Chapter 4. Distributed Generation

- 1 Electricity Generation in Transition
- 2 Distributed Generation with Fossil Fuels
- 3 Concentrating Solar Power (CSP)
- 4 Biomass for Electricity
- 5 Micro-Hydropower Systems
- 6 Fuel-Cells

Electricity Generation in Transition

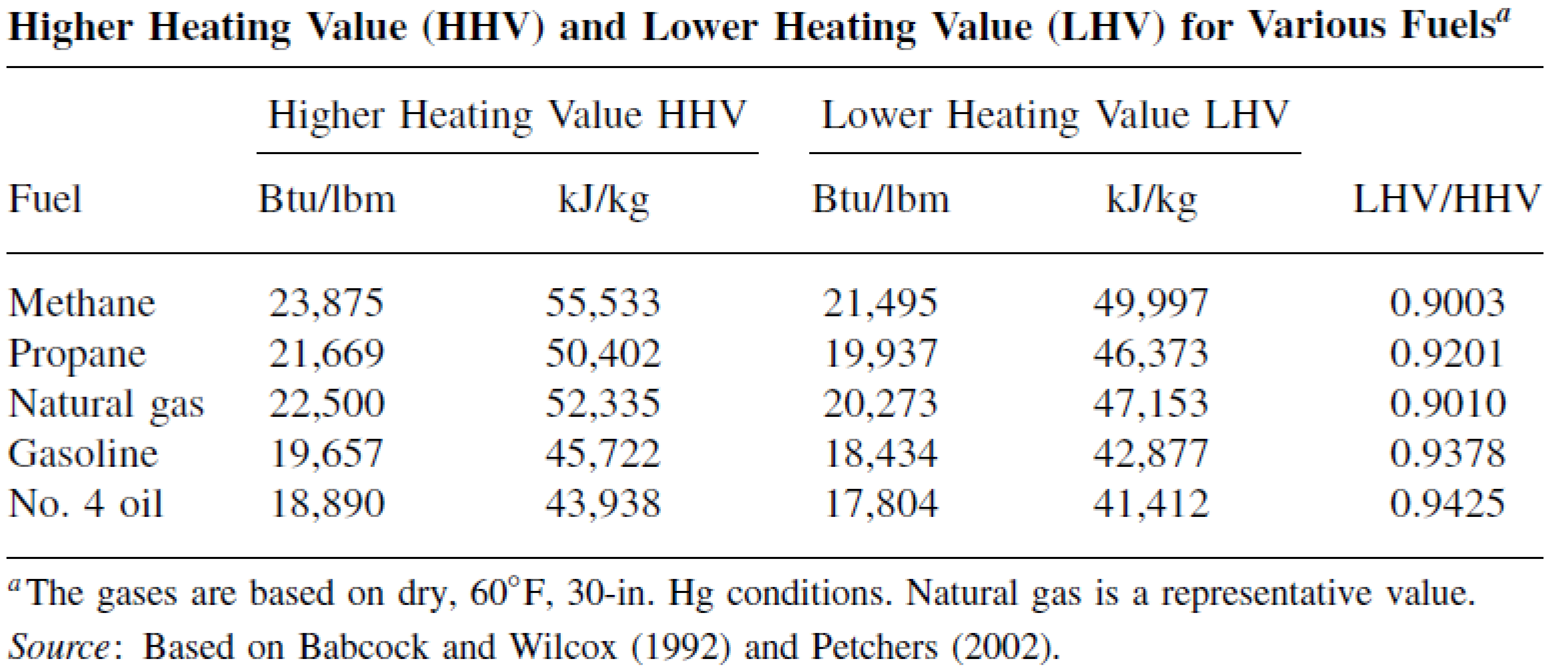
- Opening the T&D grid to independent power producers
- Small-Scale plants
- Energy Efficiency
- Economic Advantage of Co-Generation (Heat and Power) and Tri-Generation (Heat, Power, Cooling)
- Environmental Advantage → transition toward small-scale, decentralized energy systems
- Distributed Generation (DG): "small-scale power generation, in the size up to 50 MW, located on the distribution system close to the point of consumption"
- Owners of DG: Utility and Customers or Sellers to Utility

Heating Value

- HV(Heating Value): How much heat a fuel can generate
  - [Btu/lb-m] or [kJ/kg]
- Two (2) HV’s from the same fuel: Gross HV and Net HV
- HHV (Gross) and LHV (Net)
  - Hydrocarbon produces heat and water vapor
  - Water vapor is released and its latent heat is not recovered.
  - Actual Energy extractable from the fuel is therefore lowered.
  - Heat Values of combustion (HV) for a fuel: Inclusion of the latent heat or not
    - Higher Heating Value (HHV): includes latent heat (Gross HV)
    - Lower Heating Value (LHV): excludes latent heat (Net HV)

Distributed Generation with Fossil Fuels

- HHV (inclusion of Latent Heat) and LHV (exclusion) for Various Fossil Fuels



Higher Heating Value (HHV) and Lower Heating Value (LHV) for Various Fuels[a]

	Higher Heating Value HHV		Lower Heating Value LHV		
Fuel	Btu/lbm	kJ/kg	Btu/lbm	kJ/kg	LHV/HHV
Methane	23,875	55,533	21,495	49,997	0.9003
Propane	21,669	50,402	19,937	46,373	0.9201
Natural gas	22,500	52,335	20,273	47,153	0.9010
Gasoline	19,657	45,722	18,434	42,877	0.9378
No. 4 oil	18,890	43,938	17,804	41,412	0.9425

[a] The gases are based on dry, 60°F, 30-in. Hg conditions. Natural gas is a representative value.

Source: Based on Babcock and Wilcox (1992) and Petchers (2002).

- *Note: lbm: pound-mass cf. lbf: pound-force

Distributed Generation with Fossil Fuels

- Example: A micro-turbine has a natural gas input of 13,700 Btu (LHV) per kWh electricity generation output. Find (a) its LHV efficiency and, with the LHV/HHV ratio of 0.9010 for natural gas, (b) its HHV efficiency.

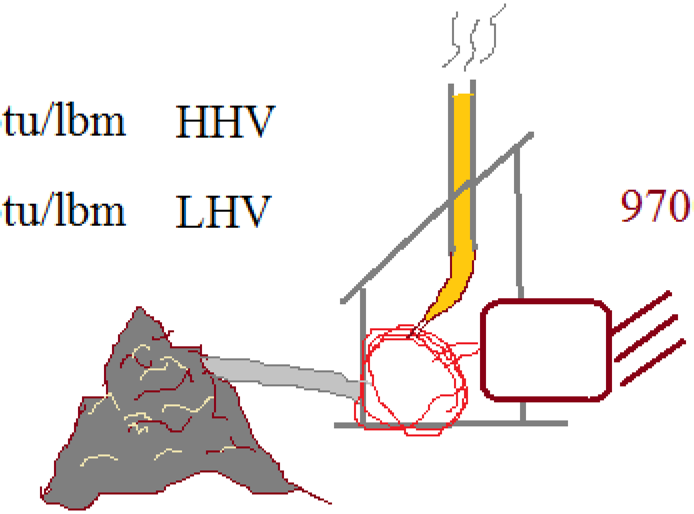
HHV and LHV – Example- Handout

- On an HHV basis, a 600-MW coal-fired power plant has a heat rate of 9700 Btu/kWh. The particular coal being burned has an LHV of 5957 Btu/lbm and an HHV of 6440 Btu/lbm.

  a. What is its HHV efficiency?

  b. What is its LHV efficiency?

  c. At what rate will coal have to be supplied to the plant (tons/hr)?



6440 btu/lbm HHV

5957 btu/lbm LHV

9700 BTU (HHV)/kWh

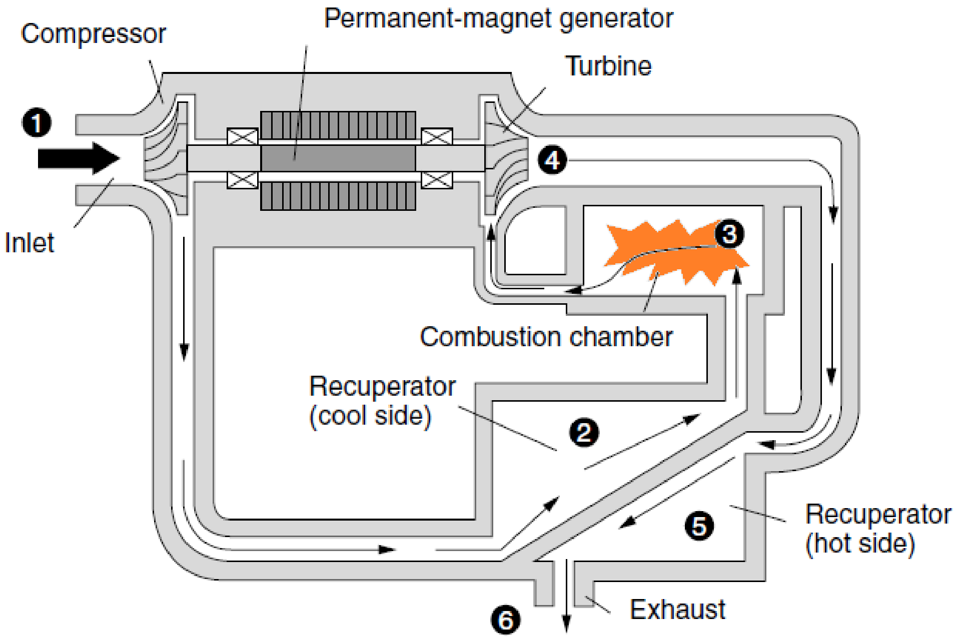
Micro-combustion Turbines

- Traditional gas turbine (for utility and industrial facilities): ~ 100 MW
- A new generation of very small gas turbines
  - Micro—turbine
  - 0.5kW – 500kW range

Specifications for Example Microturbines[a]

Manufacturer, Model	Capstone C30
Rated power	30 kW
Fuel input	390,130 Btu/hr (LHV)
Heat rate (LHV)	12,800 kJ (13,100 Btu)/kWh
Efficiency (LHV)	26%
Exhaust gas temp.	275°C (530°F)
NO_x emissions	< 9 ppmV (0.49 lb/MWh)
CO emissions	< 40 ppmV @ 15% O2
Turbine rotation	96,000 rpm
Dimensions H, W, D	1.90 × 0.71 × 1.34 m (75 × 28 × 53″)
Weight	478 kg (1052 lb)
Noise	65 dBA @ 10 m (33 ft)

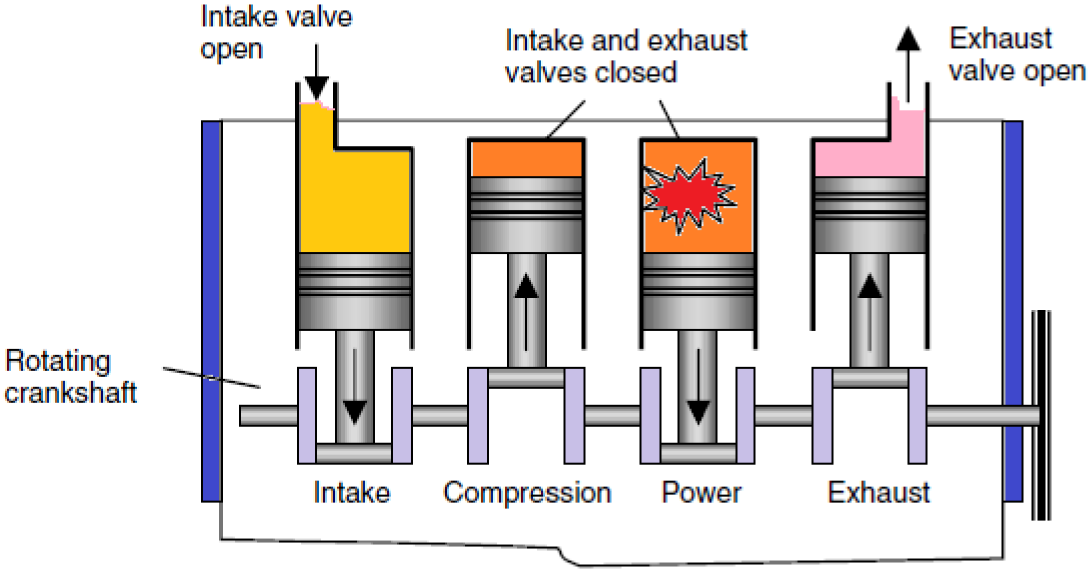
[a] Emissions are for natural gas fuel.



