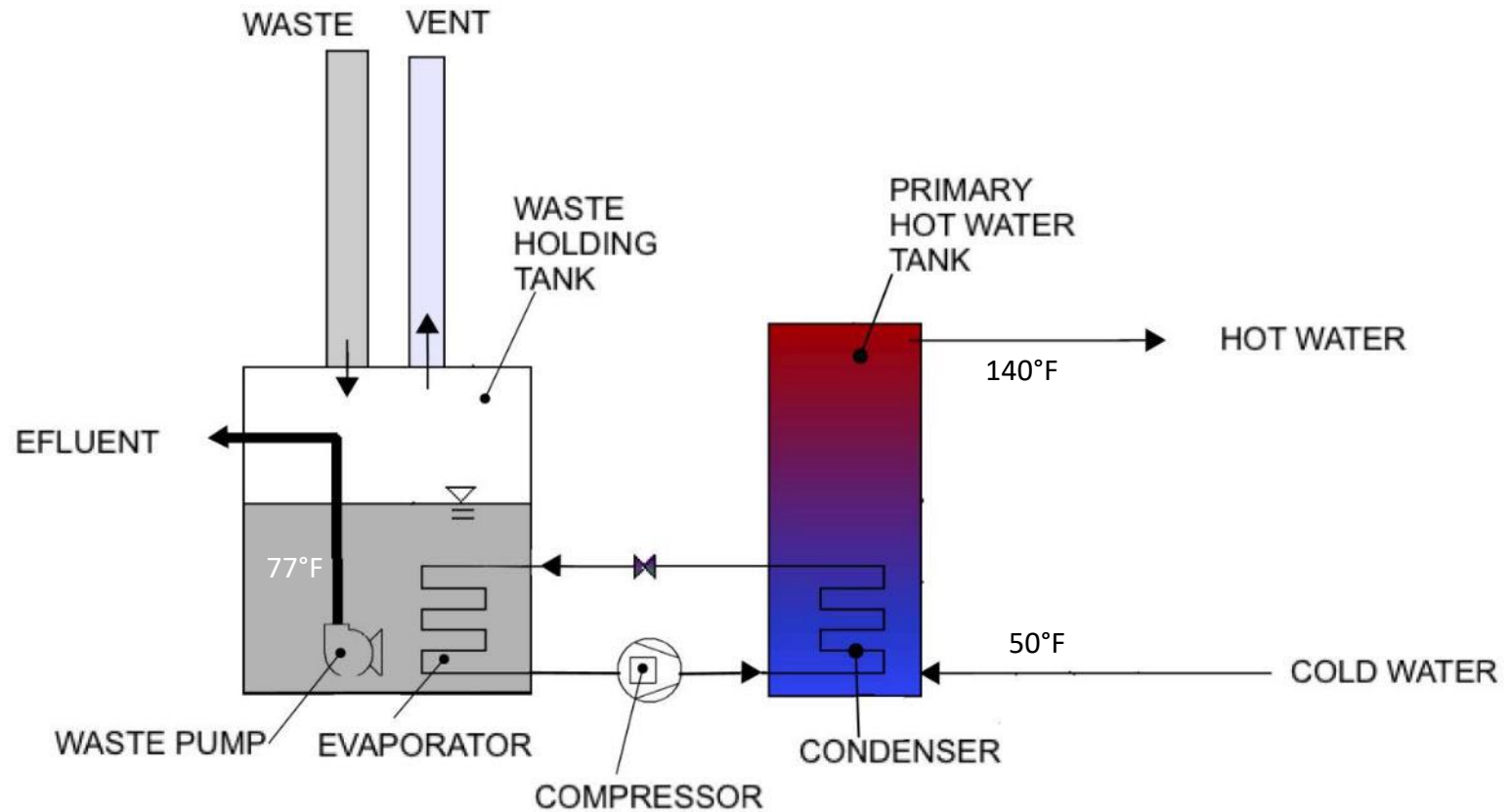
$$T_{\text{cold}} = 300^{\circ}\text{K}$$

$$\eta_{\text{en}} = 100\%$$

$$\eta_{\text{ex}} = 100\% * ((T_{\text{hot}} - T_{\text{cold}}) / T_{\text{hot}}) = 67.5\%$$



