Track: The Power Connection: Electric Generation for Gas Utilities

Unit #3: Electric Generation Process

Presentation Outline

- Electric Generation Methods
- Processes for Power Generation
- Role of Natural Gas in Electric Generation
- Energy Storage Systems

Electric Generation Methods

- Thermal
- Hydro
- Nuclear
- Renewable
- Geothermal

Electric Generation

Electric Generation Methods – The technologies and techniques through which energy is captured from a source and converted into electricity.

"What?"

Electric Generation Processes – The systems and steps involved in converting energy from a source into electricity.

"How?"

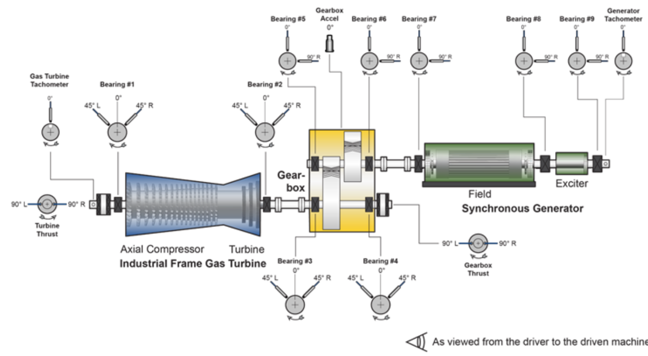
Work to Electricity – Rotational Generators

Electric Generators are a key component of most energy generation methods. **Rotational generators** capture work in the form of a rotating shaft, and use it to spin configurations of magnets and coils of wire. The changing magnetic fields created by this rotation induce current in the wires, which is electricity.

Rotational generators are the traditional, scale-able way to convert large amounts of mechanical energy to electricity. **Gear-boxes** help convert high-torque, slower spin to lower-torque, faster spin and visa versa, conserving energy.

Wind and hydro power use air and water to turn a generator shaft directly.

Fuel-based energy generation must use heat and resulting pressures from fuel directly, or a separate medium like water or steam to turn a turbine, which can in turn spin a generator shaft.



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Work to Electricity – Linear Generators

More recent **linear generators** capture work in the form of linear motion, and use it to move magnets or coils of wire back and forth. Just like a rotational generator, the changing magnetic fields created by this motion induces current in the wires, which is electricity.

Linear generators can be smaller and have fewer moving parts than rotational generators, and can be useful in capturing otherwise inaccessible energy such as that from:

- Waves
- Vibrations
- Pressure

A recent development in this area is using linear generators to capture energy in natural gas pressure reducing stations. Energy was used to pressurize the gas for transport, and it can be partially captured on the back end when depressurizing.

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Thermal Generation

Thermal generation uses the burning of fuel to drive mechanical processes that can be converted into electricity.

Source: **Fuels such as natural gas, oil, coal, etc.**

Mechanism: **Burning fuel exerts kinetic forces on objects through the phase changes, expansion, and/or convection of gases and fluids.**

Some key equipment: **Engines, turbines, generators.**

Upstream Processes: Many fuels must be extracted from the Earth and processed in some way before transport or burning.

Original Source: Solar energy captured in ancient food chains and modified through geological processes over millions of years.

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Hydro

Hydro generation uses the natural movement of water to drive mechanical processes that can be converted into electricity.

Source: **Movement of water between elevations.**

Mechanism: **Moving or falling water exerts kinetic force on objects as it is pulled downward by gravity.**

Some key equipment: **Dams, reservoirs, turbines, generators.**

Upstream Processes: Water in geographically advantageous locations must usually be restricted, creating reservoirs which modify landscapes.

Original Source: Solar energy captured in the evaporation of water and creation of wind to cause precipitation in higher elevations.

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Nuclear

Nuclear fission generation uses heat generated from the natural **decay** of heavy radioactive materials into lighter ones at an atomic level to drive mechanical processes that can be converted into electricity.

Source: **Radioactive materials and the quantum phenomena their atoms experience.**

Mechanism: **A controlled chain reaction of decaying radioactive materials generates heat, which can in turn be converted to kinetic forces on objects through the boiling and expansion of water into steam.**

Some key equipment: **Reactor, coolant, turbines, generators.**

Upstream Processes: Radioactive material must be extracted from the Earth and processed before transport and use.

Original Source: Solar phenomena before the creation of the Earth.

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Nuclear

Nuclear fusion generation uses energy generated from the forced **combination** of light materials into heavier ones at an atomic level to drive mechanical processes that can be converted into electricity.

Source: **The quantum phenomena atoms experience when forcibly combined.**

Mechanism: **A controlled combination of materials at an atomic level generates heat and other phenomena which can be captured and converted to electricity.**

Some key equipment: **TBD.**

Upstream Processes: Suitable material must be extracted or collected from the Earth and processed before transport and use.

Original Source: Solar phenomena before the creation of the Earth.

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Wind

Wind generation uses the natural movement of air to drive mechanical processes that can be converted into electricity.

Source: **Movement of air between atmospheric areas of high and low pressure.**

Mechanism: **Moving air exerts kinetic force on objects as it is pulled through the atmosphere.**

Some key equipment: **Towers, blades, gearboxes, generators.**

Upstream Processes: Few other than the construction of the turbines themselves.

Original Source: Uneven heating and cooling of the Earth by the sun generates areas of high and low air pressure, which causes wind as air moves from areas of high to low pressure.

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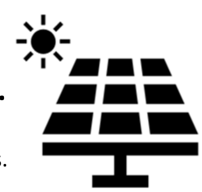
Solar

Solar generation uses the energy inherent in light to drive mechanical or electrical processes that can be converted into electricity.

Source: **Energy inherent in light from the sun.**

Mechanism: **The excitement of electrons created by light in certain combinations of materials which can drive electrical charge** OR **the heat generated by sunlight when concentrated which can be converted to kinetic forces on objects through the boiling and expansion of water into steam.**

Some key equipment: **Photovoltaic panels** OR **mirrors, boilers, turbines, generators.**



Upstream Processes: Few other than the construction of the solar panels or mirrors themselves.

Original Source: Light from the sun, which in turn is a result of nuclear fusion.

