



The Essence of Thermodynamics: Energy, Entropy, Exergy, and 2nd Law Efficiency

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WEBINAR

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Acknowledgement

This presentation is partially based on the publications below:

Çengel, Y. A.,

“Ramifications of the second law of thermodynamics on innovation and sustainable future,”

Int. J. Research, Innovation and Commercialization,
Vol. 2, No. 2, pp. 91-104, 2019.

Çengel, Y. A.,

“Perspective on the Ontological Ramifications of the 2nd Law of Thermodynamics,” *Int. J. Exergy*, Vol. 28, No. 3, pp.

301-316, 2019.

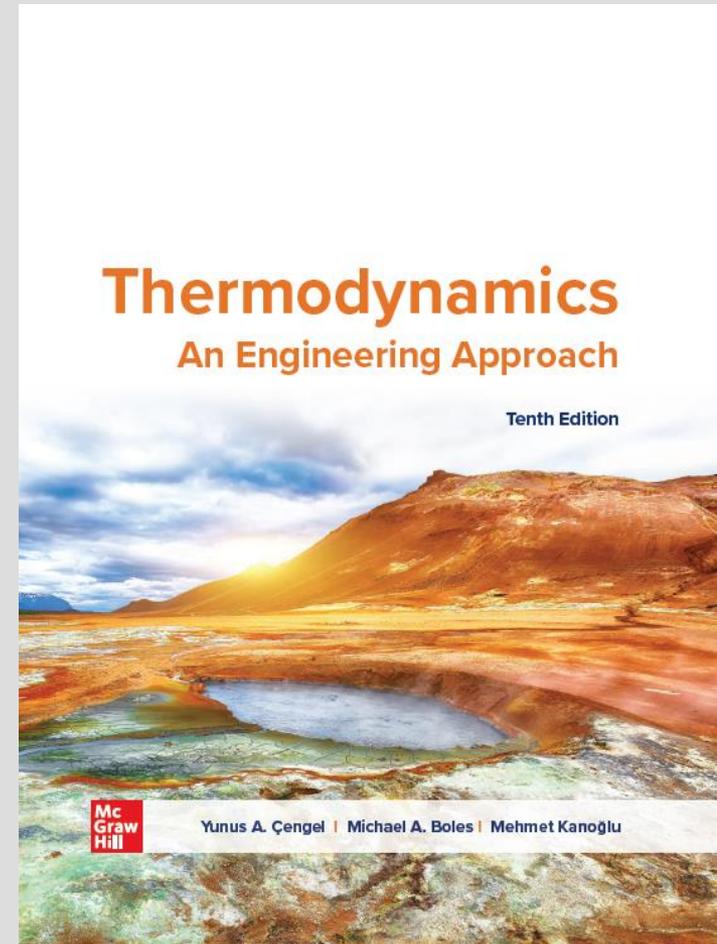
Çengel, Y. A.,

“On Entropy, Information, and Conservation of information,” *Entropy*, 23, 779, 2021.

<https://doi.org/10.3390/e23060779>

Çengel, Y. A.,

“Power generation potential of LNG regasification terminals,” *Int J Energy Res. Pp. 1-12*, 2020.



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ENERGY



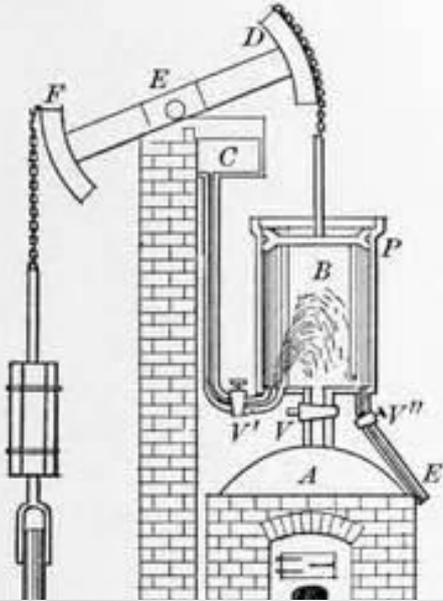
Why thermodynamics?

- **Thermodynamics:** The science that deals with energy and the associated concepts of entropy and exergy.
- **Course objectives:**
 - Grasping the **basic principles** (1st and 2nd Laws).
 - Developing an **intuitive understanding** of conservation of energy and energy transformations.
 - Gaining familiarity with **real-world applications**.
 - Being comfortable with **entropy and exergy analysis** to identify and minimize waste.
 - Getting a good understanding of the concepts of **efficiency and effectiveness**.