# Heat Pump DWH with Sewer Heat Recovery



$$T_{\text{hot}} = 333^{\circ}\text{K}$$

$$T_{\text{cold}} = 283^{\circ}\text{K}$$

$$\eta_{\text{en}} = 400\% \text{ (COP} = 4.0\text{)}$$

$$\eta_{\text{ex}} = 400\% * ((T_{\text{hot}} - T_{\text{cold}}) / T_{\text{hot}}) = 60.0\%$$

# Sourcing Overhead

- Extraction Land-use
- Extraction Environmental Damage
- Extraction Energy
- Initial Conversion Environmental Damage
- Initial Transport



# What is an Energy Source?

- Solar (including solar thermal, solar electric, bio-fuel, wind, wave and hydroelectric)
- Wind
- Fossil (reintroduction of biofuel from outside the biosphere)
- Nuclear
- Geothermal (true geothermal sourcing, not ground-coupled energy storage)
- Astronomical (tidal)
- **Hydrogen (not)**
- **Electricity (not)**



# Characteristics of Energy Sources

## Environmental Impact of Procurement

- Environmental damage
- Resource intensity (water, power, diverted use)

## Reliability

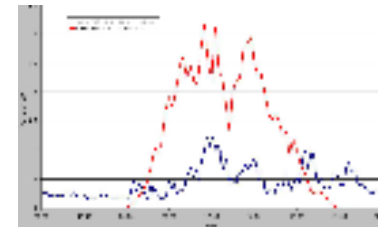
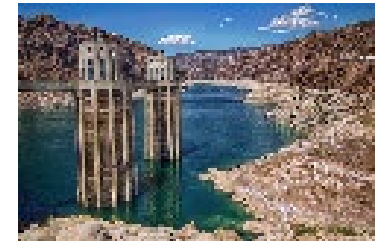
- Immediate
- Long term

## Controllability

- Load tracking
- Dispatchability

## Characteristics of Initial Conversion

- Full load efficiency
- Part load efficiency
- Emissions
- Waste products



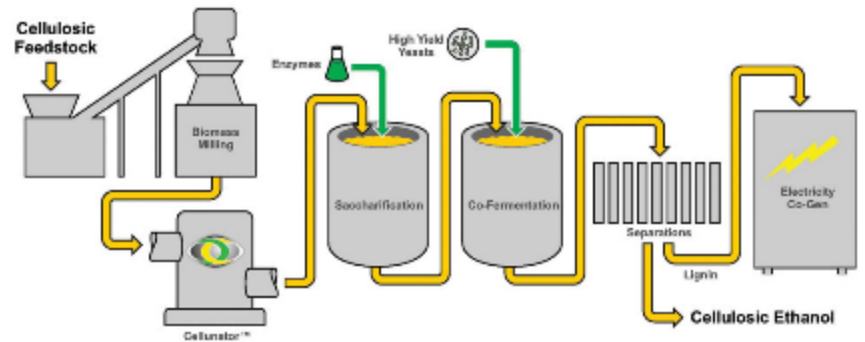
# Types of Energy Sources

- Base Load Source  
(limited controllability)
- Peaking Source  
(precise controllability)
- Expedient Source  
(not controllable)