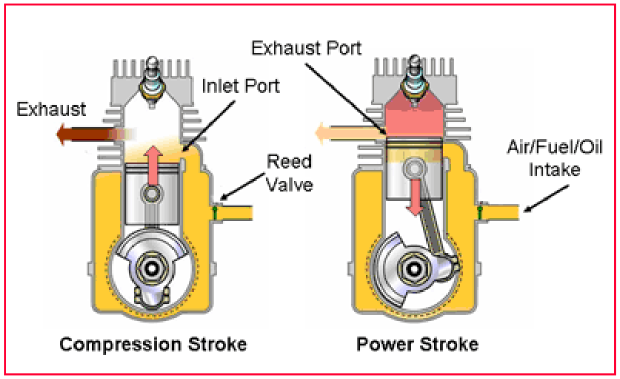
Air is compressed (1), preheated in the recuperator (2), combusted with natural gas (3), expanded through the turbine (4), cooled in the recuperator (5), and exhausted (6). From Cler and Shepard (1996).

Reciprocating Internal Combustion Engines (ICE)

- Reciprocating (that is, "Piston-Driven") ICE
- ICE: combustion takes place inside engine
- Size: 0.5 kW – 6.5 MW
- Efficiency: 37 – 40 %(LHV)
- Fuels: Gasoline, Natural Gas, Kerosene, Propane, Alcohol, Waste Gas, Hydrogen
- Conventional 4-stroke cycle found in automobiles
- **Alternative 2-stroke engine**: (Intake + Exhaust & Power)
  - Not as efficient as 4-stroke
  - More emission

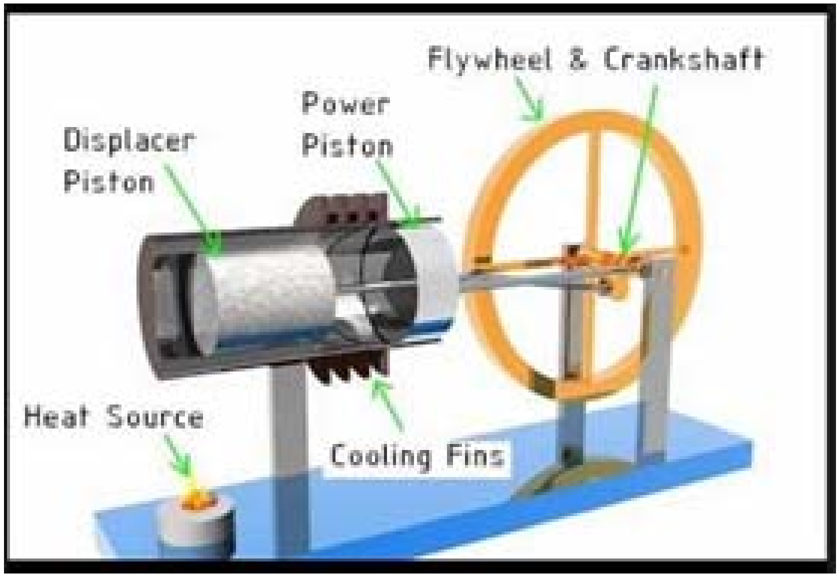


Basic four-stroke, internal combustion engine.



Stirling Engines

- External Combustion Engine (ECE) – Energy is supplied to the working fluid from a source outside of the engine →Steam Cycle Engine
- Stirling Engine: Piston-driven reciprocating engine of external combustion
- ECE: Any fuel
- Piston Movement:
  - Controlled by rotating crankshaft



Stirling, Home and Solar on Pinterest
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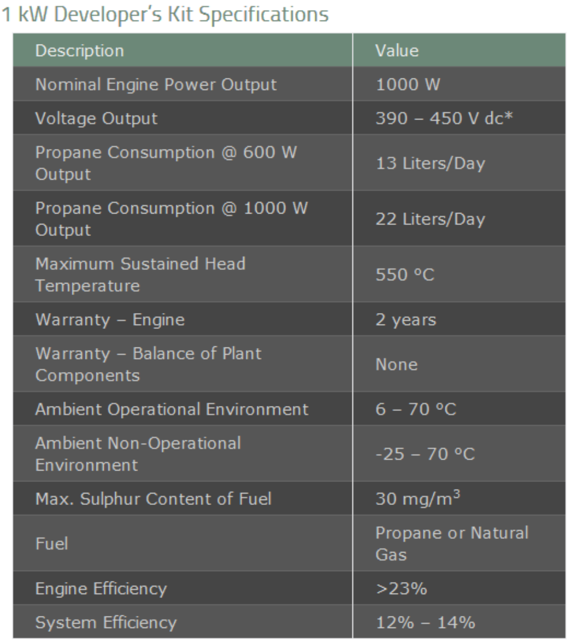
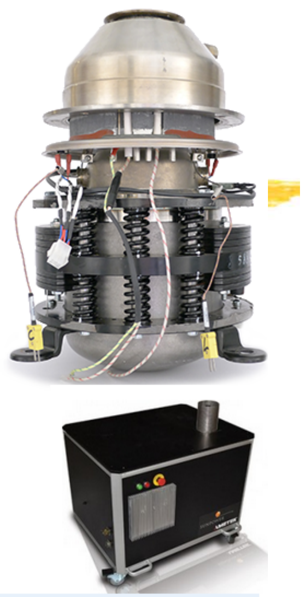
Stirling Engine → Electricity

- Engine Size: 1kW – 25 kW
- Fuel: Propane
- Efficiency: 30 % (or less)
- Quiet (fuel burns slow)
- Low Emission
- No Vibration
- Market: Automobiles, boats, RVs, small aircraft, (and submarines)
- Market for Power Generation
  - Small-scale power systems for battery charging
  - Other off-grid application
  - Co-Generation



1 kW Developer's Kit Specifications

Description	Value
Nominal Engine Power Output	1000 W
Voltage Output	390 – 450 V dc*
Propane Consumption @ 600 W Output	13 Liters/Day
Propane Consumption @ 1000 W Output	22 Liters/Day
Maximum Sustained Head Temperature	550 °C
Warranty – Engine	2 years
Warranty – Balance of Plant Components	None
Ambient Operational Environment	6 – 70 °C
Ambient Non-Operational Environment	-25 – 70 °C
Max. Sulphur Content of Fuel	30 mg/m^3
Fuel	Propane or Natural Gas
Engine Efficiency	>23%
System Efficiency	12% – 14%



sunpowerinc.com/1kw-stirling-engine/

WhisperGen on-grid Stirling Engine unit.
Source URL: http://www.whispergen.com/

Concentrating Solar Power (CSP) Technologies

- CSP
  - 1
  - 2
  - 3
  - 4
- Prototypes
  - 1
  - 2
  - 3

love4earth - STIRLING POWER PLA.
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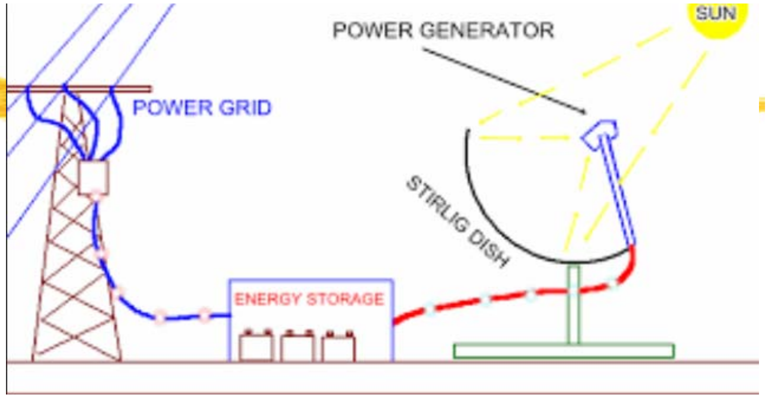
1 Solar Dish – Stirling Engine Power System

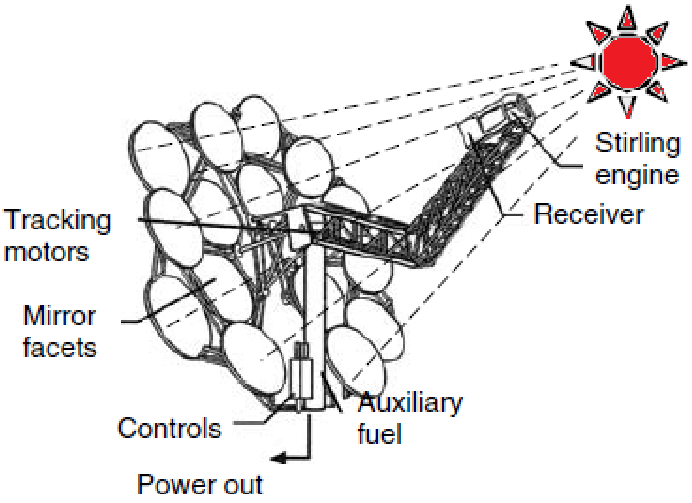
- Concentration: Multiple mirrors of a parabolic dish shape
- Dish tracking for sun and focusing on thermal receiver
- Thermal receiver converts to heat that delivers to a ( ) engine
- Heat Transfer Medium and Working fluid: ( ) or ( )
- Cold Side of Stirling engine: Water-cooled, fan-augmented radiator
- Efficiency: 20% (average), 30 %(record measured peak) → Highest Efficiency in all solar conversion technology
- Two Competing Systems: 25 kW with 20% Efficiency
  - Dish by SAIC (Science Applications International Corp), Stirling Engine by STM (Sterling Thermal Motors)
  - Boeing/SES (Stirling Energy Systems)