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Geothermal

Geothermal generation uses the heat created and stored below the Earth's crust to drive mechanical processes that can be converted into electricity.

Source: **Heat that radiates from the Earth's mantle into the outer crust.**

Mechanism: **Heat is brought up from below the ground and can be converted to kinetic forces on objects through the boiling and expansion of water into steam.**

Some key equipment: **Wells, pumps, turbines, generators.**

Upstream Processes: Few other than the construction of the wells and plants themselves.

Original Source: Heat still present from the creation of the Earth, radioactive decay, gravitational pressure, and frictional heating in Earth's liquid mantel.

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Processes for Power Generation

- Turbine-Driven Generation
- Internal Combustion Engines
- Steam Turbines
- Combined Cycle Systems
- Hydroelectric Power
- Fuel Cells, Wind Turbines
- Photovoltaic Systems
- More

Gas Turbines

Turbines are devices that can convert kinetic energy from a moving gas or fluid into mechanical energy.

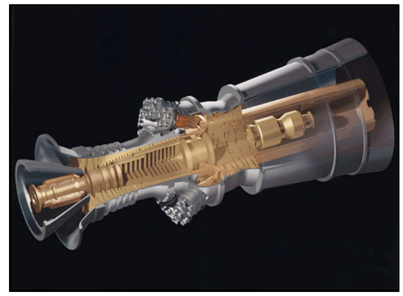
Gas turbines ignite fuel with an oxidizer (air) at high pressure and velocity, and direct the hot gases from the burning fuel onto blades which create torque on a central shaft, causing it to spin.

This spinning shaft can be used to spin magnets or coils in a **generator**. The movement and constant switching of polarity of magnetic fields through coils of wire creates electricity.

Power plants that commonly rely on gas turbines:

- Natural gas
- Oil

Common efficiency at converting fuel to electricity ≈ 30% - 50%



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Internal Combustion Engines

Internal combustion engines are **heat engines** that convert kinetic energy from the rapid expansion of burning fuel in a confined space into mechanical energy.

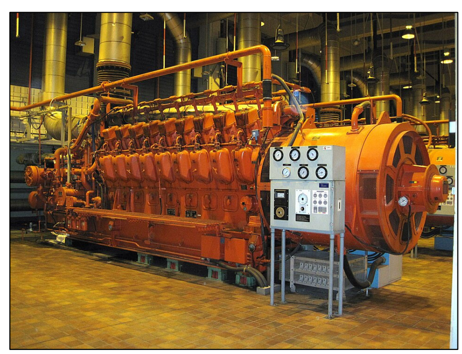
These engines ignite fuel with an oxidizer (air) in a **combustion chamber**, which causes the resulting high temperature and pressure gases to exert force on a component that creates torque on a central shaft, causing it to spin.

Internal combustion engines, like gas turbines, must be paired with a **generator** to produce electricity.

Power plants that commonly rely on internal combustion engines:

- Natural gas
- Oil (Deisel)

Common efficiency at converting fuel to electricity ≈ 30% - 50%



By Jean-Daniel Drapeau-Mc Nicoll - De l'usine d'épuration des eaux usées de Montréal, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=11762515

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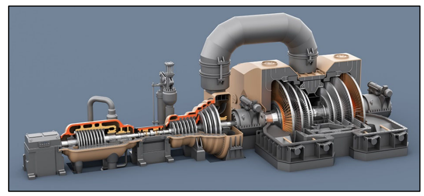
Steam Turbines

Steam turbines are driven by high-pressure steam, generated by boiling water in a confined space. The pressurized steam pushes against blades which create torque on a central shaft, causing it to spin.

As before this spinning shaft can be used to spin magnets or coils in a **generator**, generating electricity.

Power plants that commonly rely on steam turbines:
- Nuclear
- Coal

Common efficiency at converting fuel to electricity ≈ 30% - 50%



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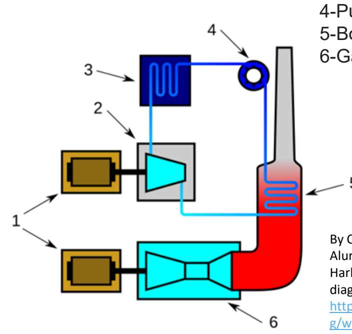
Combined Cycle Systems

Combined cycle power plants improve on the efficiency of traditional gas turbine and steam turbine power plants by combining them. Fuel is burned in a gas turbine to drive a generator, and waste heat from this process is then used to boil water into steam which is used to drive a steam turbine with generator.

Power plants that commonly use combined cycle:
- Natural gas
- Oil

Common efficiency at converting fuel to electricity ≈ 60%

Legend:
1-Electric generators
2-Steam turbine
3-Condenser
4-Pump
5-Boiler/heat exchanger
6-Gas turbine



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Hydroelectric Power

Hydroelectric power plants use various designs of hydro turbines to convert kinetic energy from water movement due to gravity into mechanical energy.

These turbines are driven by water hitting or flowing through them, often using blades, to create torque on a central shaft, causing it to spin.

Once again, this rotation is used in an electrical generator.

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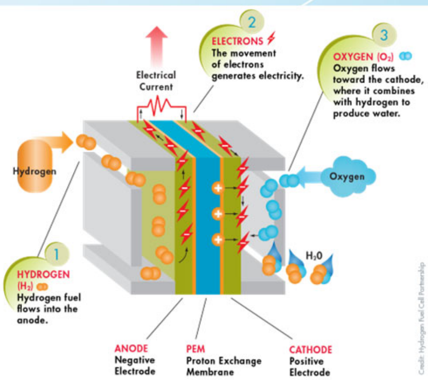
Fuel Cells

Fuel cells use an electrochemical reaction to convert chemical energy stored in a fuel into electrical energy.

Hydrogen fuel cells are the most common fuel cell. Hydrogen releases energy when combined with oxygen in the air, making water. When done by simple burning, this generates heat. In a fuel cell, this combination of molecules is more controlled than in combustion.

Hydrogen fuel cells use a catalyst to separate hydrogen protons from their electrons. These two components follow different pathways to recombine with oxygen, creating water. The separate flow of electrons through a circuit in this pathway is electricity.



Fronter Energy, Inc.