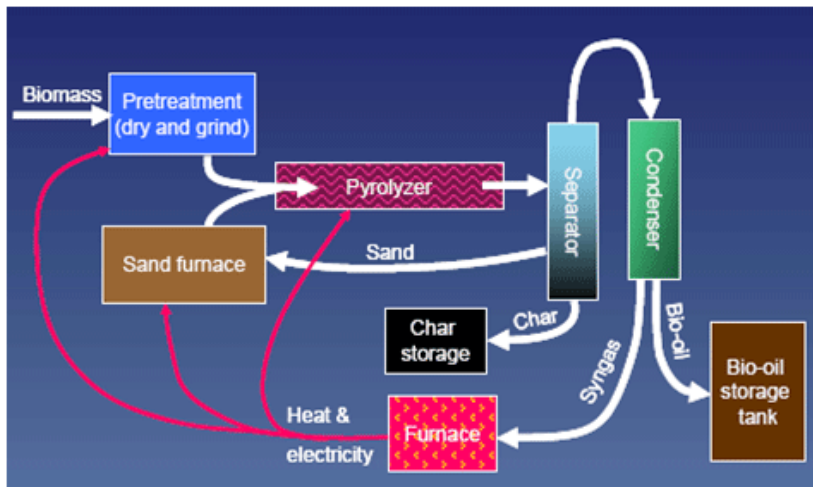


# Sourcing Trade-offs

## Conversion of Biomass to Fuel



Biomass Pyrolysis



vs.

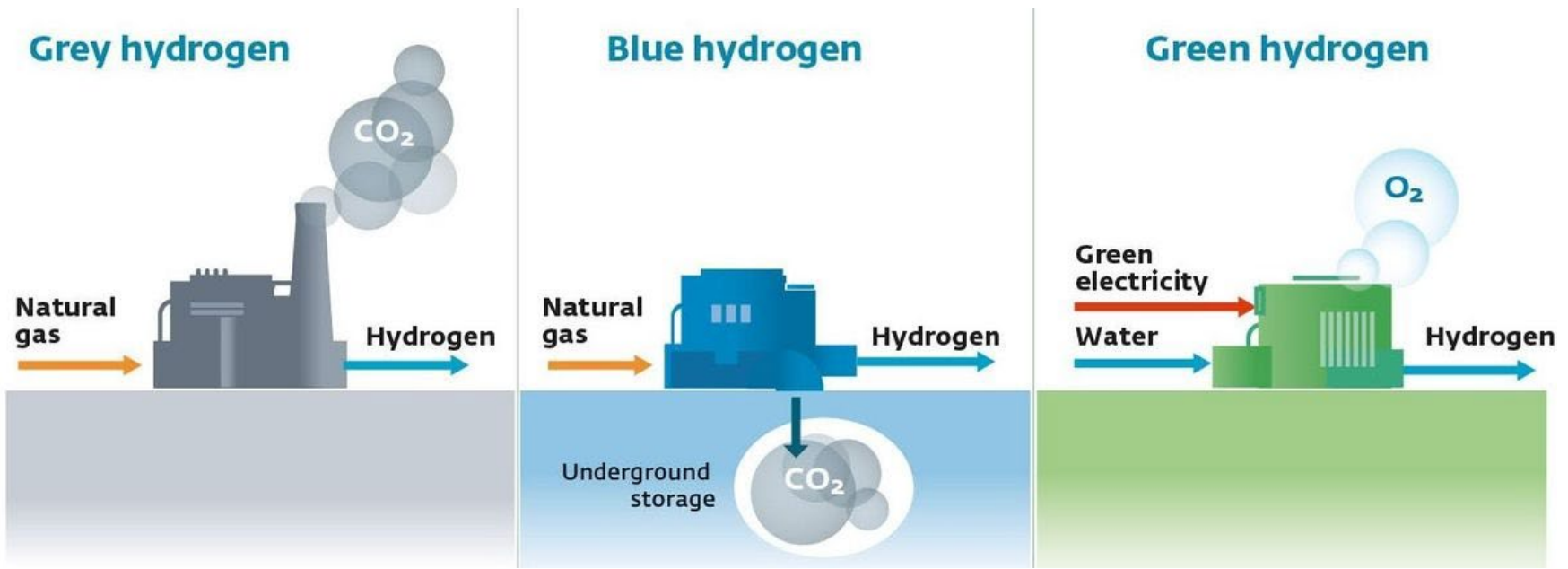
Chemical/Microbial Conversion

## How do you decide?

- Efficiency
- Environmental impact
- Resource utilization
- Capital intensity

# Sourcing Emissions: Hydrogen

746



# Energy Transport

- Energy sources and energy end-uses are usually not co-located
- Energy is consumed in moving energy from sourcing site to end-use site.
- Connected vs. disconnected transport
- Energy conversion sometimes required for transport (solar thermal power plants - electricity – electric heat pumps)
- Energy storage implications of transport.