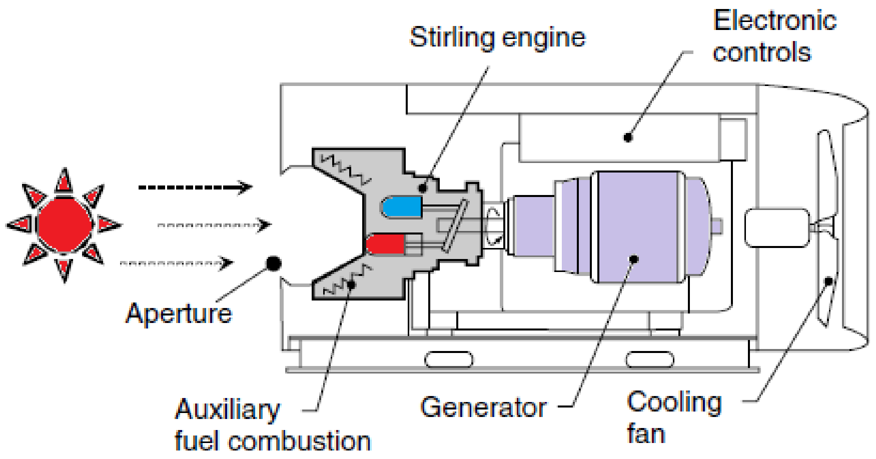
Solar Dish – Stirling Engine Power System

- Dish (SAIC)
- Stirling Engine (STM)

- Best for sunny deserts: CA, AZ, NV
- Short construction time
- Easy permit
- No emission



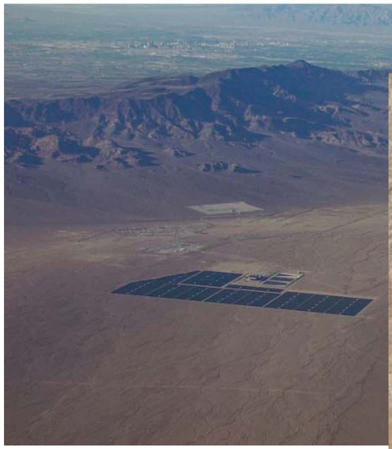
(a) The complete SAIC/STM system

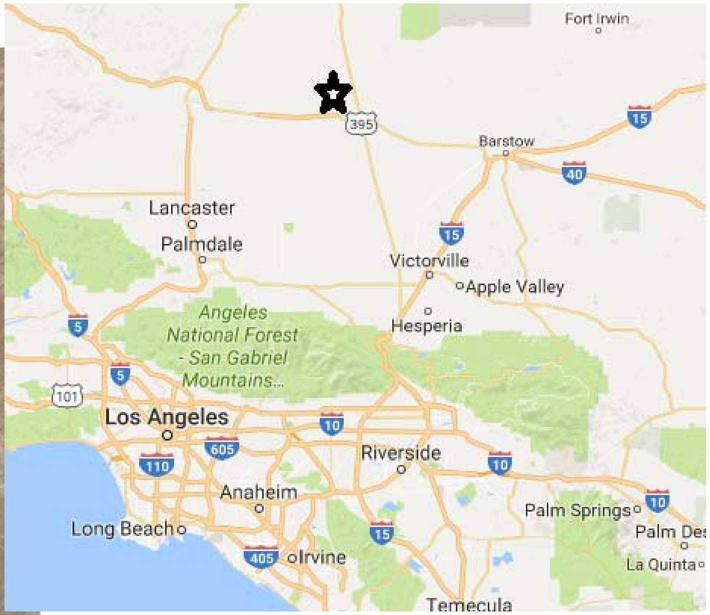


(b) The STM Stirling engine.

2 Parabolic Trough

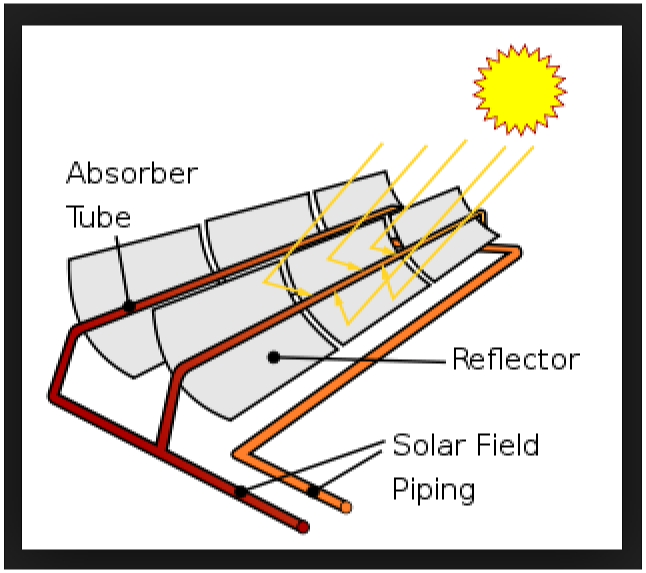
- SEGS (Solar Electric Generation Systems): 354 MW parabolic trough solar plant. Mojave Desert, Barstow, CA





Parabolic Trough

- SEGS (Solar Electric Generation Systems): 354 MW parabolic trough solar plant.
- Receiver (at focal point) or Heat Collection Elements (HCE)
- Thermal (   ) – Heat Transfer Fluid



Solar power plants in the Mojave De..
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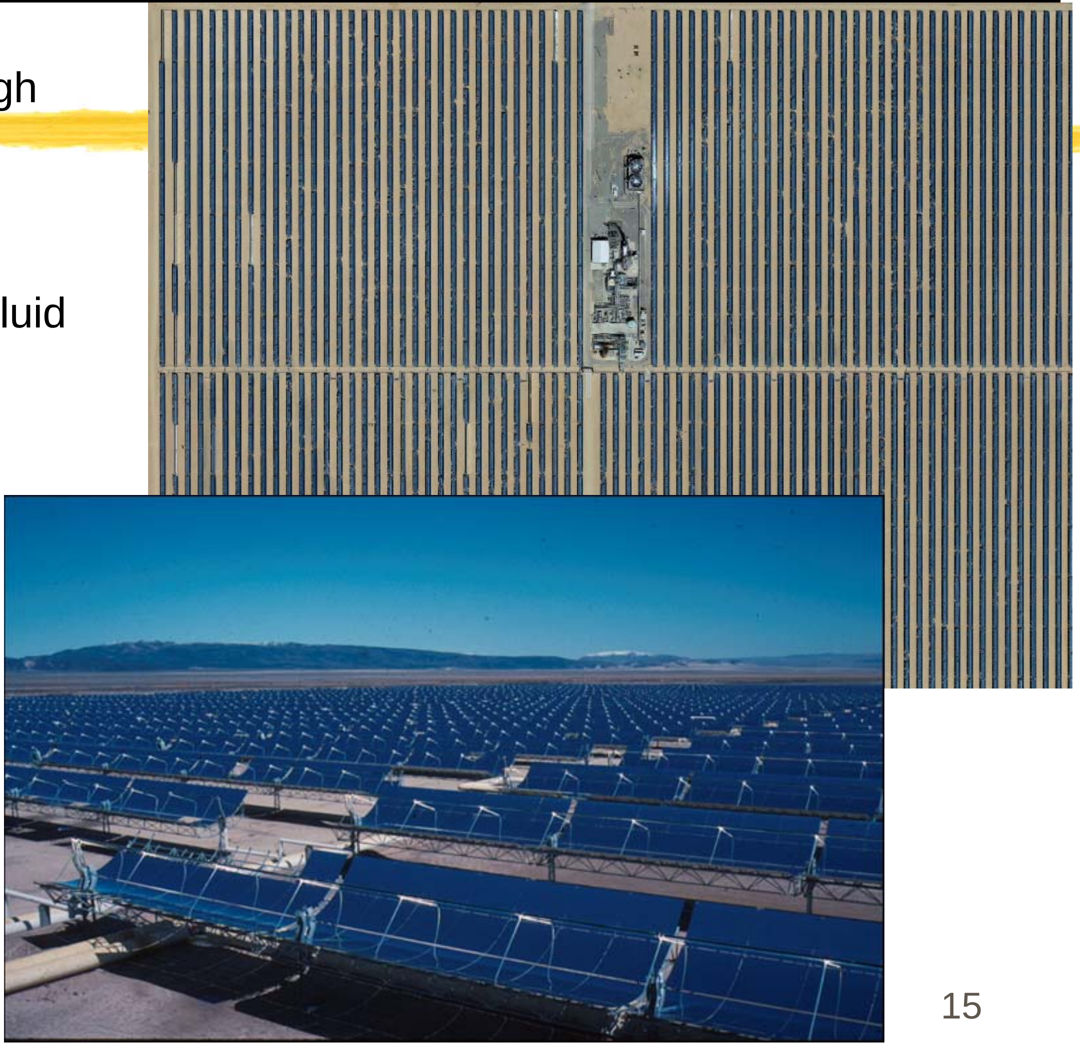
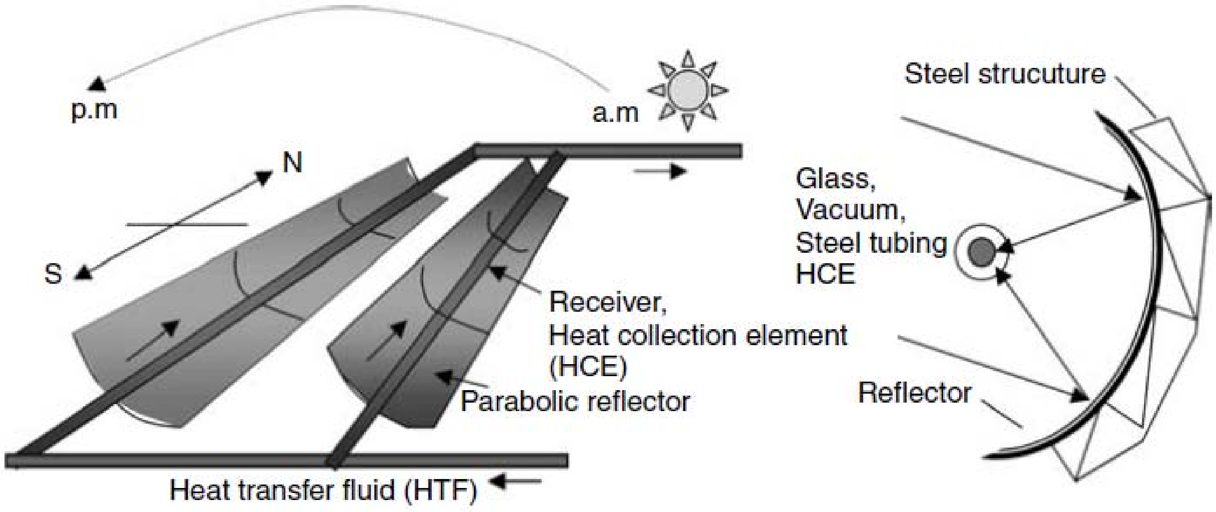