ENERGY:

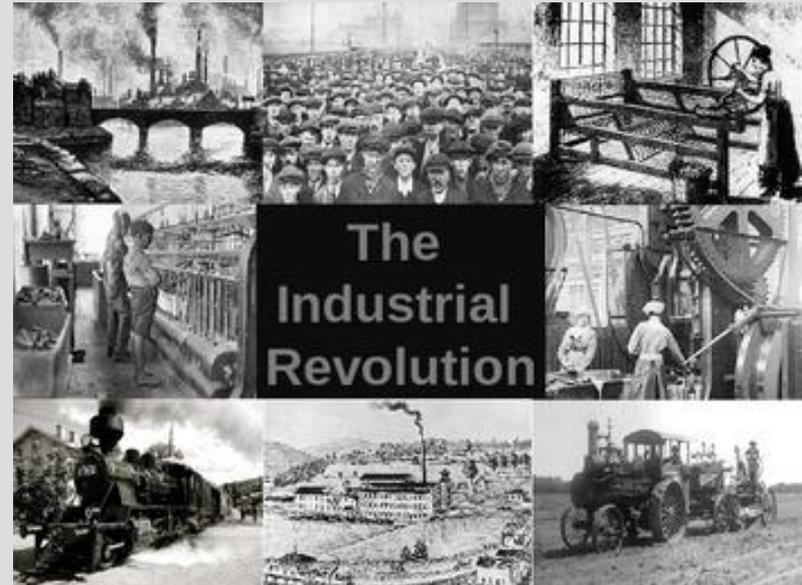
History and origin

Historical Context: Atmospheric steam engines



The industrial revolution = History of thermodynamics

- The construction of the first commercially successful steam engine by **Thomas Newcomen in 1712** (patented in 1698 by Thomas Savory) marked the beginning of the switch from manual labor to machine power.
- The invention in **1775 of James Watt's efficient steam engine** that reduced the coal use to one quarter accelerated the change.
- With the demonstration of
 - ✓ a **steam locomotive by R. Trevithick** in 1801,
 - ✓ the electro-magnetic rotation used in **electric motor by Michael Faraday** in 1821, and
 - ✓ the **gasoline engine by E. Lenoir in 1859**,
- industrialization was on its way to infuse all segments of society.



SOLAR ENERGY

(Nuclear Fusion Energy)



Interconnecting seemingly the unrelated (Hydro Power): Sun → Evaporation → Rain → Potential Energy



Relating the seemingly unrelated: Biochemical energy = Solar energy

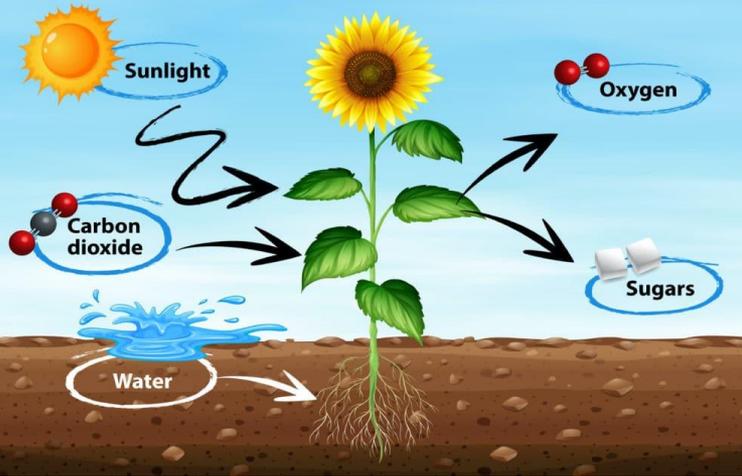


Biofuel/Bioenergy:

Sun → Plants → Chemical energy → Food, fuel

Photosynthesis: Sunlight+CO₂+H₂O → Energy (sugar) + O₂

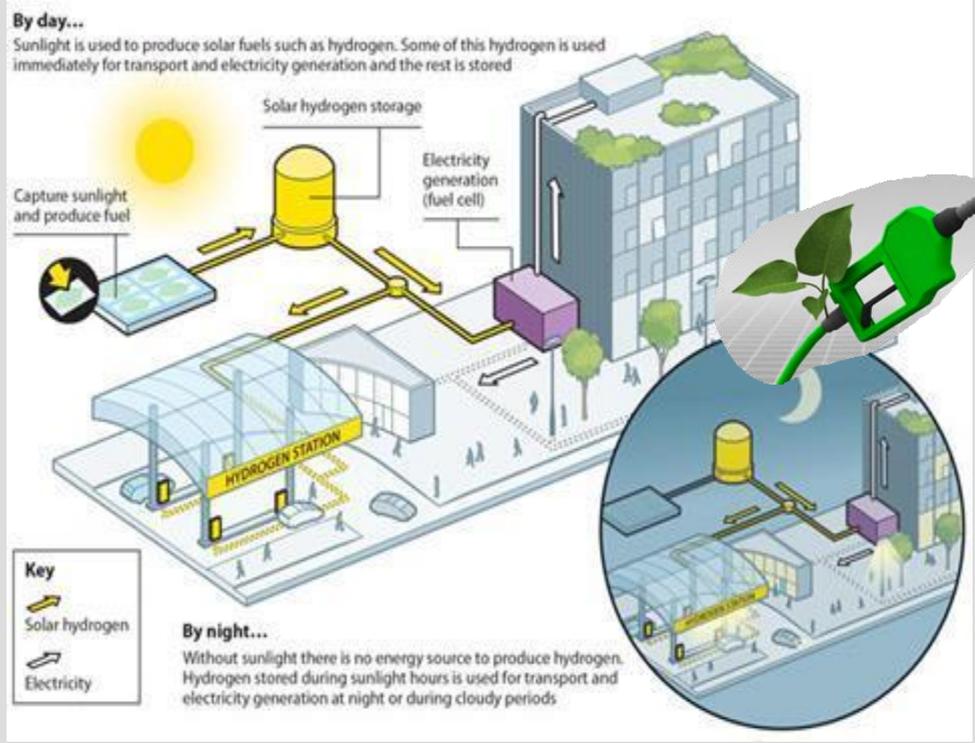
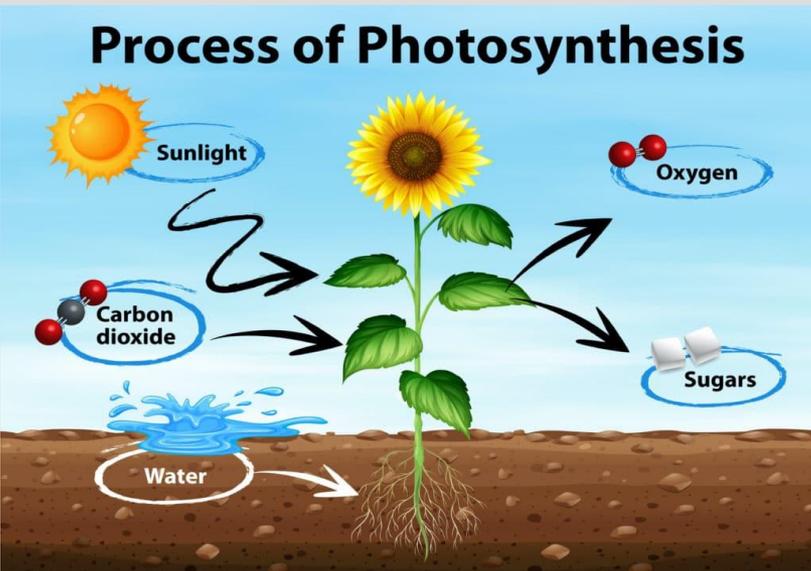
Process of Photosynthesis