The promise of hydrogen fuel cells is clean energy with higher efficiency than regular combustion of the fuel and without harmful emissions. Hydrogen takes energy to produce, however. Depending on the energy used, these benefits are diminished.

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Wind Turbines

Wind turbines are devices that can convert kinetic energy from naturally occurring wind into mechanical energy.

Wind hits the blades of a large structure, which creates torque on a central shaft, causing it to spin.

Again, this is paired with an electric generator to produce electricity.

Collections of wind turbines (farms) are often categorized as **onshore** or **offshore**, which describes whether they are installed on land or in the water.

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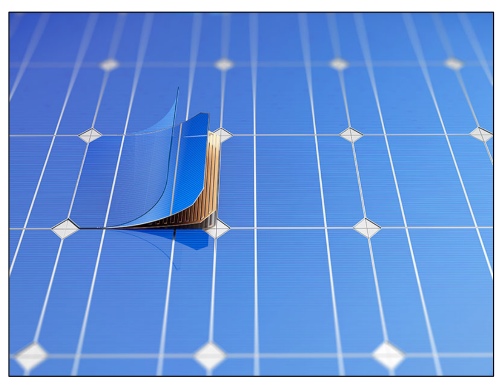
Photovoltaic

Photovoltaic solar cells are devices that capture energy from sunlight and, through the photovoltaic effect of special semiconducting materials, convert it directly into electricity.

Sunlight is absorbed by a semiconducting material that has been modified to create a "p-n junction." This sunlight excites electrons in the material, separating them from holes, which each take different paths to be recombined in the material. The separate flow of electrons through a circuit in this pathway is electricity.



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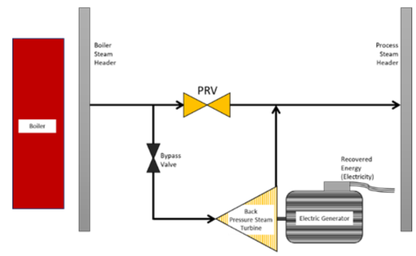
More

Other forms of power generation include:

- Wave capture through the use of rotational or linear generators.
- Energy from natural gas pressure reducing stations captured by linear generators.
- Back-pressure steam turbine generators which can capture electricity from reducing high-pressure steam from a process to lower-pressure steam that can be used for heating or another process.
- Methane in the form of biogas can be created or captured from wastewater treatment, landfills, and industrial digesters fed organic waste to be burned for electricity generation.



https://chp.ecatalog.ornl.gov/benefits/bpst-benefits

Back-pressure steam turbine generator

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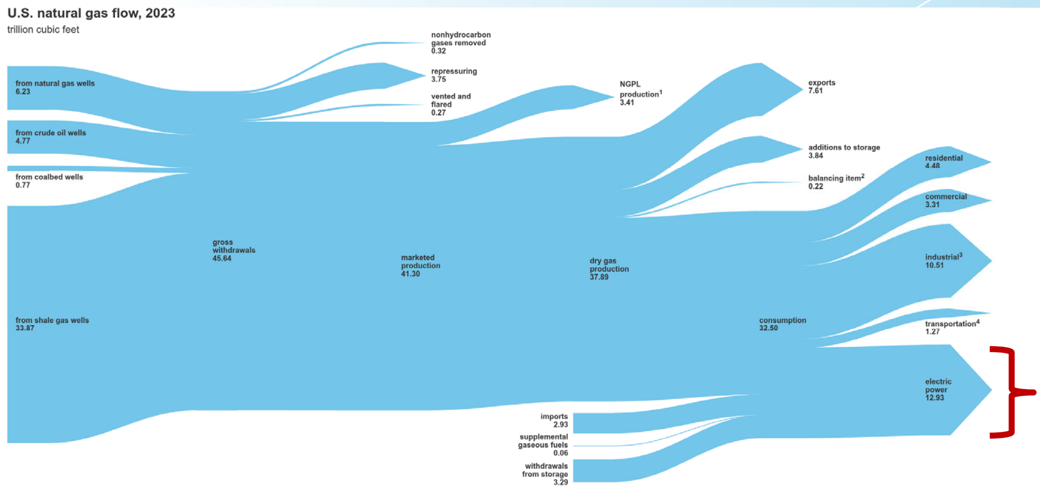
Role of Natural Gas in Electric Generation

- Combined Cycle
- Simple-Cycle Plants

Natural Gas in Electric Generation



[1] Natural gas plant liquids production (NGPL), gaseous equivalent. | [2] Quantities lost and imbalances in data due to differences among data sources. Excludes transit shipments that cross the U.S.-Canada border (i.e., natural gas delivered to its destination via the other country). | [3] Lease and plant fuel, and other industrial. | [4] Natural gas consumed in the operation of pipelines (primarily in compressors) and as fuel in the delivery of natural gas to consumers, plus a small quantity used as vehicle fuel. | Notes: • Data are preliminary. • Values are derived from source data prior to rounding for publication. • Totals may not equal sum of components due to independent rounding.

https://www.eia.gov/totalenergy/data/flow-graphs/natural-gas.php

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Natural Gas in Electric Generation

Natural gas serves a critical role in electric generation. Not only does its inclusion amongst other sources of electricity diversify and strengthen the grid, it:

- Is **flexible** and **responsive**, serving as both baseline and peaking generation.
- It is **cost-effective**: cheaper than many alternative fuels and needing lower capital investment than some other electricity sources to be brought online.
- It has **fewer harmful emissions** and waste products than other fossil fuels used for electrical generation.
- It **can be sourced domestically** in the US, building energy independence.
- It **can be stored** in meaningfully large amounts.
- **Infrastructure is well established**, creating a lower barrier to expansion of electrical generation services.

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Simple Cycle Plants

Simple cycle plants – Gas or oil burning plants that use just one gas turbine to generate electricity with no waste heat recovery.

Benefits:

- Low capital cost
- Fast construction
- Quick to reach full power

Downsides:

- Efficiency caps below 50%

Due to the lower efficiencies, but faster response times, these plants are commonly used to meet peaking grid demand. Low run times mean less energy is wasted, but power is there if/when needed.

Combined Cycle Plants

Combined cycle plants – Gas or oil burning plants that use both a gas turbine and a steam turbine to generate electricity, recovering waste heat from the first process for the second.