Parabolic Trough

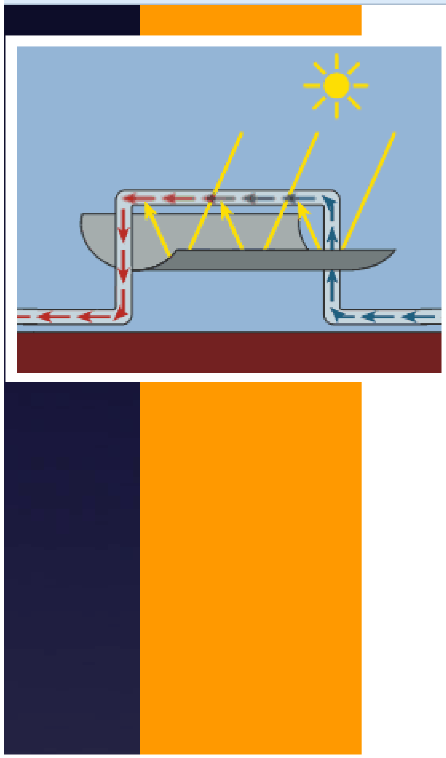
- SEGS (Solar Electric Generation Systems)
- HCE (Heat collection element): Heat transfer fluid → steam turbine/generator
- Heat Transfer Fluid: (   ), (   ), (   )
- Night-hour consideration
  - Heat Storage in (   )
  - Grid-connection



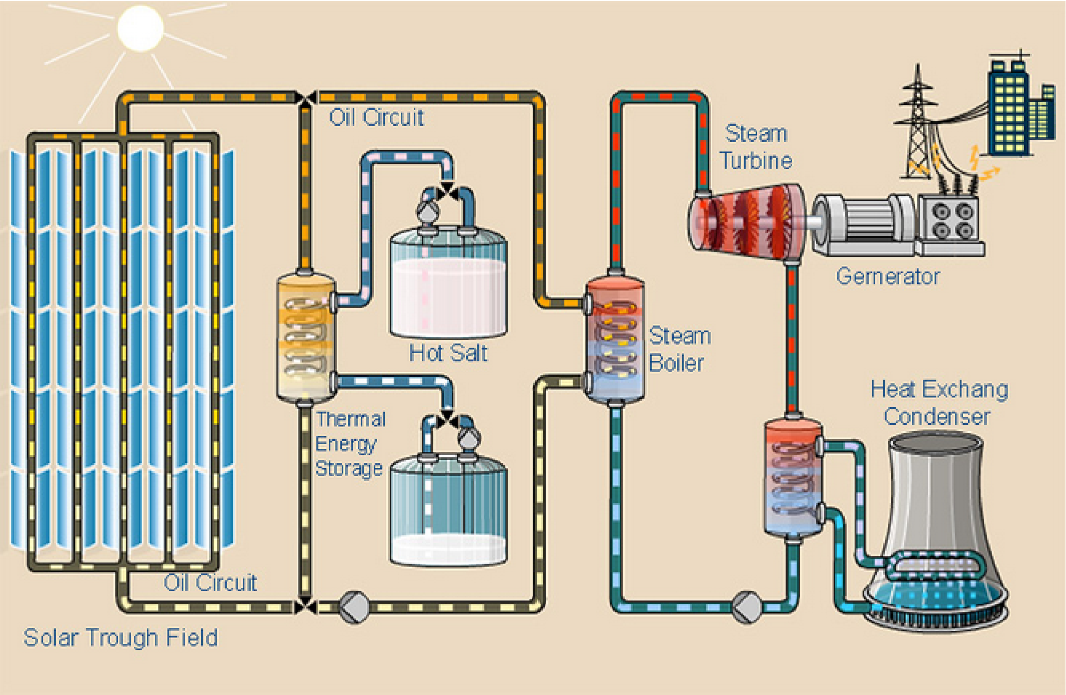
Parabolic Trough

- SEGS (Solar Electric Generation Systems)
- Solar-to-Energy Efficiency at 10%
- Generation cost at $0.12/kWh (least expensive solar electricity)

https://www.mtholyoke.edu/~wang30y/csp/PTPP.html

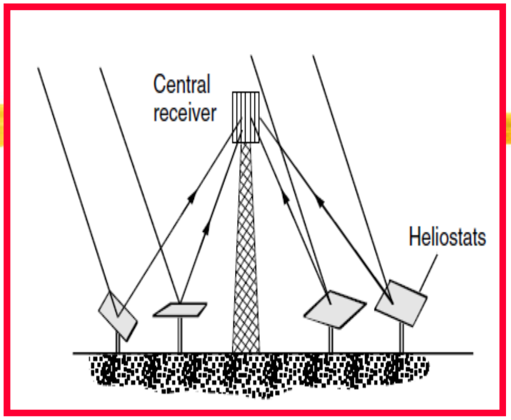


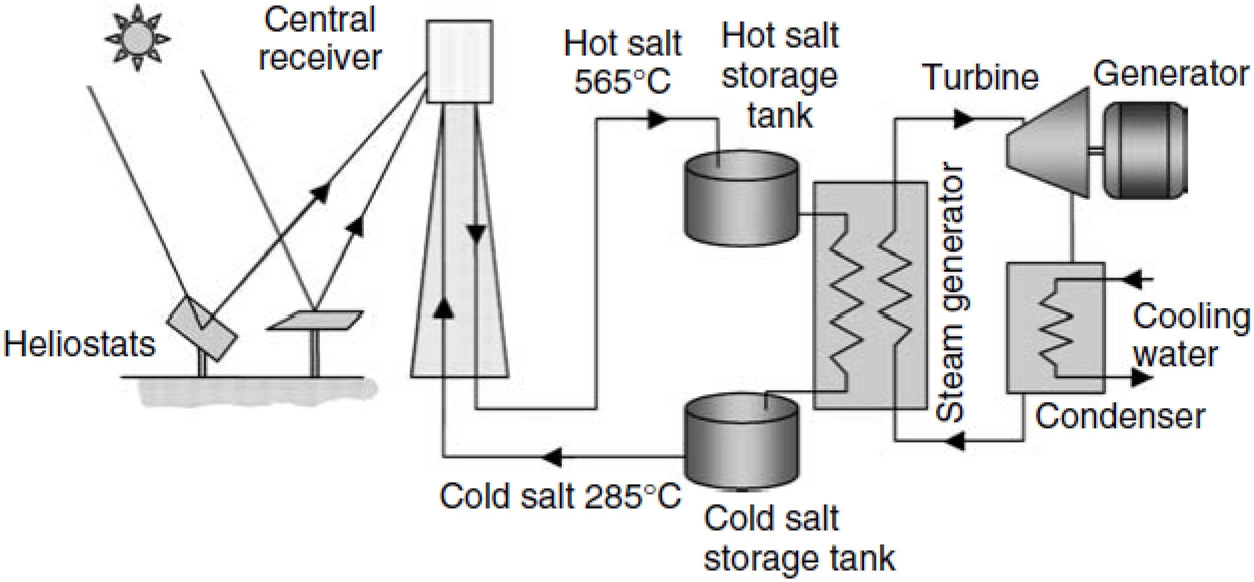
Schematic of a PTPP with a thermal storage system



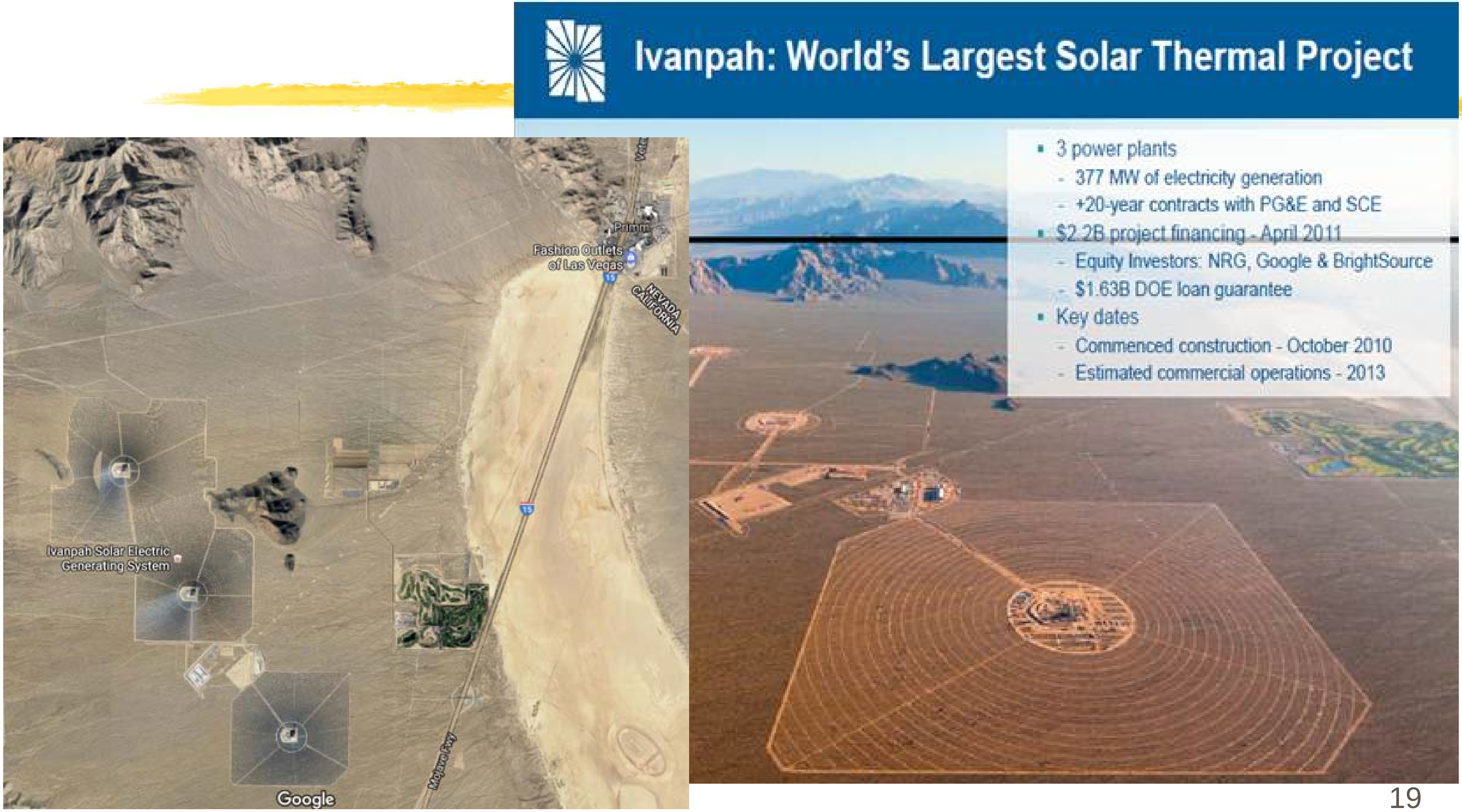
3 Solar Central Receiver Systems (CRS)

- CRS
- Heliostats: Computer controlled mirrors
- Receiver Tower – (   )
  Thermal Storage





Central Receiver System



Ivanpah: World's Largest Solar Thermal Project

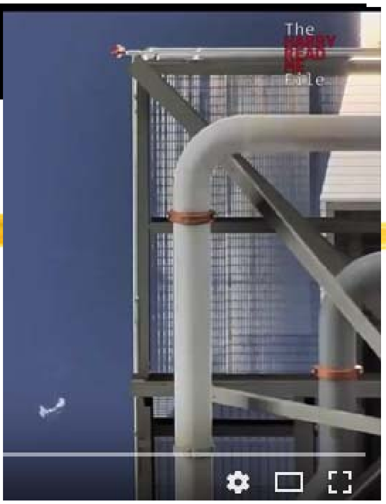
- 3 power plants
  - 377 MW of electricity generation
  - +20-year contracts with PG&E and SCE
- $2.2B project financing - April 2011
  - Equity Investors: NRG, Google & BrightSource
  - $1.63B DOE loan guarantee
- Key dates
  - Commenced construction - October 2010
  - Estimated commercial operations - 2013