# Energy Transport Issues

## Source Compatibility

- Electrical vs. material

## Losses

- Pumping loss/voltage drop
- Thermal losses

## Hazards

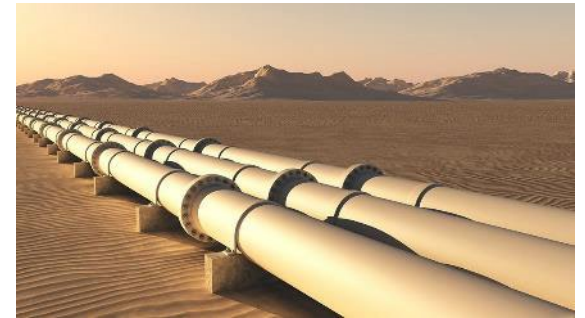
- Human, property environmental damage
- Loss of service

## Infrastructure Capitalization

- Sunk costs vs. re-purposable assets
- Land use

## Granularity

- “The last mile”
- Reliable continuity

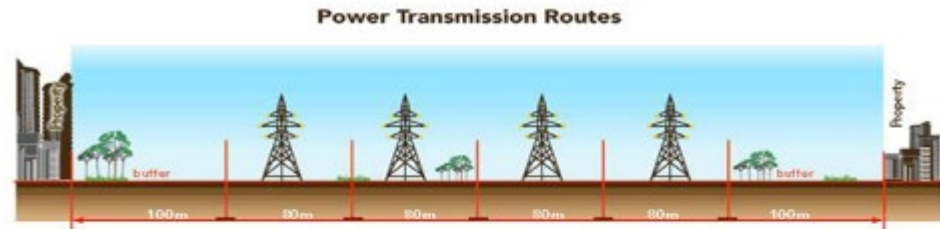


# Power Transmission Routes

## Overhead lines vs. Underground Transmission

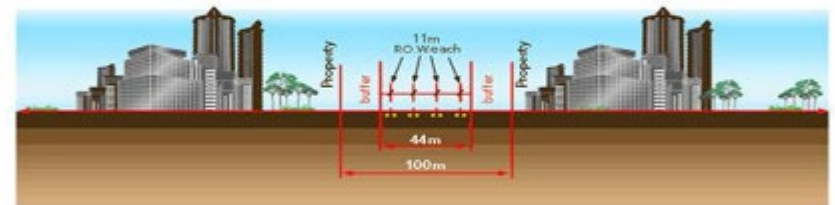
### EHV Transmission Lines – Central Generation

- Overhead right of way 540m wide.
- Cost of each 4 overhead circuits (70 mW each) is \$2 million per km
- Urban Land value is \$250/m<sup>2</sup>, land cost = 540m x 1000m x \$250 = \$135,000,00 per km.
- Total cost = \$137,000,000 per km



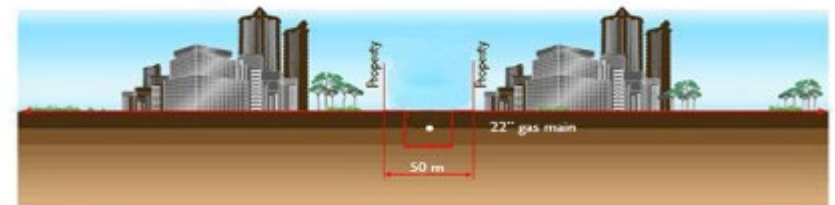
### Underground Electric – Central Generation

- Underground corridor could reduce to 100m wide
- For a typical 4 circuit corridor, cost would be \$20 million per km
- Urban Land value is \$250/m<sup>2</sup>, land cost = 100m x 1000m x \$250 = \$25,000,000 per km.
- Total cost = \$45,000,000 per km.