Benefits:

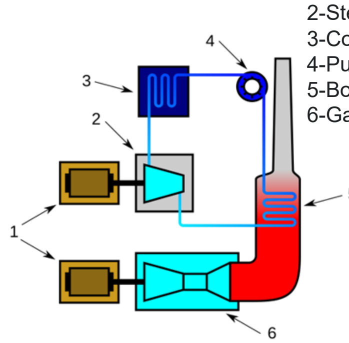
- Efficiencies around 60%
- Quick to produce power

Downsides:

- Higher capital cost
- Slower construction
- Slow to reach full power

Due to the higher efficiencies, but slower response times, these plants are commonly used to meet grid base and marginal loads. Longer run times at higher efficiencies mean less energy is wasted, but quick startup to meet peak demands is limited.

Legend:
1-Electric generators
2-Steam turbine
3-Condenser
4-Pump
5-Boiler/heat exchanger
6-Gas turbine



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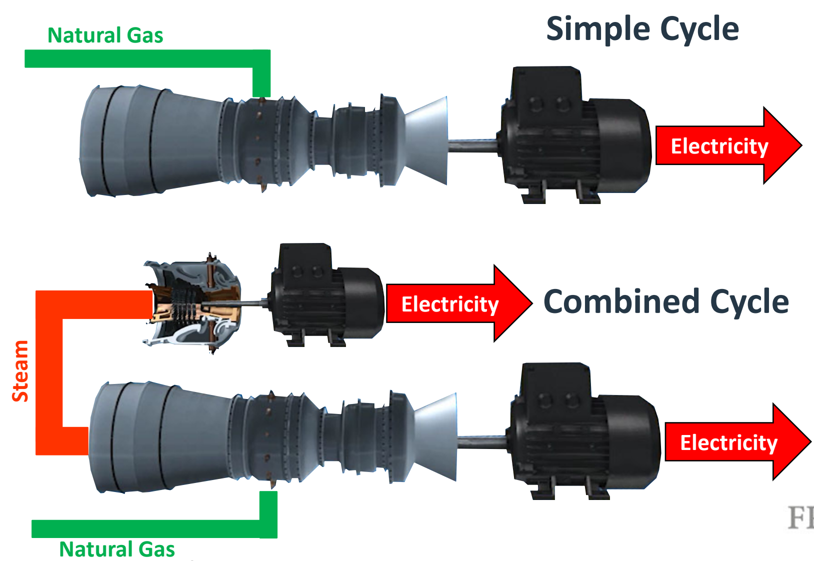
Simple vs. Combined Cycle



Energy Storage Systems

- Hydro-Pumped Storage
- Compressed Air
- Batteries
- Flywheels
- Natural Gas Generation as an Electric Storage Method
- Hydrogen to Power
- Ice Thermal Storage

Energy Storage

Energy storage is an old, but rapidly developing piece of the electricity grids. While traditional batteries have been around since the 1800s, grid-scale storage has not been possible with this technology until relatively recently. Hydro-pumped storage, on the other hand, has been around since the early 1900s.

Energy **storage** gives electrical grids flexibility in **production** and **use**. It fills a key gap between the two and is critical for:

- Reducing energy losses.
- Reducing energy costs by shifting peak loads to periods of low demand when generation is cheaper.
- Ensuring grid stability during unexpected events.
- More effectively integrating intermittent power sources, such as wind and solar, into the grid.

Source: https://en.wikipedia.org/wiki/Pumped-storage_hydroelectricity

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Hydro-Pumped

Hydro-pumped storage plants use excess energy from the grid to pump water from a low elevation to a higher one.

When this energy is needed, water is used to drive turbines, just as with standard hydroelectric power plants.

Benefits:

- Proven, dependable technology
- Scale-able
- Long-lasting

Shortfalls:

- Limited to geographically accommodating regions
- New reservoirs can have great environmental and social impacts
- Medium grid responsiveness

First grid-scale implementation: Early 1900s

Efficiency: 70% - 85%

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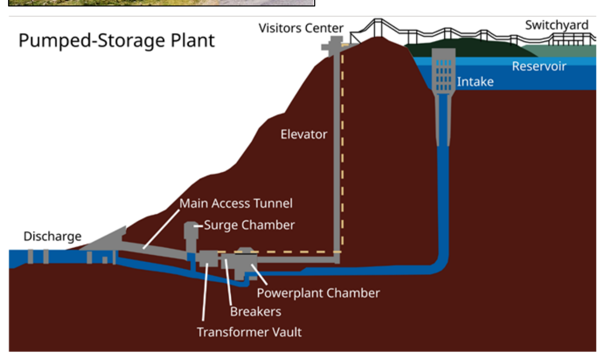

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Source: https://en.wikipedia.org/wiki/Pumped-storage_hydroelectricity
https://css.umich.edu/publications/factsheets/energy/us-grid-energy-storage-factsheet

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Pumped Storage

Pumped Hydroelectric Storage (Hydro): Cost & Performance Specifications	
Discharge Duration	6 - 24 hours
Capital Costs ($/kW; $/kWh)	$1,500 – 1,700; $150 – 180
O&M Costs ($/kW-year)	$13 – 17
Fuel Cost to Operate ($/kWh)	$0.08 - 0.09
Energy Capacity (based on existing installations)	Up to 40,000 MWh
Power Capability (based on existing installations)	4,000 MW
Expected Life	50 - 60 years
Roundtrip Efficiency	75 - 85% (evaporation contributes to efficiency losses)
Energy Density (Wh/L)	~2
Power Density (W/L)	~1.5
Dispatch Response Time	Seconds to Minutes
Technology Applications	Baseload generation and large-scale bulk energy storage Peak shaving and frequency/voltage regulation
Technology Drawbacks	Siting requirements and environmental concerns can be inhibitive (no new installations since 1980's); high capacity floor

Energy Storage Comparison Analysis with Gas-Fueled Technologies, ICF

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Compressed Air

Compressed air storage (CAES) plants use excess energy from the grid to pump air into a confined space, effectively storing this energy as pressure.