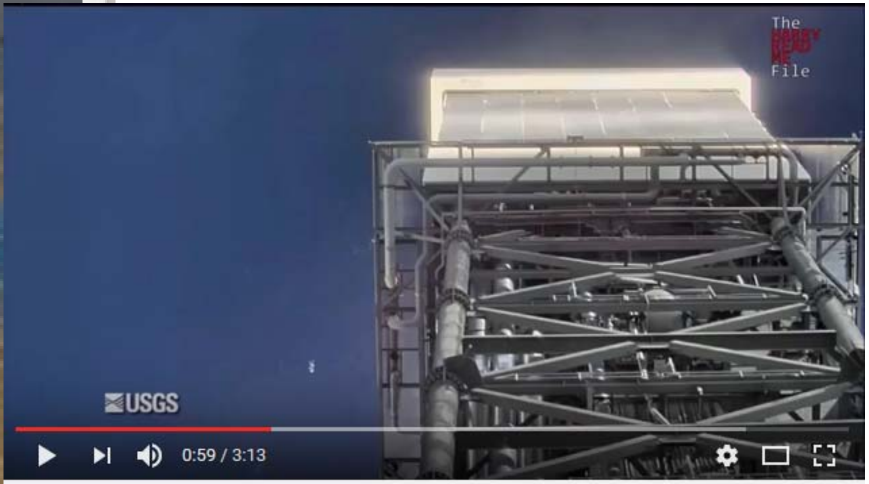
Central Receiver System

Ivanpah: World's Largest Solar Thermal

Report: Ivanpah solar project kills 3,500 birds

James Meier, The Desert Sun 5:30 p.m. PT April 23, 2015





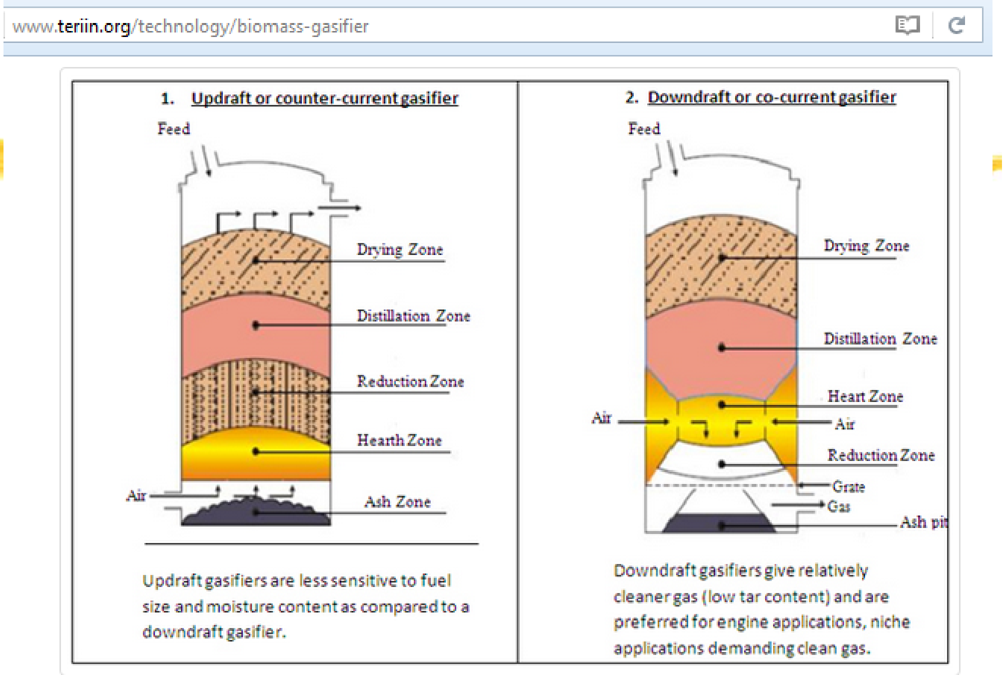
USGS releases bird and insect incineration footage from Ivanpah Solar Electric Facility

Comparison of Concentrating Solar Power Systems

	1 Dish Stirling	**2 Parabolic Trough**	**3 Central Receiver**
Intensity of solar radiation focused on to receiver (“sun”)	3000 suns * 1 sun = 1 kW/m^2	100 suns	1000 suns
Efficiency	21%	14%	16%
Land Area Required/MW	4 acres	5 acres	8 acres
Electricity Supply Reliability (with Thermal Storage)	Low	Better	Better
Cooling Needs	No cooling required (Best)	Yes (Poor)	Yes (Poor)

Biomass for Electricity

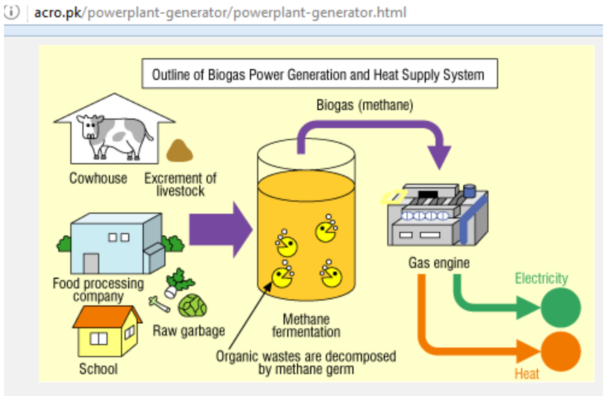
- Waste Residues → Fuel → Steam Turbine/Generator
- 20% efficiency
- Generation cost at $0.09/kWh
- Co-firing approach: Burn Biomass along with coal (less emission)
- Biomass for Gas Turbine
    - Gasification: Conversion of biomass fuel to gaseous combustible gas ("producer gas") through a thermochemical reactions. Low heating value gas.
- CIG/GT (Coal-Integrated Gasifier/Gas Turbine) System
- BIG/GT (Biomass-Integrated Gasifier/Gas Turbine)System: $0.05/kWh



www.teriin.org/technology/biomass-gasifier

Updraft gasifiers are less sensitive to fuel size and moisture content as compared to a downdraft gasifier.

Downdraft gasifiers give relatively cleaner gas (low tar content) and are preferred for engine applications, niche applications demanding clean gas.

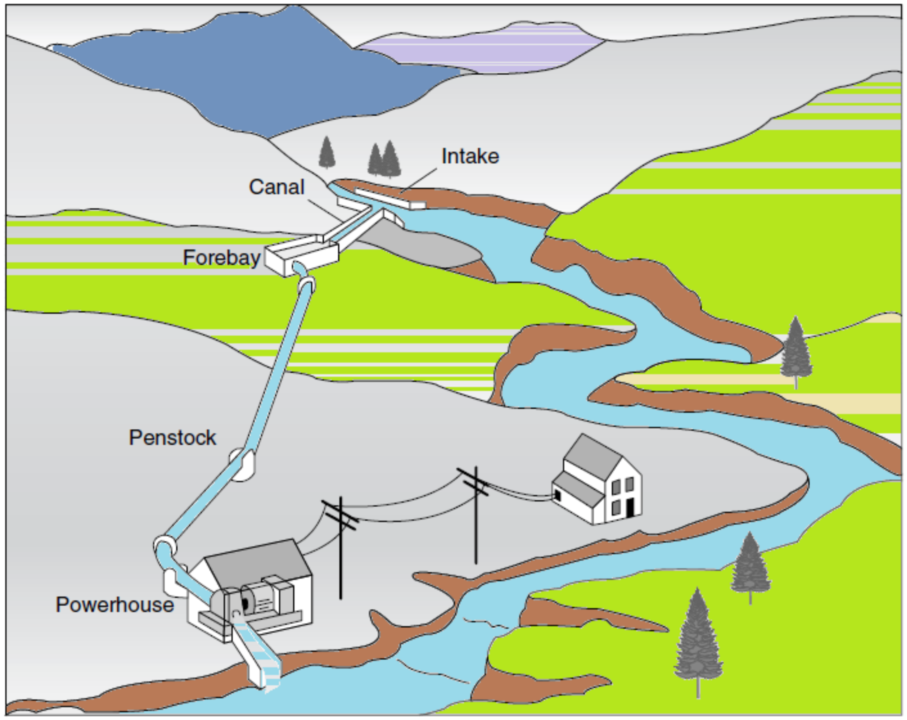


acro.pk/powerplant-generator/powerplant-generator.html

Outline of Biogas Power Generation and Heat Supply System

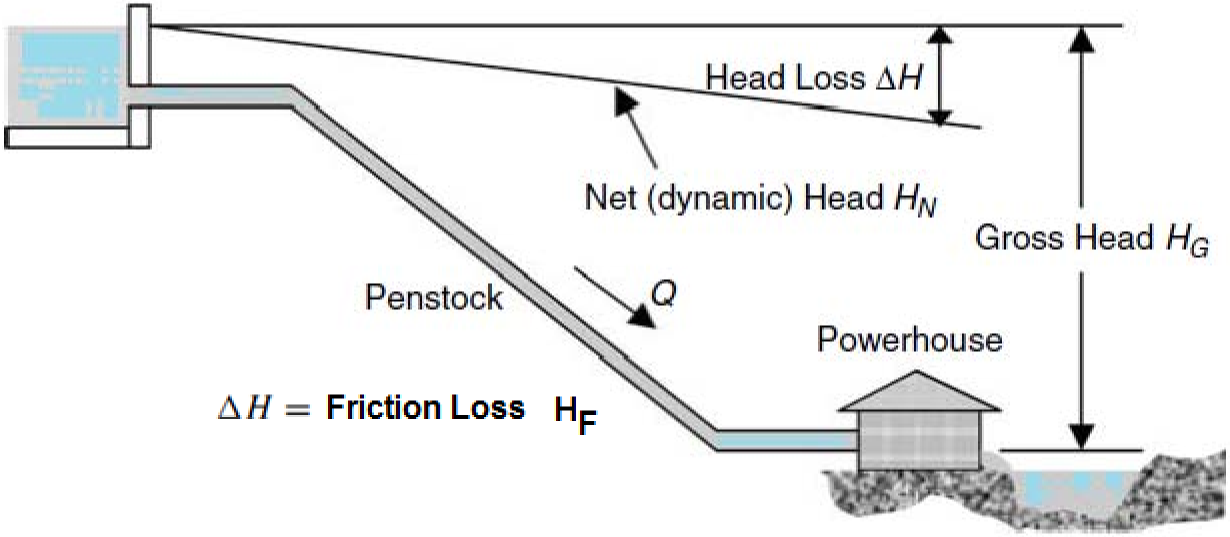
Micro-Hydropower Systems

- Hydropower generation: 9% of U. S. electricity
- Large scale – 30 MW or bigger
- Small-Scale Hydropower: 100 kW – 30 MW
- Micro-Scale Hydropower: smaller than 100 kW
- “Run-of-the-river” System:
  No dam; no ecosystem disruption
- “Penstock”: A sluice or gate of intake structure for controlling water flow.
- River → Penstock → Hydraulic Turbine → Generator