Leaf: A sophisticated chemical factory powered by sunlight (No noise, no waste. Aesthetic, edible, recyclable)

Science: Natural Leaf (Photosynthesis)
Sun → Energy (sugar) + O₂

Green technology: Artificial Leaf
(different technologies and products; many patents)
Sun → Energy (liquid fuel) + O₂



Technology = Science + Human ingenuity/creativity

FOSSIL FUELS (Solar Energy):

Sun → Plants → Disintegration → Chemical Energy



Sun: The primary energy source of planet earth

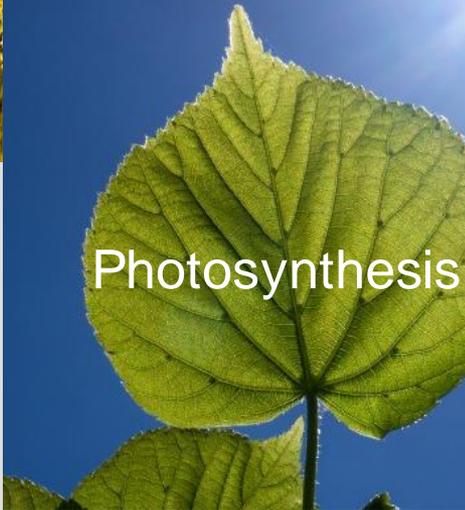
Plants: Energy source of animals and humans

SUN (energy source)

PLANTS (Convert solar energy to chemical energy)

Photosynthesis

ANIMALS and HUMANS
(Consume plants)



Essence of Thermodynamics:

The 1st and the 2nd Laws

Thermodynamics in a nutshell: The four pillars

Balance equations for any system

- **Mass balance:** Mass change = Mass transfer

$$m_{in} - m_{out} = \Delta m_{\text{system}}$$

- **Energy balance:** Energy change = Energy transfer

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{\text{system}}}_{\text{Change in internal, kinetic, potential, etc. energies}}$$