### Underground Gas – Distributed Generation

- Underground corridor could reduce to 50m wide
- For a typical 24" gas line, installation cost is \$250,000/km
- Urban Land value is \$250/m<sup>2</sup>, land cost = 50m x 1000m x \$250 = \$12,500,000 per km.
- Total cost = \$12,750,000 per km.



# Effective Transport Radius

## **Thermal Transport Radius inverse to Temperature Difference**

- High temperature heating and low temperature cooling negatively impact production efficiency
- Extreme heating and cooling temperatures increase losses per unit distance.
- Low temperature difference increases required flow per unit capacity and pumping or fan energy.

## **Electrical Transport Radius Inverse to Voltage**

- Transformation losses small percentage of total power
- For given power and resistance loss, doubling voltage reduces conductor size by factor of 4.

# Case Study – Waste to Energy



## Energy Density of Raw Source

- Low energy density of waste product decreases effective collection radius

3.2 kWh/kg is the lower heating value of agricultural waste

0.65 kWh of electricity per kg of agricultural waste (20% efficiency)

0.15 kWh maximum losses for materials handling (5% of input)

5,000 kg truck gets 4 mpg (stop and go) = 0.002 kWh/kg-mile

80 miles is maximum radius for waste collection.

# Vulnerability of Transport Infrastructure



Fossil Fuel – Supply Chain



Gas pipes - seismic



Electric distribution - weather

# Energy Storage

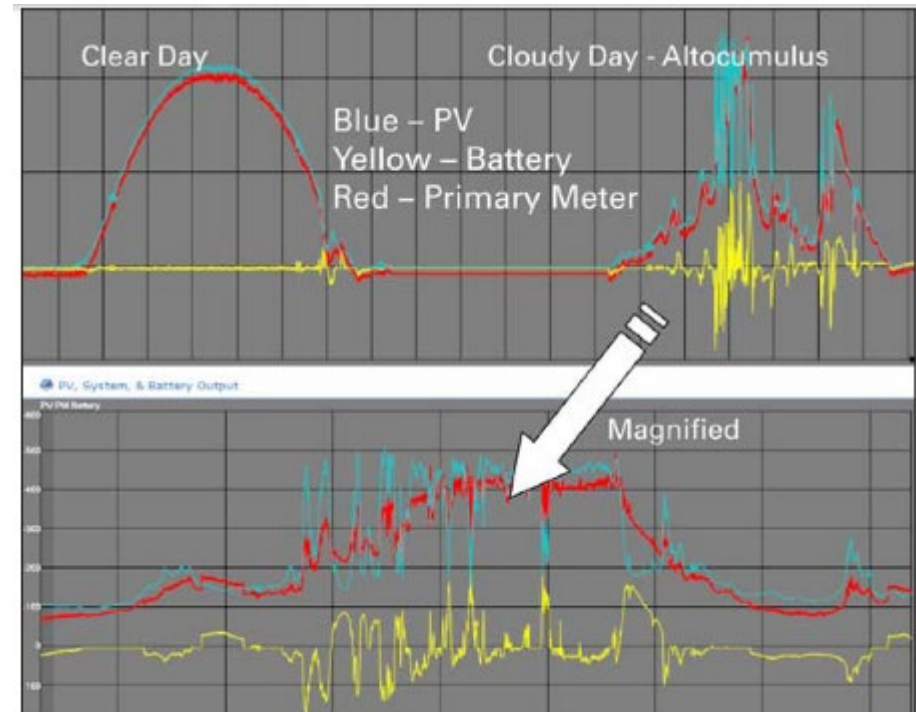
- Energy sources often don't track energy loads
  - Renewable sources don't track
  - Infrastructure sizing and part-load operation
- Energy loads may necessarily be disconnected from energy sources
  - Continuous supply vs. intermittent supply
  - Mobile loads
- Energy density
  - Volume
  - Weight
  - Money
- Round-trip efficiency