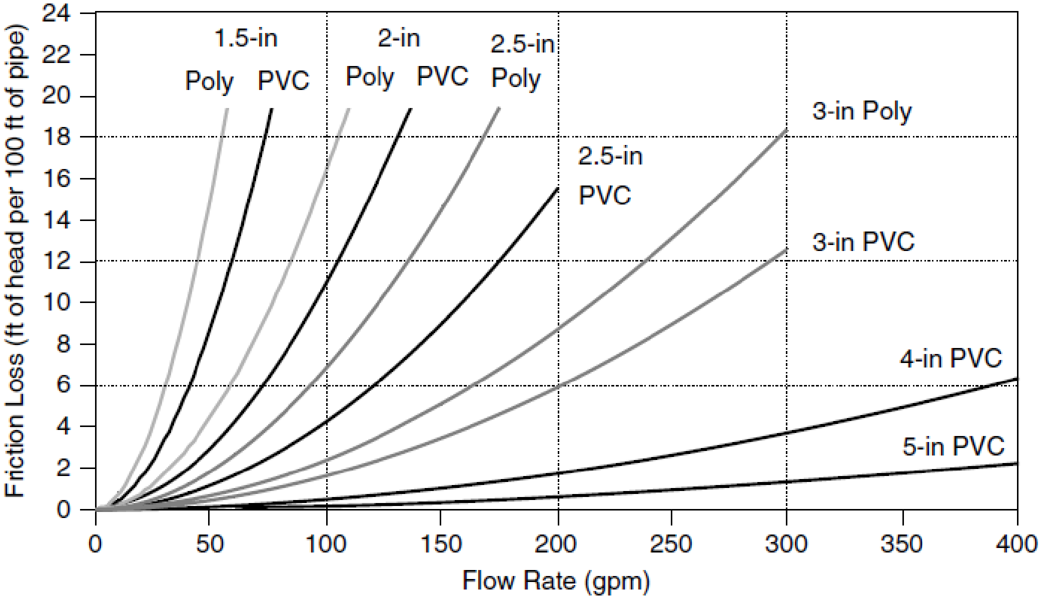
Micro-Hydropower Systems

- P(W) = ???
- Net Head (H_N) = Gross Head (H_G) – Friction Head (Pipe Loss)(H_F)



Micro-Hydropower Systems – Example - Handout

- Net Head = Gross Head – Friction Head (Pipe Loss)
- Friction Head Example:
- Q1: “150 gpm is taken from a creek and delivered through 1000 ft of 3-in diameter polyethylene (PE) pipe to a turbine 100 ft lower than the source. Using the rule-of-thumb, estimate the power (W) delivered by the turbine/generator.”
- Q2: In a 30-day month, how much electric energy (Wh) would be generated?

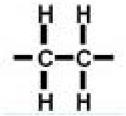


With 50% Efficiency:

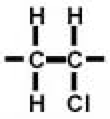
$$P(\text{kW}) \approx 5Q(\text{m}^3/\text{s})\ H_N(\text{m})$$

$$P(W) \approx \frac{Q(\text{gpm})\ H_N(\text{ft})}{10}$$

Polyethylene (PE)



Polyvinyl chloride (PVC)

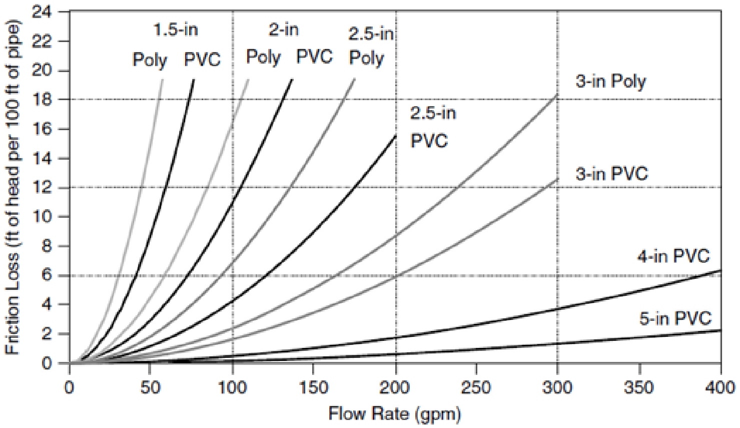


Micro-Hydropower Systems

- What would be the theoretical maximum power deliverable for a given pipeline?

$\boxed{HF = \text{Friction Loss}}$

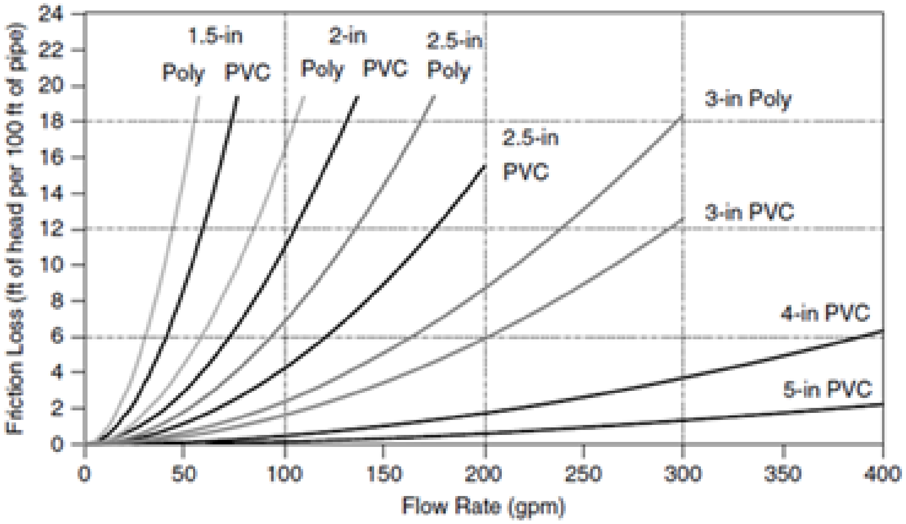
$H_F \propto Q^2$



- Theoretical maximum power delivered by a pipeline occurs when the <u>Friction Loss (head) of the pipeline is 1/3 of the Gross Head.</u>

Micro-Hydropower Systems – Example2

- Optimal Power Example: $\boxed{HF = \frac{1}{3} H_G}$
- Q: Water is taken from a creek and delivered through 1000 ft of 3-in diameter polyethylene (PE) pipe to a turbine 100 ft lower than the source. (a) Find the optimal flow rate for the 1000 ft of 3-in PE pipe; (b) How much power then can be generated?
- ANSWER



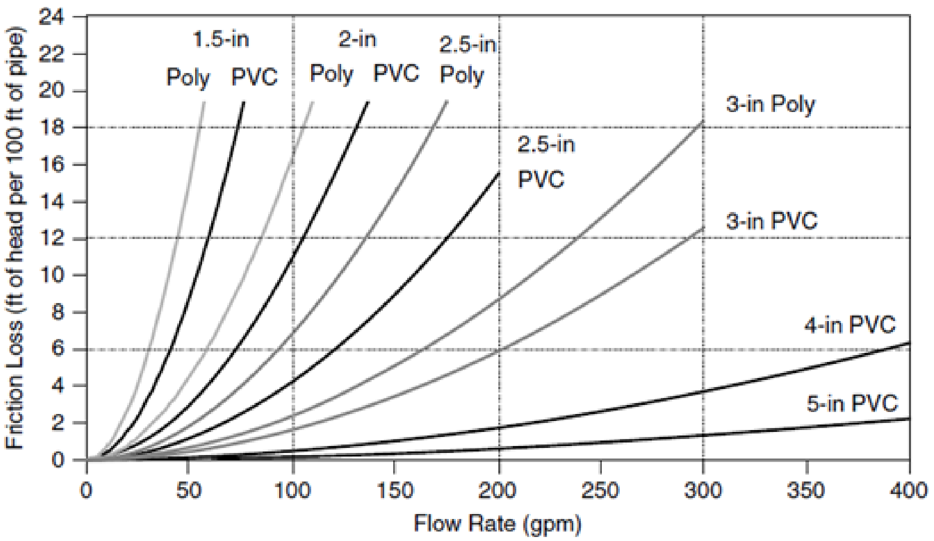
Class Activity 3: Micro-Hydropower Systems

Suppose 200 gpm of water is taken from a creek and delivered through 800 ft of 3-inch diameter PVC pipe to a turbine100 ft lower than the source. If the turbine/generator has an efficiency of 40%, find the electrical power that would be delivered. In a 30-day month, how much energy would be provided?

$$P(W)_{\text{delivered}} = \frac{eQ(\text{gpm})\ H_N(\text{ft})}{5.30}$$

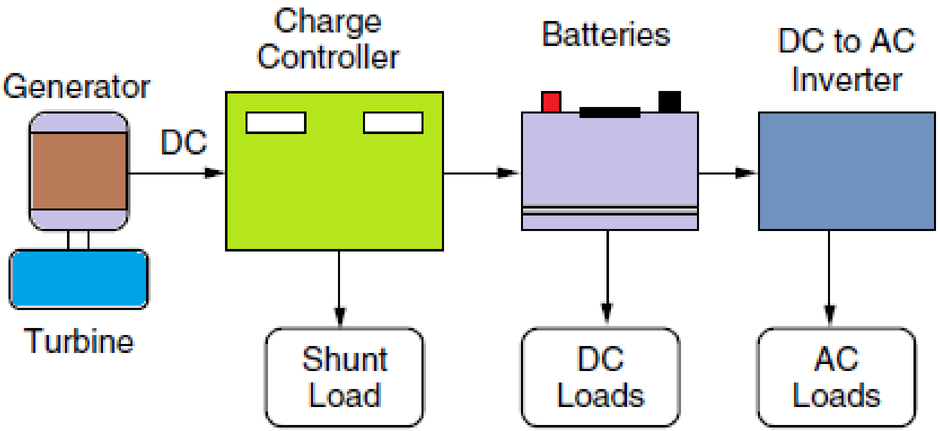
$$P(\text{kW}) = 9.81eQ(\text{m}^3/\text{s})\ H_N(\text{m})$$

e is the efficiency of the turbine/generator



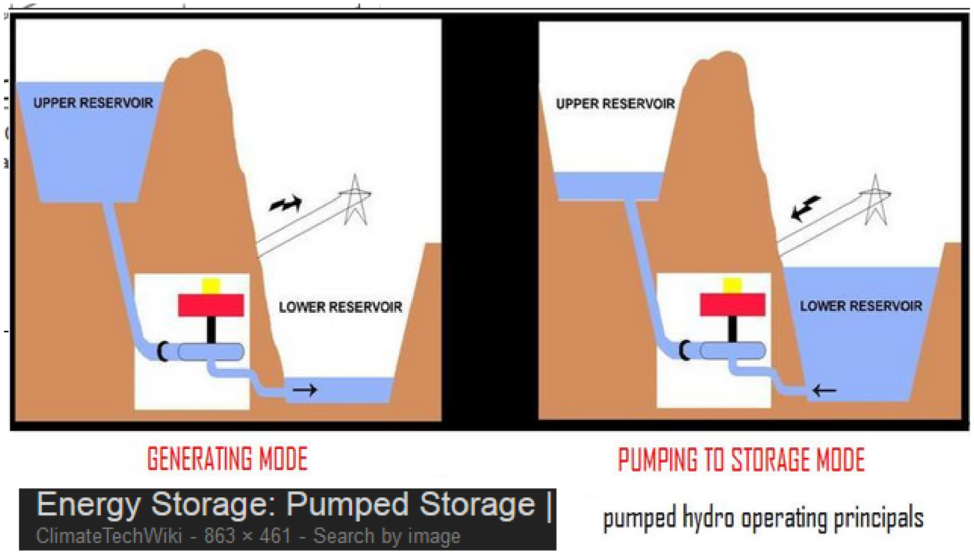
Micro-Hydropower Systems – Energy Storage