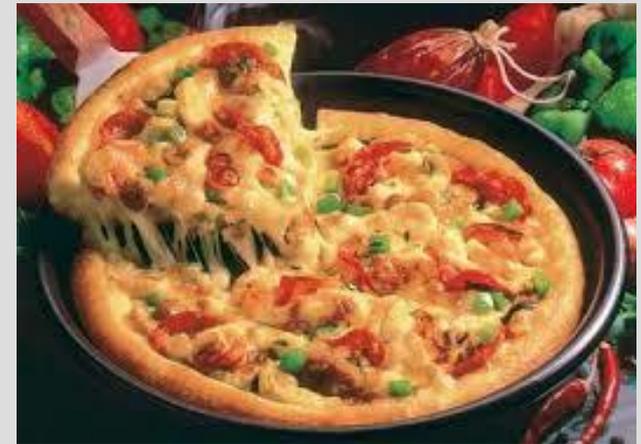
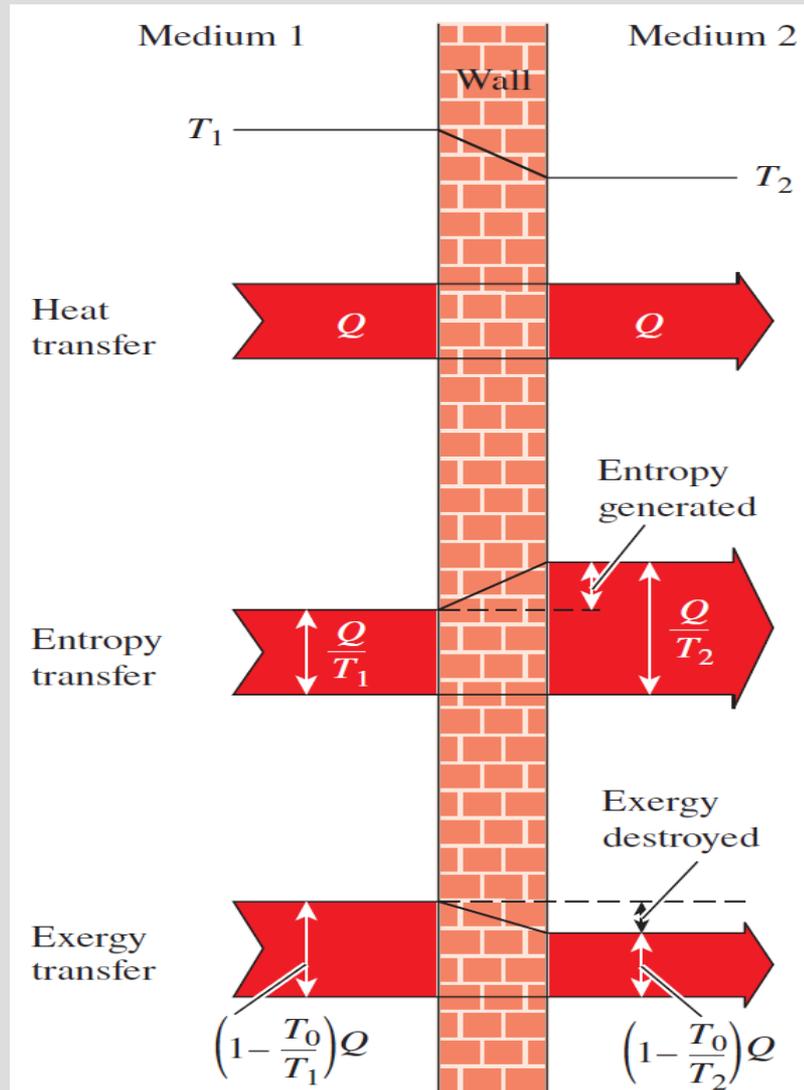
- **Entropy balance:** Entropy change = Entropy transfer + Entropy generation

$$\underbrace{S_{in} - S_{out}}_{\text{Net entropy transfer by heat and mass}} + \underbrace{S_{gen}}_{\text{Entropy generation}} = \underbrace{\Delta S_{\text{system}}}_{\text{Change in entropy}}$$

- **Exergy balance:** Exergy change = Exergy transfer - Exergy destruction

$$\underbrace{X_{in} - X_{out}}_{\text{Net exergy transfer by heat, work, and mass}} - \underbrace{X_{\text{destroyed}}}_{\text{Exergy destruction}} = \underbrace{\Delta X_{\text{system}}}_{\text{Change in exergy}}$$

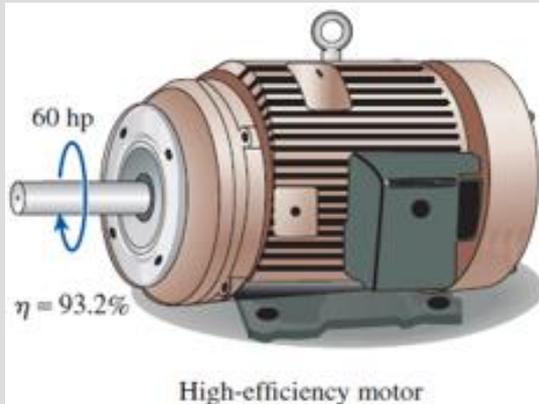
Energy is conserved;
Entropy is generated;
Exergy is destroyed.



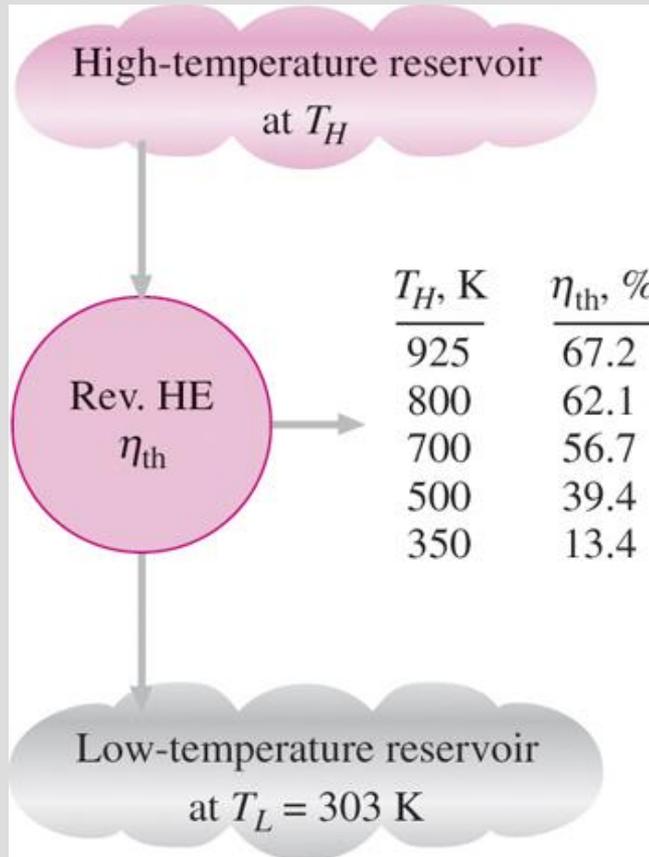
Exergy: Work Potential of Energy

The atmosphere: Infinite energy; but zero work potential

The **useful work potential** of a given amount of energy at some specified state in a given environment is called **exergy**.