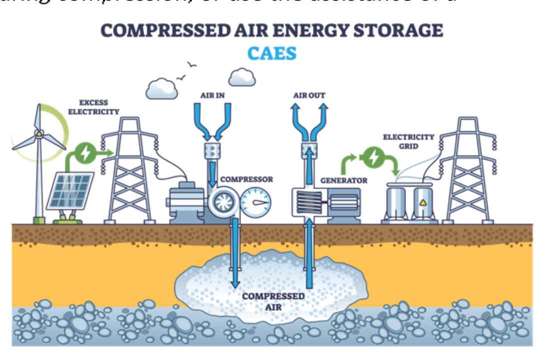
When this energy is needed, air is released to drive turbines. If air can be heated before expansion, efficiency can improve. Systems that store and utilize heat generated during compression, or use the assistance of a natural gas for this, are options.

Benefits:
- Use existing natural underground formations.
- Scale-able
- Long-lasting

Shortfalls:
- Limited to geographically accommodating regions, such as those with underground salt domes.
- Poor planning or management can cause negative environmental impacts.

First grid-scale implementation: Late 1970s

Efficiency: 40% - 75%



Source: https://en.wikipedia.org/wiki/Compressed-air_energy_storage
https://css.umich.edu/publications/factsheets/energy/us-grid-energy-storage-factsheet

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Compressed Air Storage

Underground Compressed Air to Power (CAES): Cost & Performance Specifications	
Discharge Duration	4 - 24 hours
Capital Costs ($/kW; $/kWh)	$1,000 – 1,200; $100 – $120
O&M Costs ($/kW-year)	$16 – 18
Fuel Cost to Operate ($/kWh)	$0.09 – 0.17
Energy Capacity (based on existing installations)	Up to 2,500 MWh
Power Capability (based on existing installations)	>100 MW
Expected Life	20 - 40 years
Roundtrip Efficiency	41 - 75%
Energy Density (Wh/L)	~12
Power Density (W/L)	~0.5
Dispatch Response Time	5 - 15 minutes
Technology Applications	Baseload generation and large-scale bulk energy storage Peak shaving and frequency/voltage regulation
Technology Drawbacks	Siting requirements can be inhibitive; high capacity floor

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Batteries

Batteries use excess energy from the grid to create chemical reactions that store this energy chemically in a material or fluid.

When this energy is needed, this chemical reaction can be reversed to release this stored energy. There are numerous different types of batteries in use or in development.

Benefits:
- Versatile
- High grid responsiveness

Shortfalls:
- Limited capacity and lifespan
- Costly

First grid-scale implementation: Early 2010s

Efficiency: 60% - 95%

Source: https://ravenvolt.com/blog/the-evolution-of-battery-storage-solutions/
https://css.umich.edu/publications/factsheets/energy/us-grid-energy-storage-factsheet

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Lithium-Ion Battery

Li-Ion batteries store energy via electro-chemical potential. Lithium ions move through an electrolyte from the anode to the cathode when discharging, and vice-versa when charging.

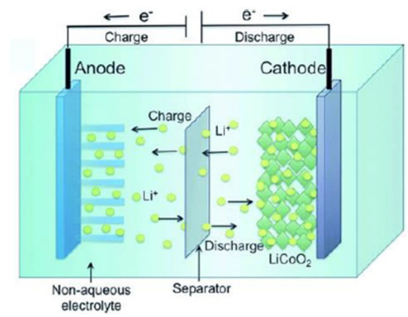
Benefits:

- Long life 10-20 years

Shortfalls:

- Energy capacity degradation over time; safety concerns
- Short duration 1-8 hours

Roundtrip Efficiency: around 85%



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Lithium-Ion Cost & Performance

Lithium-Ion Battery Storage: Cost & Performance Specifications	
Discharge Duration	1 - 8 hours
Capital Costs ($/kW; $/kWh) Forecasted Capital Costs (year 2030)	$900 – 1,700; $400 – 600 (2020) $450 – 900; $200 – $300 (2030)
O&M Costs ($/kW-year)	$10 – 20
Fuel Cost to Operate ($/kWh)	$0.08 – 0.09
Energy Capacity (based on existing installations)	Up to 5 MWh
Power Capability (based on existing installations)	>100 MW
Expected Life[1]	10 - 20 years (Energy augmentations can be performed at regular intervals to restore capacity to 100% of original)
Roundtrip Efficiency	85% (current leakage contributes to efficiency losses)
Energy Density (Wh/kg)	~210
Power Density (W/kg)	~2,000
Dispatch Response Time	milliseconds
Technology Applications	Grid frequency and voltage stabilization Demand response, ancillary services, backup power
Technology Drawbacks	Energy capacity degradation over time; safety concerns

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Redox Battery

Redox Flow Batteries store energy via electro-chemical potential. Anolyte and catholyte aqueous solutions are stored in separate tanks. To discharge the battery, the solutions are pumped to a chamber divided by a semi-permeable membrane that allows electrons to flow between the anolyte to the catholyte

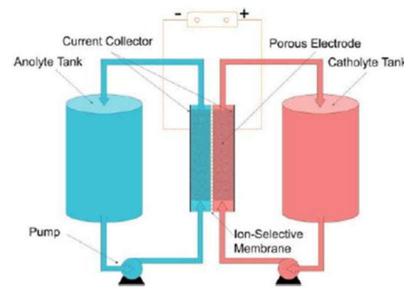
Benefits:

- 4-12 hour duration
- Milliseconds dispatch time

Shortfalls:

- Relatively low energy & power densities
- 5-10 year life

Roundtrip Efficiency: around 65% - 85%



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Redox Battery

Redox Flow Battery: Cost & Performance Specifications	
Discharge Duration	4 - 12 hours
Capital Costs ($/kW; $/kWh)	$1,400 – 1,600; $250 – $350
O&M Costs ($/kW-year)	$10 - 12
Fuel Cost to Operate ($/kWh)	$0.08 - 0.11
Energy Capacity(1) (based on existing installations)	Up to 120 MWh (Capacity is directly related to amount of electrolyte and therefore can be easily increased)
Power Capability (based on existing installations)	>100 MW
Expected Life	5 - 10 years / ~12,000 cycles
Roundtrip Efficiency	65 - 85%
Energy Density (Wh/kg)	~35
Power Density (W/kg)	~166
Dispatch Response Time	milliseconds
Technology Applications	Grid frequency and voltage stabilization Peak shaving and baseload generation
Technology Drawbacks	Relatively low energy and power densities

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Flywheels

Flywheels use excess energy from the grid to spin large, heavy cylinders in very low friction environments, storing this energy as mechanical energy.