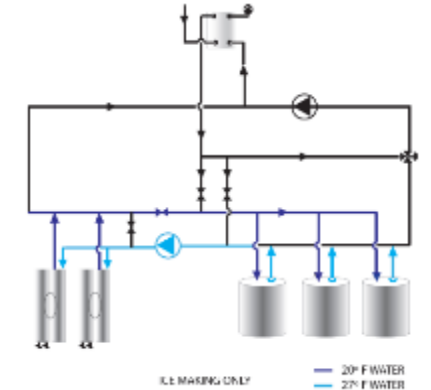
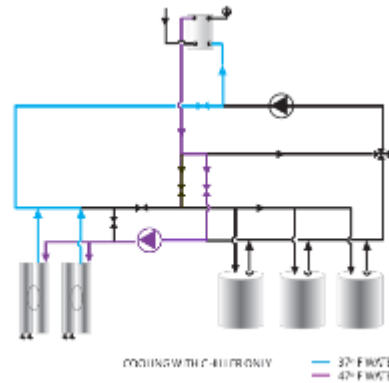
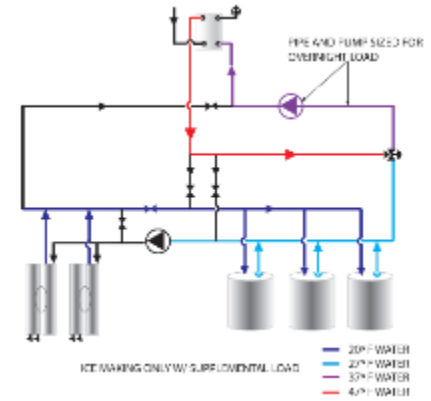
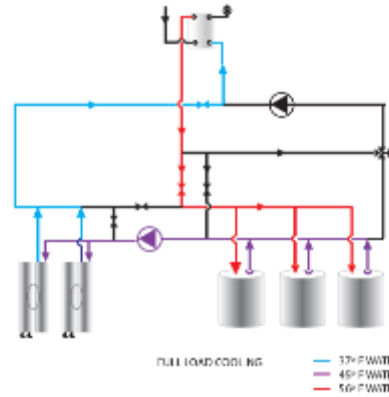
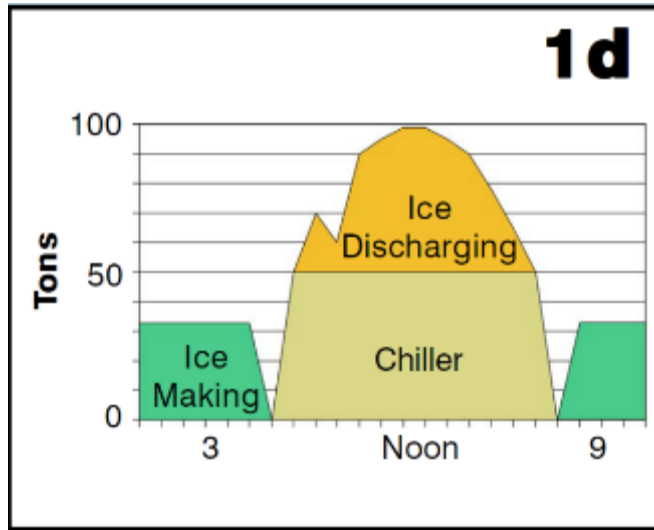
# Storage to Enhance Grid Stability

## Utility Ramp Rate Specifications Govern Generation Asset Dispatch

- Utility ramp specification – maximum allowable rate of change for generation assets
- Sudden onset of non-controllable assets (renewables) can be dampened to meet ramp specification (loss of production)
- Sudden loss of non-controllable assets (renewables) must be countered by other assets
  - Spinning reserves – operating and frequency response
  - Energy storage
- Moment to moment renewable energy ramps can be non-spec.