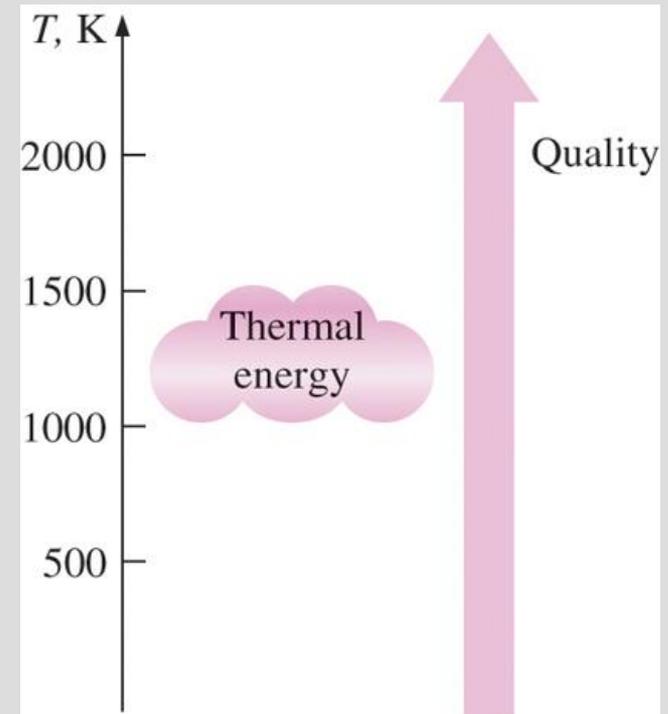


Example: Geothermal energy at 100°C and 200°C:
The **higher** the 'hot' resource temperature, the **higher** the efficiency



$$\eta_{th,rev} = 1 - \frac{T_L}{T_H}$$

The fraction of heat that can be converted to work as a function of source temperature.



The higher the temperature of the thermal energy, the higher its quality (exergy.)

Low-exergy heat sources (A 2nd-law application): Low-temperature wall/floor radiant heaters



- Enables the use of **low-exergy** waste heat or low-temperature heat sources.
- **Efficient** and quite.
- Takes advantage of **radiation effect** for thermal comfort and efficiency.

Comparison of the 1st and 2nd Laws:

(Energy is conserved, Entropy is generated, Exergy is destroyed)

- **1st law:** Deals with conserved (*physical/tangible*) quantities of **matter and energy**. (Closes the door to perpetual motion machines.)
- **2nd law:** Deals with the non-conserved quantities of **entropy and exergy** as well as **quality of energy**. (Establishes the metrics to quantify waste and to assess the degree of perfection.)
- The **2nd law is closely related** to the concepts of **sustainability, green practices, effectiveness, efficiency, and performance**.
- **Energy efficiency and renewable energy** are also associated with the 2nd law.
- The 2nd-law concepts can also be applied to **other aspects of life** to assess their **efficiency and effectiveness**, and, thus the best utilization of resources.



The 3 legs of thermodynamics:

Energy conservation, effectiveness, efficiency

1. Law

Matter/energy
conservation



2. Law

Effectiveness

Output-based
(not input)

Efficiency

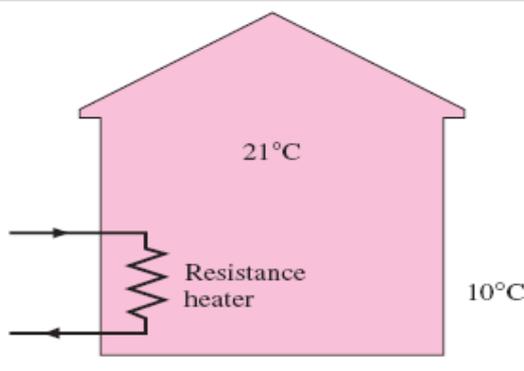
Electric resistance heaters:

Efficiency: 100% yet very wasteful (conversion of electricity to heat)

Heat pumps: COP of 4+



2nd-law efficiency of resistance heaters: (1st-law efficiency = 100%, COP = 1)



A dealer advertises electric resistance heaters that have an efficiency of 100%. Assuming an indoor temperature of 21° C and outdoor temperature of 10° C, determine the second-law efficiency of these heaters.

$$\text{COP}_{\text{HP,rev}} = \frac{1}{1 - T_L/T_H} = \frac{1}{1 - (283 \text{ K})/(294 \text{ K})} = 26.7$$

That is, it would supply the house with 26.7 units of heat (extracted from the cold outside air) for each unit of electric energy it consumes.