When this energy is needed, the spinning flywheels are used to turn generators that convert this mechanical energy back into electrical energy.

Benefits:

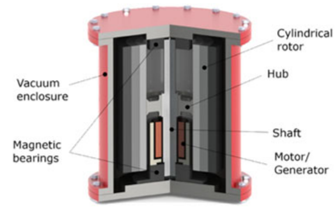
- Long life
- High grid responsiveness

Shortfalls:

- Limited capacity

First grid-scale implementation: Early 2000s

Efficiency: around 85%



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Source: https://en.wikipedia.org/wiki/Flywheel_energy_storage
https://css.umich.edu/publications/factsheets/energy/us-grid-energy-storage-factsheet

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Flywheel Cost & Performance

Flywheel Energy Storage: Cost & Performance Specifications	
Discharge Duration	minutes – 2 hours
Capital Costs ($/kW; $/kWh)	$2,000 – 4,000; $10,000 – $15,000
O&M Costs ($/kW-year)	$10 - 20
Fuel Cost to Operate ($/kWh-year)	$0.08 - 0.10
Energy Capacity (based on existing installations)	Up to 5 MWh
Power Capability (based on existing installations)	>10 MW
Expected Life	100,000 cycles
Roundtrip Efficiency	70 - 90% (friction contributes to efficiency losses)
Energy Density (Wh/kg)	20 – 80
Power Density (W/kg)	~5,000
Dispatch Response Time	< 4 milliseconds
Technology Applications	Grid frequency and voltage stabilization Uninterruptable power supply (UPS)
Technology Drawbacks	40 – 100% energy capacity loss / 24 hours

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Natural Gas Generation

Since natural gas is a physical product that can be stored for later use, it can be considered an energy storage solution. This is different from how much of the natural gas grid operates: natural gas is generated at about the rate it is consumed.

With **natural gas energy storage and generation**, large amounts of natural gas are stored either underground or as liquified natural gas (LNG) in tanks. This can then be called upon during periods of high demand when other generating sources aren't available or cost-effective to run.

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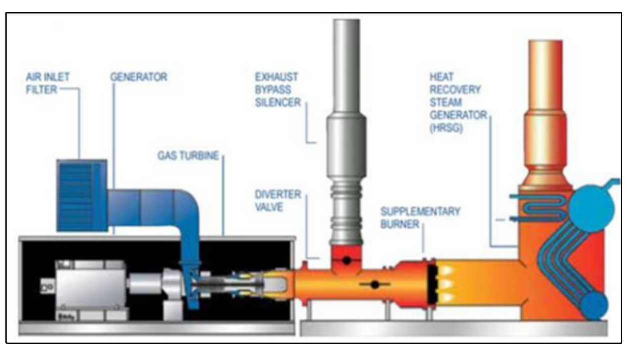
Natural Gas – Industrial CHP

Industrial CHP systems have long been used in industrial manufacturing plants for electricity generation and steam that is used in manufacturing processes.

Benefits:
- > 24 hours of duration
- Milliseconds response time

Shortfalls:
- Engineering and design is complex

Efficiency: 70% - 80%



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Natural Gas – Industrial CHP

Industrial CHP: Cost & Performance Specifications	
Discharge Duration	>24 hours
Capital Costs ($/kW, $/kWh)	$1,200 – 1,800
O&M Costs ($/kW-year)	$30-45/kW-year (FOM), ~$10/MWh (VOM)
Fuel Cost to Operate ($/kWh)	$0.015 – 0.020, including thermal credit
Energy Capacity (based on existing installations)	~5,000 - 80,000 MWh (in addition to onsite generation)
Power Capability (based on existing installations)	~1-20 MW (in addition to onsite power generation)
Expected Life	15 - 20 years
Roundtrip Efficiency	Recip. Engine: 70-80%; Gas Turbine: 70-75% (CHP efficiency, HHV)
Dispatch Response Time	Milliseconds to seconds (depends on operational status)
Technology Applications	Baseload onsite generation, demand response, spinning reserve, other grid services
Technology Drawbacks	Engineering and design process can be complex

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Natural Gas – Modular Engines

Modular Gas Engines fueled by natural gas are a mature technology, commonly used in both power generation and CHP applications.
Benefits:
> 24 hours of duration
Milliseconds to minutes response time
Shortfalls:
High maintenance
Efficiency: 36% - 42%

Reciprocating Engine Power Plant *(source: Wartsila)*

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Natural Gas – Modular Gas Engines

Modular Gas Engines: Cost & Performance Specifications	
Discharge Duration	>24 hours
Capital Costs ($/kW, $/kWh)	$1,300 – 1,800
O&M Costs ($/kW-year)	$35/kW-year (FOM), ~$6/MWh (VOM)
Fuel Cost to Operate ($/kWh-year)	$0.03 - 0.05
Energy Capacity (based on existing installations)	20,000 – 40,000 MWh per engine
Power Capability (based on existing installations)	5 - 10 MW per engine
Expected Life	~30 years
Efficiency	36 – 42% (electrical efficiency, HHV)
Dispatch Response Time	Milliseconds to minutes (depends on operational status)
Technology Applications	Peak power, demand response, spinning reserve, grid support for variable loads
Technology Drawbacks	Relatively high maintenance, requires support to manage vibration

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Fuel Cells & Electrolysis

While batteries can use a diverse set of chemical reactions to store and release energy, fuel cells are a unique technology on their own. They can be paired with electrolysis to work like batteries.

Electrolysis – Splitting of water into hydrogen and oxygen using electricity.

Fuel Cell – Combines hydrogen and oxygen into water, producing electricity.