# Ice Thermal Storage for Peak Electrical Demand Control



# Storage for Disconnected End-Use

## Mobile

- Energy Density
- Recharge Rate
- Controllability
- Containment
- Charge retention
- Cycle life

## Stationary

- Round-trip efficiency
- Controllability
- On-demand recharging
- Cycle life
- Upward scaleability



# Fossil Fuels vs. Electrical Storage for Mobile Applications

	Gasoline	Lithium Ion Battery
Energy density	12.9 kWh/kg	0.25kWh/kg
Round Trip Efficiency	One-way	85% two-way
End-Use Conversion Efficiency	20%	93%
Lifespan	1 year (tank 20 years)	2000 cycles
Speed of Charge	4500 kW (gas pump)	7 – 400 kW
Energy Input/Output form	Liquid – heat to kinetic	Electric – electric to kinetic
Environmental Overhead	CO2 generation; drilling	Mining, electricity sourcing

# Energy Storage Characteristics

			<b>Energy Form</b>	<b>Energy Density kWh/lb</b>	<b>Energy Density kWh/ft3</b>	<b>Round Trip Efficiency</b>
		<b>Diesel Fuel</b>	chemical	5.83	294.0	na
		<b>Liquified Natural Gas</b>	chemical	6.77	181.7	na
		<b>Natural Gas (200 bar)</b>	chemical	6.77	76.0	na
		<b>Lead Acid Batteries</b>	electrical	0.02	2.8	65%
		<b>Lithium Ion Batteries</b>	electrical	0.11	18.9	90%
		<b>High Speed Flywheel</b>	kinetic	0.007	0.7	95%
		<b>Graphene Ultracapacitor</b>	electrical	0.021	2.4	95%
		<b>Hydrogen Gas (700 bar)</b>	chemical	18.1	44.1	45-50%
		<b>Ammonia (liquid)</b>	chemical	2.4	110.0	30%
		<b>Water Ice</b>	thermal	0.04	2.6	95%

# Getting to the Bottom Line

## **Analysis Must Include**

- Global environmental impacts
- The local efficiency improvement of a technology
- The impact of the technology on the entire system
- Exergy analysis

# Systemic Analysis of Hydrogen Fuel Cell Cars

## **Conversion efficiency**

- 60% - 70% to electricity using hydrogen as fuel.

## **Sourcing overhead**

- 72% natural gas reforming
  - CO<sub>2</sub> produced at sourcing
- 62% electrolysis of water
  - Electricity is not a source; sourcing overhead for electricity

## **Energy transport**

- 350 Bar distribution pressure vs. 100 bar for natural gas
- Transport energy about 0.8% per 100 miles

## **Energy storage**

- Energy Density – 18.1 kWh/lb, but 44.1 kWh/ft<sup>3</sup>
- 45-50% round-trip efficiency

# Hydrogen Fuel Cell Cars: The Bottom Line

## **Natural gas (fossil fuel) Source to Kinetic Energy**

- Conversion efficiency much better than heat engine.
- Similar capital intensity for distribution infrastructure
- Storage provisions more extensive than LNG or gasoline.
- Local conversion infrastructure similar to heat engine.
- Intermediate electricity output more flexible than kinetic energy.
- CO<sub>2</sub> emissions at source conversion not end-use conversion.