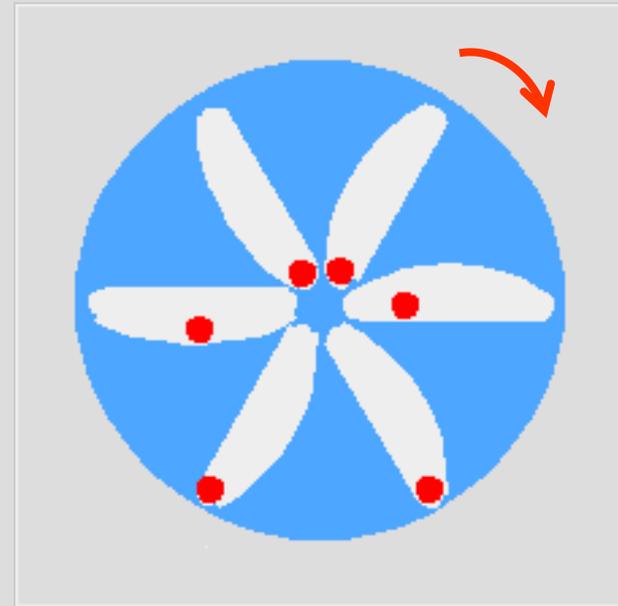
The second-law efficiency of this resistance heater is

$$\eta_{\text{II}} = \frac{\text{COP}}{\text{COP}_{\text{rev}}} = \frac{1.0}{26.7} = \mathbf{0.037 \text{ or } 3.7\%}$$

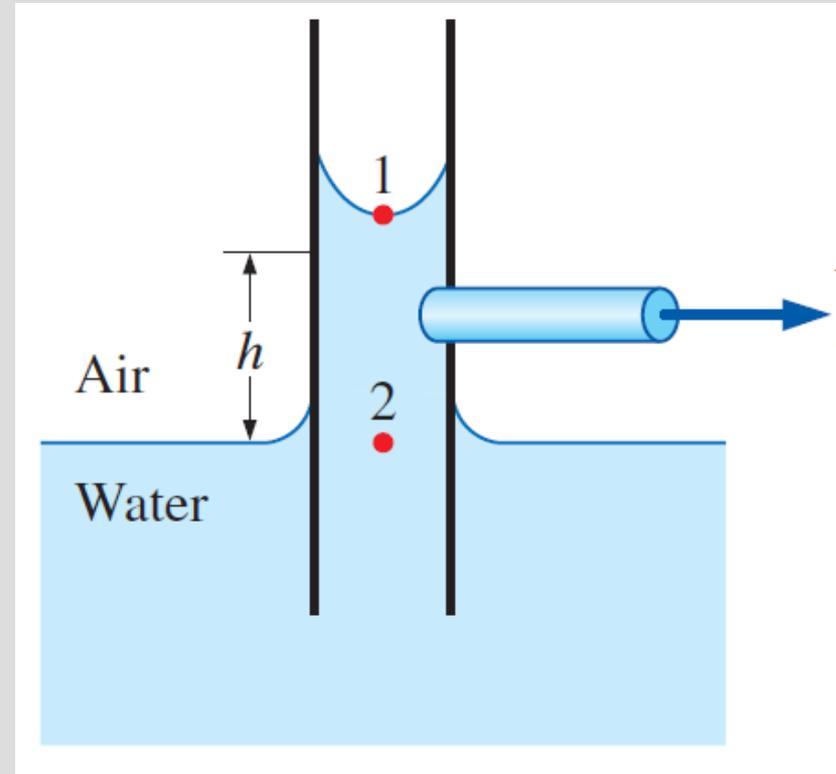
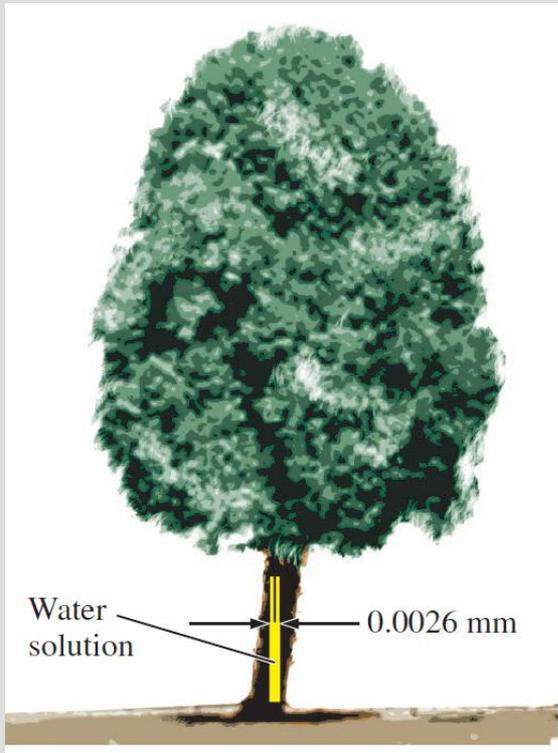
The 1st Law: Conservation of Energy

Real-life examples

Challenging the law of conservation of energy: Making use of 'Moment = Force x moment arm'



Rise of water in a tube due to the capillary effect: Lift water in stages; then build a hydrowater plant?



Will water leak out through an attached horizontal tube?

Impossible today, but possible tomorrow?

If it violates the laws of physics, No!