Both processes have been around for decades. The benefits of electrolysis and fuel cells are their:

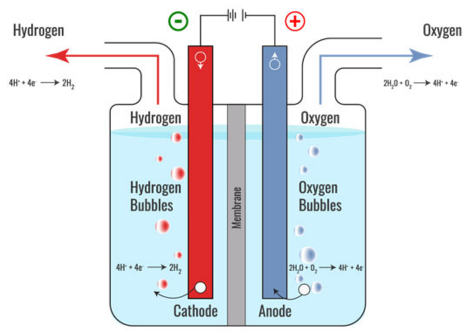
- Absence of moving parts.
- Absence of advanced chemicals or reactions.
- Absence of unwanted byproducts.

Electrolysis

Electricity can be converted into stored energy in the form of hydrogen fuel through **electrolysis.**

Using an anode and a cathode separated by a membrane and separate gas collection systems, both hydrogen and oxygen gas can be collected from the splitting of water (H_2O) molecules using electricity.

Excess electricity from the grid during off-peak times can be stored this way.



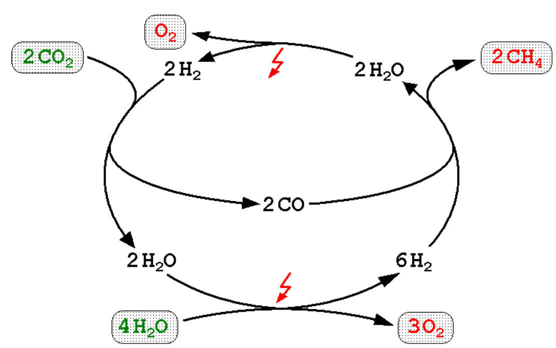
Electrolysis of water

Power to Gas (P2G)

Hydrogen from electrolysis can be used in multiple ways.

Power to gas (P2G) – Natural gas can be created from carbon dioxide and water through processes of electrolysis and methanation combined. This can be used for any natural gas end use, including natural gas engines or turbines that can turn this energy back into electricity.

It's important to note that each additional step added to energy conversion from one form to another introduces inefficiencies.



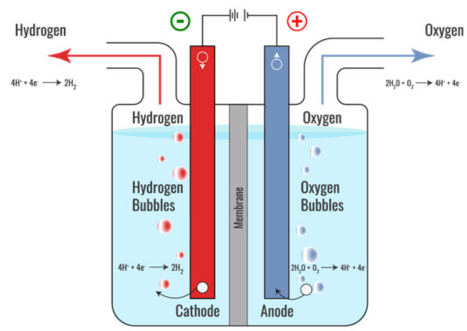
By Qniemiec - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=40715999

Source: https://en.wikipedia.org/wiki/Power-to-gas
https://energsustainsoc.biomedcentral.com/articles/10.1186/s13705-014-0029-1

Power to Hydrogen

Reducing inefficiencies in converting electricity to hydrogen, then to natural gas, then back to electricity is key.

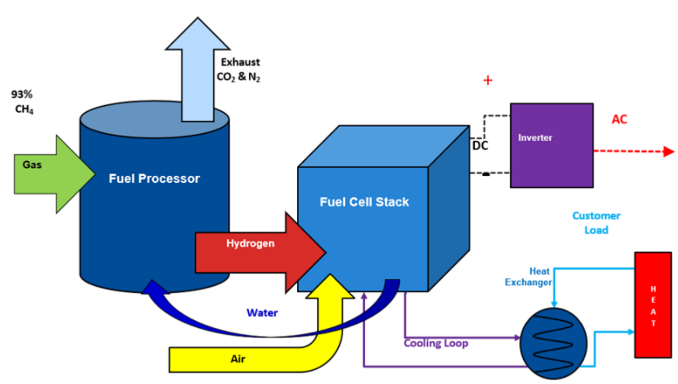
Hydrogen to power – Similar to "power to gas", this process uses excess grid electricity and electrolysis to split water into hydrogen and oxygen. Instead of going an extra step with methanation, the process stops here with hydrogen as the store-able fuel for later use by burning or fuel cells. Electricity can be generated with this hydrogen at a later time with a fuel cell.



Electrolysis of water

Fuel Cells

Fuel cells directly extract electrons from hydrogen through electrochemical reactions, generating electricity.
Benefits:
Use stored hydrogen from electrolysis or from other hydrogen sources such as natural gas.
Shortfalls:
High cost
Lower efficiency than lithium-Ion batteries
Efficiency roundtrip: 34% - 51%



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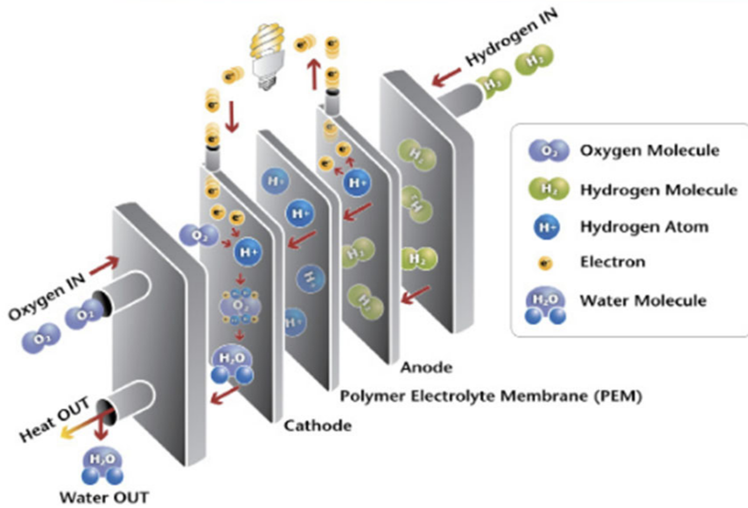
Fuel Cells



https://www.energy.gov/sites/default/files/2015/11/f27/fcto_fuel_cells_fact_sheet.pdf