- Battery-Based Micro-Hydro System
  - Small size to meet the average daily demand
  - Smaller size battery would do because of very low intermittency - 2 day storage
  - Shunt Load is to divert excessive energy to protect battery of overcharging



Micro-Hydropower Systems – Energy Storage

- Pumped-Hydro System
  - Run the pump during the low-cost off-peak hours
  - Generate and sell electricity during peak hours
  - Alleviate the intermittency of solar/wind electricity
  - Round trip energy efficiency: 70 – 80 %
  - Wind–Hydro Integration: Wind energy (pump run) stored as potential (water) energy
  - Challenges:
    - High capital cost
    - Long construction time
    - Dependent on market structure (dynamic and buy-back price)



Energy Storage: Pumped Storage |
ClimateTechWiki - 863 × 461 - Search by image

pumped hydro operating principals

Micro-Hydropower Systems – Pumped Hydro

CEZ GROUP

Czech Republic

Dalešice Pumped Storage Power Plant

The Dalešice waterworks was built as a part of the nearby Dukovany Nuclear Power Station project. It includes the Dalešice water reservoir with the capacity of 127 million m3 of water, the Mohelno equalization basin, the Dalešice Pumped-Storage Hydroelectric Power Station, and the Mohelno run-off-river hydroelectric power station.

The pumped-storage hydroelectric power station is equipped with four sets of reversing Francis turbines (112.5 MW ea) for a 90 m head.

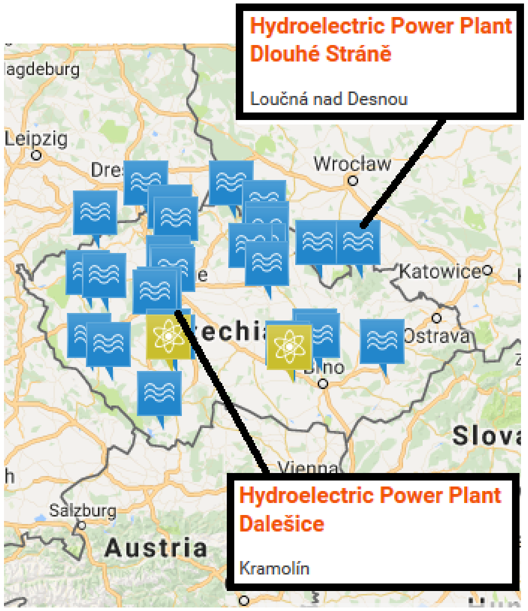
Rated Power in kW	450,000

Czech Republic

Dlouhé Stráně Pumped Storage Power Plant

The Dlouhé Stráně Hydroelectric Power Station is situated in Moravia, near Loučná nad Desnou in the district of Šumperk. It has the largest reversing water turbine in Europe, 325 MW; it has the largest head of all power stations in the Czech Republic, 510.7 m; and it has the largest installed capacity in the Czech Republic, 2 x 325 MW. Total capacity is 3,200 MWh.

Rated Power in kW	650,000



Hydroelectric Power Plant Dlouhé Stráně

Loučná nad Desnou

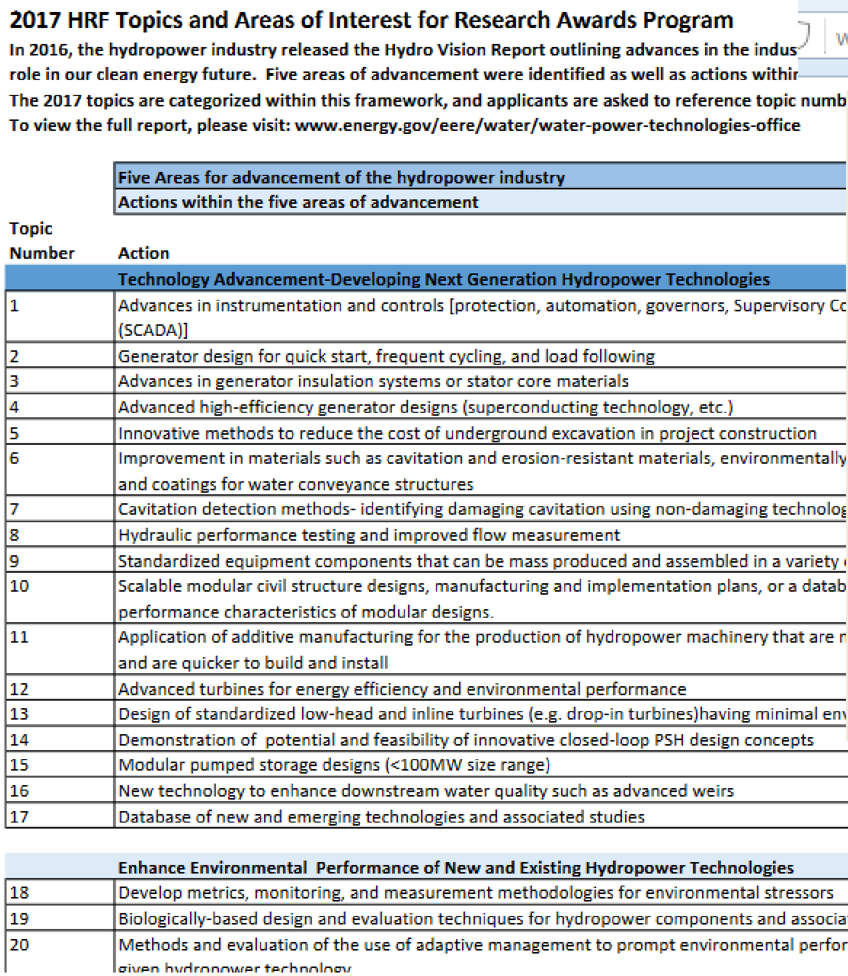
Hydroelectric Power Plant Dalešice

Kramolín

Micro-Hydropower Systems – Pumped Hydro

Pumped hydro in Spain: *The upper reservoir of the Cortes-La Muela hydroelectric station in the municipality of Valencia, Europe's largest such facility.*

Micro-Hydropower Systems – Hydro Research and Award Program



2017 HRF Topics and Areas of Interest for Research Awards Program

In 2016, the hydropower industry released the Hydro Vision Report outlining advances in the indus
role in our clean energy future. Five areas of advancement were identified as well as actions withir
The 2017 topics are categorized within this framework, and applicants are asked to reference topic numb
To view the full report, please visit: www.energy.gov/eere/water/water-power-technologies-office

Five Areas for advancement of the hydropower industry
Actions within the five areas of advancement

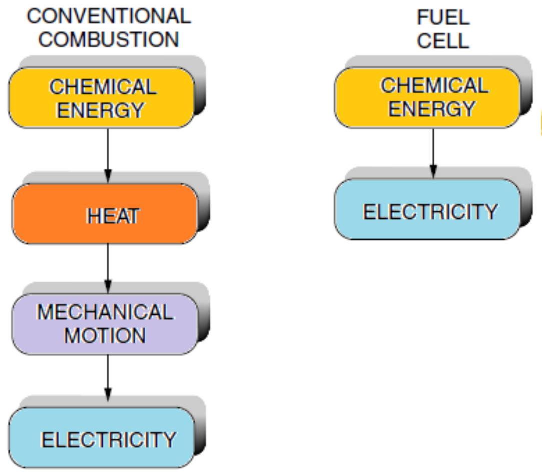
Topic Number	Action
	Technology Advancement-Developing Next Generation Hydropower Technologies
1	Advances in instrumentation and controls [protection, automation, governors, Supervisory Cc (SCADA)]
2	Generator design for quick start, frequent cycling, and load following
3	Advances in generator insulation systems or stator core materials
4	Advanced high-efficiency generator designs (superconducting technology, etc.)
5	Innovative methods to reduce the cost of underground excavation in project construction
6	Improvement in materials such as cavitation and erosion-resistant materials, environmentally and coatings for water conveyance structures
7	Cavitation detection methods- identifying damaging cavitation using non-damaging technolog
8	Hydraulic performance testing and improved flow measurement
9	Standardized equipment components that can be mass produced and assembled in a variety
10	Scalable modular civil structure designs, manufacturing and implementation plans, or a datab performance characteristics of modular designs.
11	Application of additive manufacturing for the production of hydropower machinery that are r and are quicker to build and install
12	Advanced turbines for energy efficiency and environmental performance
13	Design of standardized low-head and inline turbines (e.g. drop-in turbines)having minimal env
14	Demonstration of potential and feasibility of innovative closed-loop PSH design concepts
15	Modular pumped storage designs (<100MW size range)
16	New technology to enhance downstream water quality such as advanced weirs
17	Database of new and emerging technologies and associated studies
	Enhance Environmental Performance of New and Existing Hydropower Technologies
18	Develop metrics, monitoring, and measurement methodologies for environmental stressors
19	Biologically-based design and evaluation techniques for hydropower components and associated water control facilities
20	Methods and evaluation of the use of adaptive management to prompt environmental performance improvements to given hydropower technology

www.hydrofoundation.org/2017-research-award-application-and-instructions.html

Hydro Foundation

Fuel Cells

- “Gaseous Voltaic Battery” by William Grove in 1839
- “Fuel-Cell” by Mond and Langer, 1.5W-cell with 50% efficiency
- Francis Bacon, 5-kW alkaline fuel cell (AFC) which powered 2-ton capacity fork-lift in 1952
- NASA on-board electric power source
- Fuel Cell: Conversion of Energy Contained in a Fuel (Hydrogen, natural Gas, Methanol, Gasoline, etc) directly into electrical power
- Fuel-to-Electric Efficiency: 65%
- Fuel Cell Co-Generation (Electricity + Heat): Efficiency 80%