- There are 2 kinds of impossibilities:
- 1. If the reason of impossibility is a **lack of technology**; this impossibility can be overcome in time.
- 2. If the reason of impossibility is the **violation of physical laws**, this impossibility is to remain.
- In the future, it may be possible to build and **electric motor whose efficiency reaches 100%**. But it will never be possible to build an electric motor whose efficiency is **%101** (producing more mechanical energy than the electrical energy consumed).
- **In Basketball**, a team that trails by 50 points at the beginning of 4th quarter can still win the game.
- But a team that trails by **5 points with 1 second left** cannot.



Turning the engine off at red light: Does it save fuel?



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Leaving the heater on when nobody is home: Does it save energy?

Q. It is often claimed that you should **keep the heating system on** rather than turning it off when you are not home. This is because it takes more energy to heat up the house back to its normal temperature.
True or false?

A: The claim is false. The heater of a house supplies the energy it loses, which is **proportional to the temperature difference between the indoors and the outdoors**. A turned-off heater consumes no energy. The energy consumed during the warming-up period is less than the heat lost from a house that is already at the temperature that the thermostat is set because of the larger overall ΔT .



Hyperloop project (California, USA):

Q: Minimum energy needed to go from SF to LA?

HYPERLOOP

San Francisco

Los Angeles



hyperloop | one

The 2nd Law: Entropy, Exergy, 2nd Law Efficiency

Entropy, entropy change, and entropy generation vs.

Exergy, exergy change, and exergy destruction

Entropy of a system: **Not meaningful.**

Does not tell much about the system.

Entropy change of a system: **Not meaningful.**

May be due to irreversibilities and/or heat loss/heat gain
(For adiabatic systems, it represents irreversibilities).

Entropy generation during a process: **Meaningful.**

A measure of irreversibilities/imperfections associated with the process.

Exergy of a system: **Meaningful.**

Represents the work that can be extracted from the system.

Exergy change of a system: **Meaningful.**

Represents the increase/decrease of the work potential of the system.

Exergy destruction during a process: **Meaningful.**

A measure of wasted work potential due to irreversibilities/imperfections associated with the process.

Entropy, kJ/kg.K (a property of mass): Source of causal power?

A measure of uncertainty of the configuration of a system.
Closely associated with temperature and thus thermal energy.

- **Entropy generation:** A measure of imperfection associated with a process.
- **Entropy** is ontologically **subjective** (intangible). It is **mental** existence (a nonphysical entity) since entropy is not made of matter-energy.
- Entropy is a measure of the **changes in the composition** of a system and **the energy conversions and interactions** the system involves.
- As such, entropy cannot have a **causal effect** on physical things, and it cannot cause **any harm** to them. But the physical system itself and the changes it undergoes can.
- Example: '**Entropy death of the universe**' does not mean that entropy will cause doomsday (apocalypse). Entropy does not have any such power.
- Doomsday will be caused by the changes/processes that occur in the universe, not by the entropy.



Entropy analysis or exergy analysis?

Which is simpler and more meaningful?

Entropy generation = Exergy destruction/Room temperature



$$\underbrace{X_{in} - X_{out}}_{\text{Net exergy transfer by heat, work, and mass}} - \underbrace{X_{destroyed}}_{\text{Exergy destruction}} = \underbrace{\Delta X_{system}}_{\text{Change in exergy}}$$

Chemical exergy analysis of a bird in a cage:

- **Control volume:** The cage with the bird inside
- **Exergy input:** Exergy content of food (close to the caloric value)
- **Exergy output:** Exergy content of manure/wasted food (exergy loss with body heat is zero)
- **Exergy change of bird:** Zero (if the body size and composition remain the same)

The 2nd-law efficiency:

η_{II} = Actual performance/Best possible performance

$$\eta_{II} = \frac{\text{Exergy recovered}}{\text{Exergy expended}} = 1 - \frac{\text{Exergy destroyed}}{\text{Exergy expended}}$$

$$\eta_{II} = \frac{\eta_{th}}{\eta_{th,rev}} \quad (\text{heat engines})$$

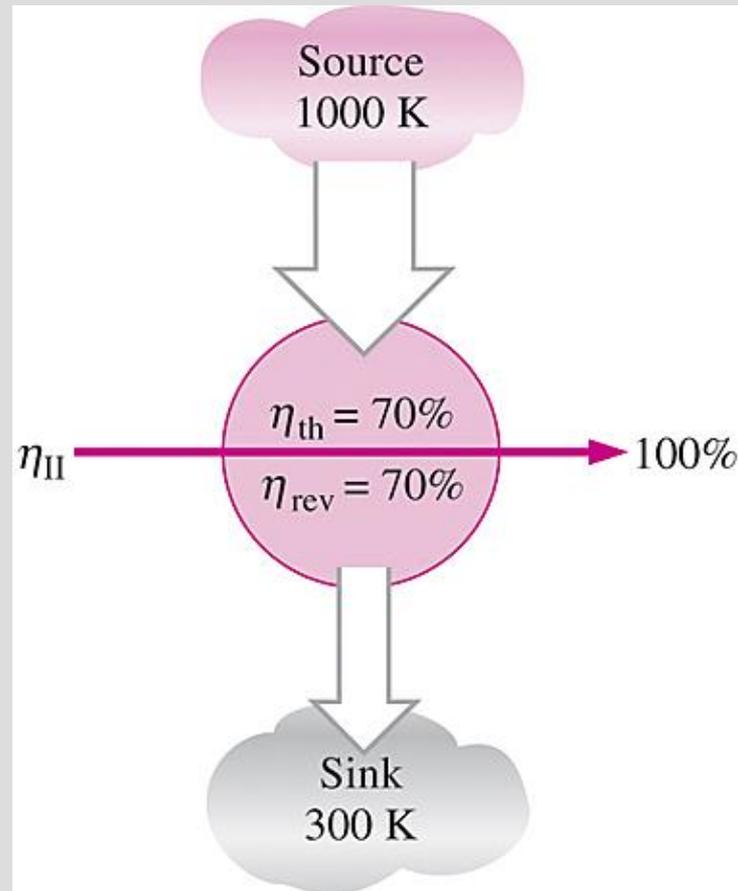
$$\eta_{II} = \frac{W_u}{W_{rev}} \quad (\text{work-producing devices})$$