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Fuel Cells

Fuel Cell Power-to-Gas (Electrolysis): Cost & Performance Specifications	
Discharge Duration	Seconds - hours
Capital Costs ($/kW, $/kWh)	$2,900 – 5,600; $500 – 1000
O&M Costs ($/kW-year)	$30 – 40, plus stack replacement
Fuel Cost to Operate ($/kWh-year)	$0.03 – 0.04
Energy Capacity (based on existing installations)	Depends on electricity source and other sources of hydrogen
Power Capability (based on existing installations)	Up to 50 MW
Expected Life	10 – 30 years / ~20,000 cycles
Roundtrip Efficiency	34 – 51% (electrical efficiency, HHV)
Energy Density (Wh/kg)	~500 - 3,000
Power Density (W/kg)	~500
Dispatch Response Time	Seconds to minutes (depends on technology and operational status)
Technology Applications	Continuous power or CHP for microgrid, incorporating PV electricity for hydrogen production as available
Technology Drawbacks	Higher cost, lower efficiency than Li-Ion batteries

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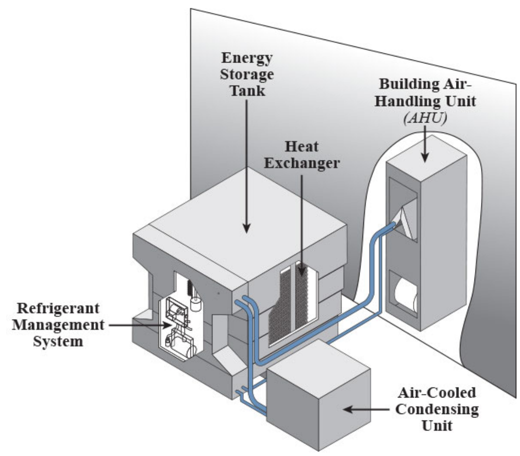
Ice Thermal Storage

Ice thermal storage is a way to use excess energy during low-demand periods on the grid to shave peak loads created by customer cooling needs.

During low-demand periods on the grid, often at night when outside temperatures are naturally cooler, chillers use energy to produce ice in well insulated containers.

During peak demand periods, stored ice can be used for building cooling needs with chilled water circulation loops tied into the building's HVAC system. This prevents the need for chillers or ACs to run during peak times.



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Cost Comparison of Energy Storage Technologies

Technology	Primary Application	Capital Costs ($/kW)	O&M Costs ($/kW-year)	Fuel Cost to Operate ($/kWh)
Short-Duration Technologies				
Flywheel Energy Storage	Small-scale frequency and voltage stabilization	$2,000 – 4,000	$10 – 20	$0.08 – 0.10
Lithium-Ion Battery 2020	Small-to-large demand response, ancillary services, frequency/ voltage stabilization	$900 – 1,700	$10 – 20	$0.08 – 0.09
Lithium-Ion Battery 2030		$450 – 900	$5 – 10	$0.08 – 0.09
Long-Duration Technologies				
Redox Flow Battery	Industrial-scale peak shaving, frequency/ voltage stabilization	$1,400 – 1,600	$10 – 12	$0.08 – 0.11
Compressed Air to Power	Utility-scale baseload generation and peak shaving	$1,000 – 1,200	$16 – 18	$0.09 – 0.17
Pumped Hydro-electric Storage	Utility-scale baseload generation and peak shaving	$1,500 – 1,700	$13 – 17	$0.08 – 0.09
Gas-Fueled Technologies				
Industrial CHP	Industrial-scale demand response, spinning reserve	$1,200 – 1,800	$30-$45/kW-year, ~$10/MWh	$0.015 – 0.020
Modular Gas Engines	Demand response, spinning reserve, balancing renewables	$1,300 – 1,800	$35/kW-year, ~$6/MWh	$0.03 – 0.05
Power-to-Gas Fuel Cell	Convert excess electricity to hydrogen for time shifting	$2,900 – 5,600	$30 – 40/kW-year, plus stack replacement	$0.03 – 0.04

Energy Storage Comparison Analysis with Gas-Fueled Technologies, ICF

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Energy Storage Comparison

Energy Storage Technology	Discharge Duration	Roundtrip Efficiency	Dispatch Response Time
Short-Duration Technologies			
Flywheel Energy Storage	minutes / hours	70 – 90%	Milliseconds
Lithium-Ion Battery Storage	1 – 4 hours	~85%	Milliseconds
Long-Duration Technologies			
Redox Flow Battery	4 – 12 hours	65 – 85%	Milliseconds
Compressed Air to Power (CAES)	4 – 12 hours	41 – 75%	5-15 minutes
Pumped Hydroelectric Storage	>10 hours	76 – 85%	Seconds to Minutes
Gas-Fueled Technologies			
Industrial CHP	>24 hours	70 – 80% (total CHP efficiency, HHV)	Milliseconds to Seconds
Modular Gas Engines	>24 hours	36 – 42%(electrical efficiency, HHV)	Milliseconds to Minutes
Power-to-Gas Fuel Cell	>24 hours	34 – 51% (electrical efficiency, HHV)	Seconds to Minutes

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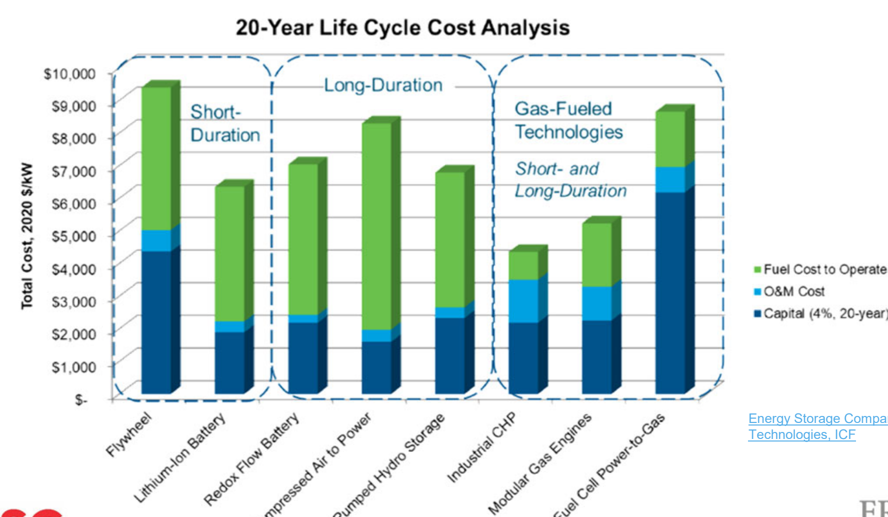
Life Cycle Cost of Energy Storage Systems



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