# Technology Breakthrough for Hydrogen Fuel Cells (Not)

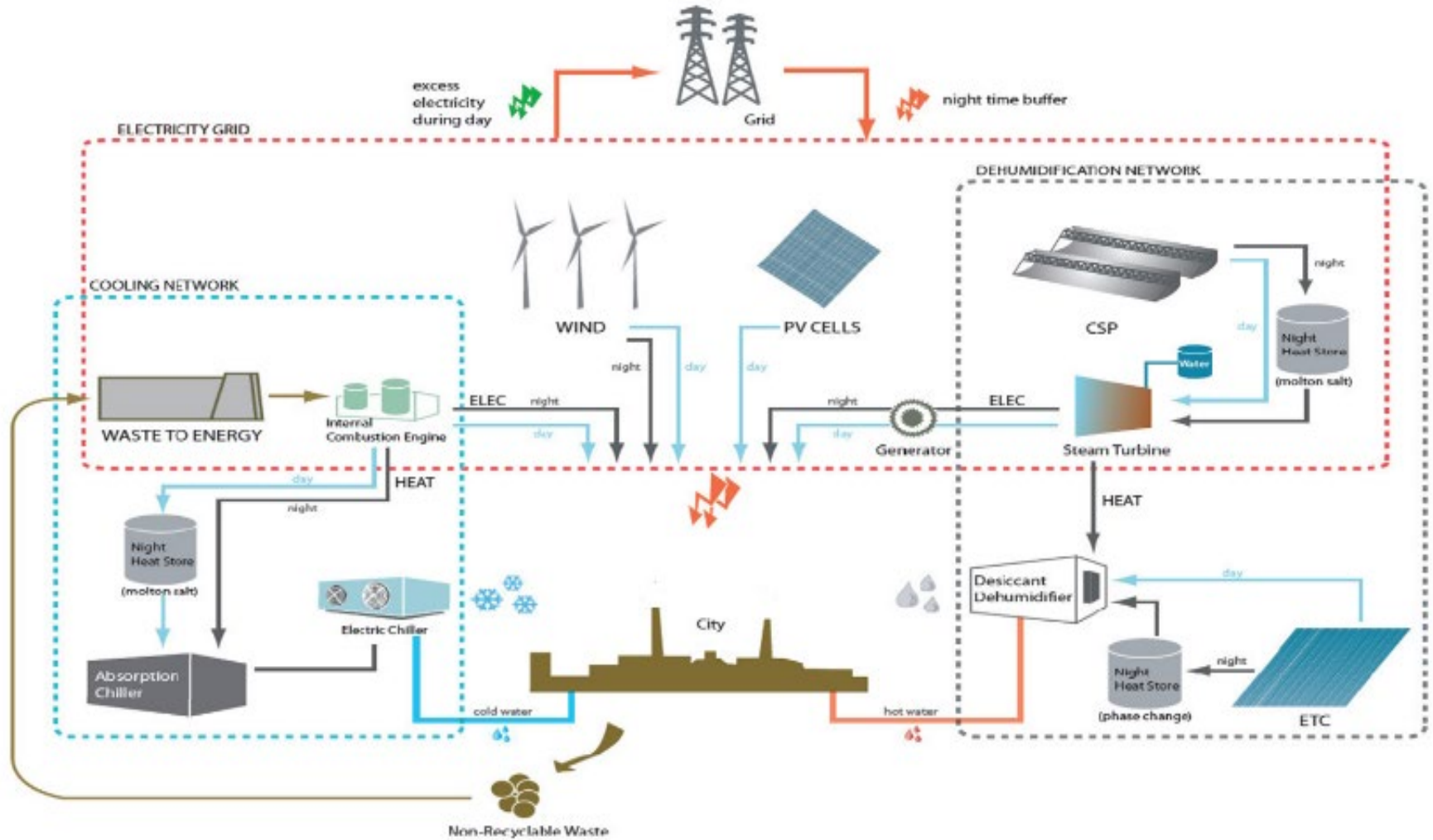
## Ammonia(NH<sub>3</sub>) Energy Storage and Transport

- Energy density – 2.4 kWh/lb, 110.0 kWh/ft<sup>3</sup>
- Conversion efficiency to motive power – 45% - 65% (SOFC)
- Overall storage of kinetic energy about 85%-90% of gasoline.
- Flammable with open release in presence of flame
- Low temperature /medium pressure storage
- Extremely hazardous for direct human contact
- Low-cost commodity chemical (\$0.75 per lb. pre-tax, using fossil fuel conversion)
- Can be manufactured by Haber-Bosch process using hydrogen (Carbon Neutral if hydrogen is green)
- Low round trip efficiency
- Roadblocks and downsides (**TBD**)

# The Take-Away

- Holistic analysis best means of predicting global energy efficiency impact.
- Exergy analysis most effective means of analyzing sourcing overhead and conversion efficiency.
- Storage and transport frequently overlooked as drivers of technology success.
- Siting of initial source conversion key strategy for maximizing Second Law efficiency.
- Make by-products end-products.

# Community Energy Infrastructure



Thank You

## **QUESTIONS AND ANSWERS**

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