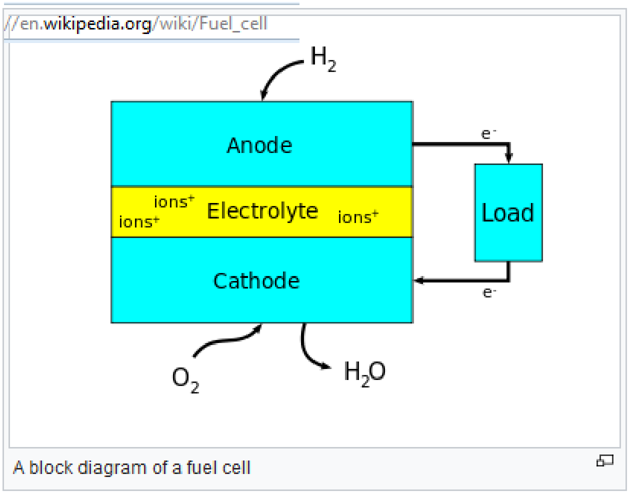


CONVENTIONAL COMBUSTION

CHEMICAL ENERGY → HEAT → MECHANICAL MOTION → ELECTRICITY

FUEL CELL

CHEMICAL ENERGY → ELECTRICITY

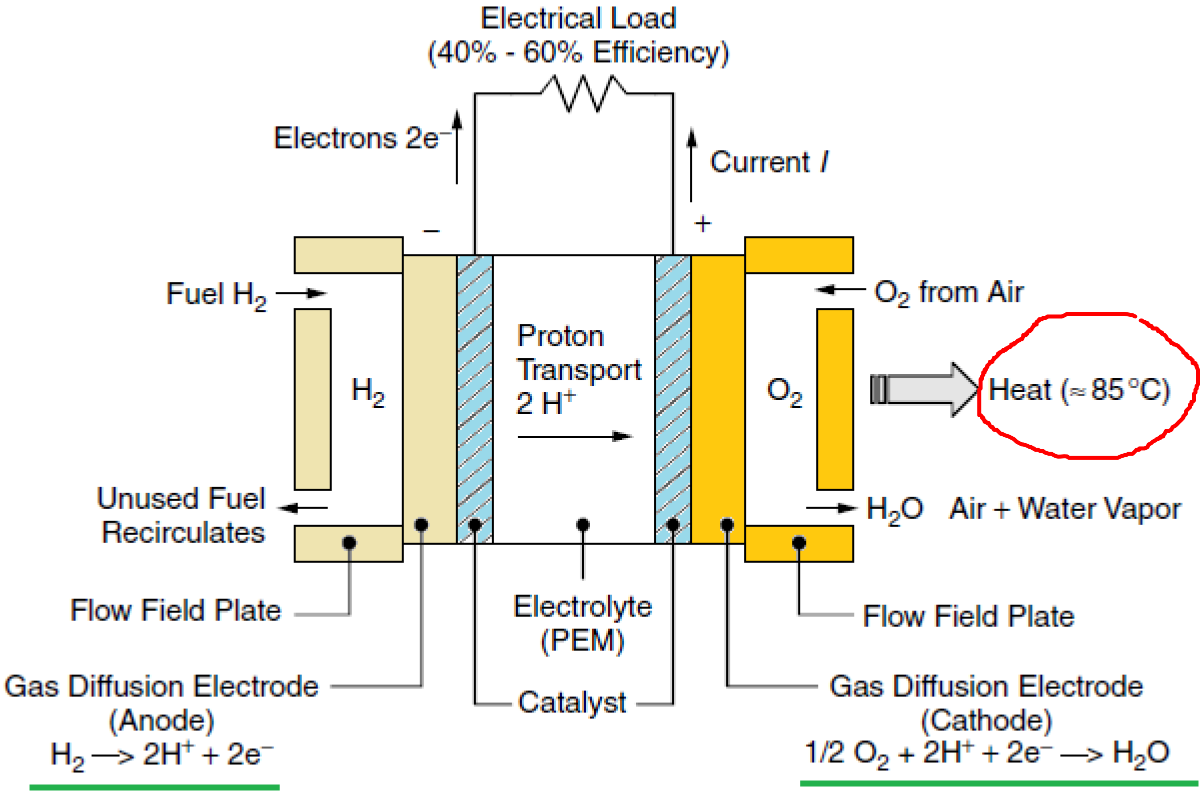


//en.wikipedia.org/wiki/Fuel_cell

A block diagram of a fuel cell

Fuel Cells – Basic Configuration

- Basic Configuration
- Membrane: **Proton-Exchange Membrane** (PEM): capable of conducting positive ions only (not electrons nor neutrons)
- **Fuel (H2)** is dissociate in to **Protons (H+) and Electrons (e-)**
- Catalyst: Help drive the reaction to the right
- At the Cathode, the protons (H+) combines with Oxygen (O2) and the (Returning) Electrons (e-) to become **water (H2O)**



Basic configuration of a proton-exchange membrane (PEM) fuel cell.

Fuel Cells – Electrical Output

Current Through the Load (I)

I = n*N*q

$$I\,(\mathrm{A}) = n\left(\frac{\mathrm{mol}}{\mathrm{s}}\right)\cdot 6.022\times 10^{23}\left(\frac{\text{molecules H}_2}{\mathrm{mol}}\right)\cdot\frac{2\text{ electrons}}{\text{molecule H}_2}\cdot 1.602\ \times 10^{-19}\left(\frac{\text{coulombs}}{\text{electron}}\right)$$

$$I\,(\mathrm{A}) = 192,945n$$

q = charge on an electron = 1.602×10^{-19} coulombs

N = Avogadro's number = 6.022×10^{23} molecules/mol

v = volume of 1 mole of ideal gas at STP = 22.4 liter/mol

n = rate of flow of hydrogen into the cell (mol/s)

I = current (A), where 1 A = 1 coulomb/s

V_R = ideal (reversible) voltage across the two electrodes (volts)

P = electrical power delivered (W)

Work or Electricity a fuel cell can deliver

Maximum Electrical Output (We)

We = 237.2 kJ/{mol of H2}

→

Power [Watts] Delivered to the Load

$$P\,(\mathrm{W}) = 237.2(\mathrm{kJ/mol}) \times n\,(\mathrm{mol/s}) \times 1000(\mathrm{J/kJ}) \cdot \frac{1\ \mathrm{W}}{\mathrm{J/s}} = 237{,}200n$$

Fuel Cells – Electrical Output

Power [Watts] Delivered to the Load

$$P(\mathrm{W}) = 237.2(\mathrm{kJ/mol}) \times n(\mathrm{mol/s}) \times 1000(\mathrm{J/kJ}) \cdot \frac{1\ \mathrm{W}}{\mathrm{J/s}} = 237{,}200n$$

$$I(\mathrm{A}) = 192{,}945n$$

Voltage across terminal

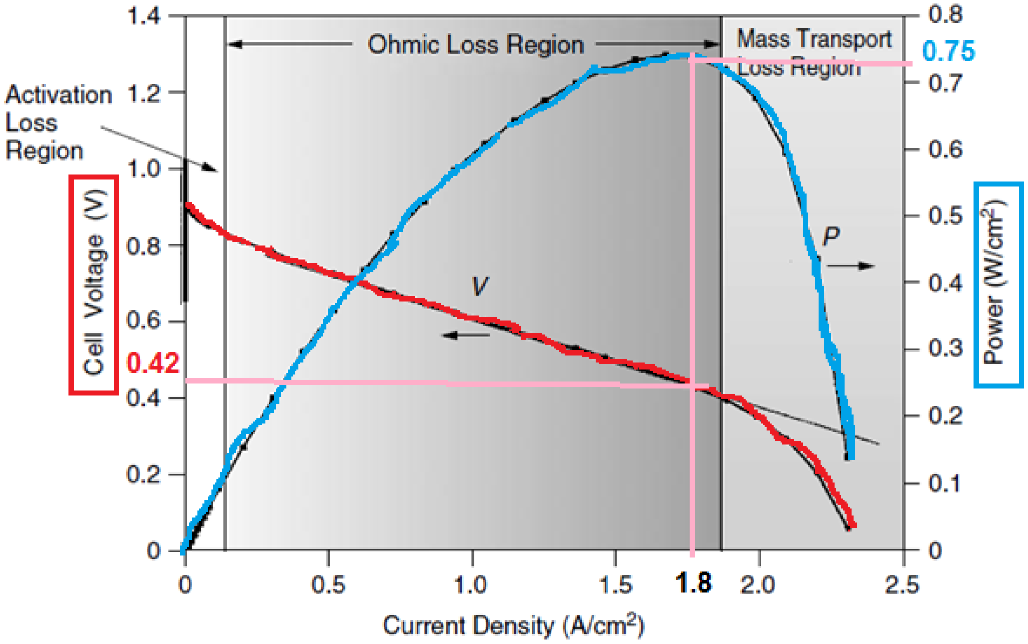
$$V_R = \frac{P(\mathrm{W})}{I(\mathrm{A})} = \frac{237{,}200n}{192{,}945n} = 1.229\ V$$

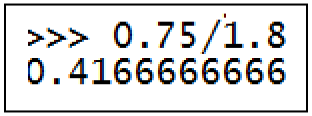
Hydrogen Rate: Hydrogen needed to ideal fuel cell per kWh

$$\text{Hydrogen rate} = \frac{n(\mathrm{mol/s}) \times 2(\mathrm{g/mol}) \times 3600\ \mathrm{s/h}}{237{,}200n(\mathrm{W}) \times 10^{-3}(\mathrm{kW/W})} = 30.35\ \mathrm{g\,H_2/kWh}$$

Fuel Cells – Electrical Characteristics of Real Fuel Cell

- **Activation Loss**: Energy required by the catalyst to initiate the reaction
- **Ohmic Loss**: current passing through the internal resistance posed by the electrolyte membrane, electrodes, and such.
- **Mass Transport Loss**: Hydrogen and Oxygen gases have difficulties reaching the electrode
- Result: V-I Curves
  - Open Circuit Voltage: ~ 1V (cf. Ideal case at 1.229 V)
  - Max Power = 0.75 W @1.8A → 0.42 V
  - V = 0.85 – 0.25J J: Current Density
  - V = 0.85 – [0.25/A]*I A: Cell Area



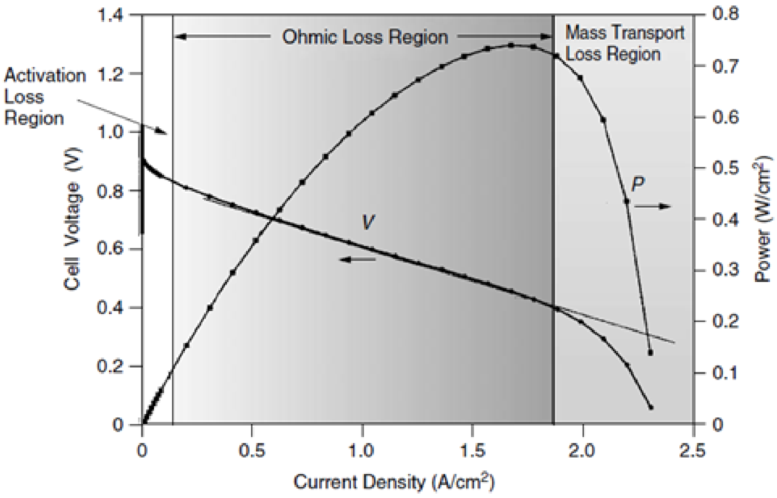


```
>>> 0.75/1.8
0.4166666666
```

$$V = 0.85 - 0.25J = 0.85 - \frac{0.25}{A}I$$

Class Activity 4 – Fuel Cell

- Rough Parameters of a Home-Scale Fuel Cell Stack
- Question: A 1-kW fuel cell stack operating on a continuous basis, providing all of the electrical needs of a typical U.S. house, generates 48 V dc with cells operating at 0.6 V each. How many cells would be needed and what should be the membrane area of each cell?



$$V = 0.85 - 0.25J = 0.85 - \frac{0.25}{A} I$$