$$\eta_{II} = \frac{W_{rev}}{W_u} \quad (\text{work-consuming devices})$$

$$\eta_{II} = \frac{\text{COP}}{\text{COP}_{rev}} \quad (\text{refrigerators and heat pumps})$$

The 2nd-law efficiency:

$\eta_{II} = 100\%$ for all reversible devices (perfection)



Second-law efficiency of all reversible devices and processes is 100%.

Q: Can the 2nd-law efficiency be greater than 1st-law efficiency?

2nd law efficiency: A measure of perfection

1st law efficiency: Degree of **completion** of energy transfer/conversion processes ($\eta_I = 100\%$ for complete conversion).

It represents the **level of performance** achieved compared to the **resources consumed**.

2nd Law efficiency: Degree of **perfection** of energy transfer/conversion processes ($\eta_{II} = 100\%$ for a perfect process).

It represents the **level of performance** achieved compared to the **best possible performance** under the same circumstances.

A process with a 2nd law efficiency of 100%:

- Is perfect (even if its 1st law efficiency is less than 100%).
 - Entropy generation = 0
 - Exergy destruction = 0
 - Waste = 0
-
- Something cannot be **more perfect than perfect** (e.g., **reversible** processes/cycles)
 - The 2nd law defines the **upper limit of excellence** on performance.
 - **Aim with the 2nd Law:** 'Perfection' and 'Zero waste'.

Q: Is $2 + 2 = 4$?

A: Maybe!

1st Law: $2 + 2 = 4$ is true for conserved quantities, like energy.

2nd Law: There are quantities for which the value of the whole is less or more than the arithmetic sum of the parts, like entropy and exergy.

Question #1: What is $2+2 = ?$

1st law: 4

2nd law: 0, 1, 4, 7,

Question #2: Is unity a source of strength? (*United we stand, divided we fall.*)

1st law: Yes, always.

2nd law: Not always – it may be a source of weakness as well.

Question #3: How do the 1st- and 2nd-law efficiencies compare?

1st law efficiency: The level of performance achieved compared to the resources consumed.

2nd law efficiency: The level of performance achieved compared to the best possible performance under the same circumstances.

Efficiency in an economy:

Producing more output for the same input (labor, energy, raw materials, ...)

Q: Average **labor cost** is \$10,000 in Country A and \$30,000 in Country B. Which country's manufactured goods are more competitive?

A: Depends on the **efficiency** of manufacturing (output per worker, energy efficiency, transportation cost, technology level, tax, ...)



Q: Country A spends \$3000 per student a year while Country B spends \$5000. Which country's graduates are better equipped with knowledge and skills?

A: Depends on the **effectiveness** of the education system.

R&D expenditures and export of high-tech products

Global R&D expenditures: \$2 trillion/year (USA:26%, China:23%)

Country	2017 or most recent year			Per \$billion R&D spending:	
	R&D spending and %GDP, \$billion PPP	No. of patent applications by residents	Export of high-tech products, \$billion	No. of patent applications by residents (per \$billion R&D)	Export of high-tech products, (per \$billion R&D)
EU	379 (%1.6)	117,000	616	309	1.6
USA	511 (%2.7)	291,000	110	569	0.2
Germany	119 (%2.9)	48,300	172	406	1.4
China	452 (%2.1)	1,244,000	504	2752	1.1
Japan	166 (%3.1)	260,200	84	1567	0.5
Korea	92 (%4.3)	180,400	73	1960	0.8
Singapore	10 (%2.2)	1,600	136	160	13,6
India	67 (%0.9)	15,000	14	224	0.2
Turkey	15 (%1.0)	8,200	3.1	547	0.2
WORLD	2,000 (%2.2)	2,250,000	1,989	1274	1.0

https://en.wikipedia.org/wiki/List_of_countries_by_research_and_development_spending

https://www.wipo.int/edocs/pubdocs/en/wipo_pub_941_2018.pdf; <https://data.worldbank.org/indicator/TX.VAL.TECH.CD?view=chart>

2nd law efficiency [actual vs. best possible performance]

Ramifications in real life: **Commuting**

Commuting to/from work: (Capacity not used is capacity wasted)

How is the **intellectual capacity** utilized? Or is it wasted? A topic or a foreign language can be learned while commuting by just listening.



2nd law efficiency [actual vs. best possible performance]

Ramifications in real life: **Students, workers**

Workers, students: (Grades, skills acquired, tangible outcomes produced)

Ratio of [(actual performance) ÷ (best possible performance under the same circumstances with the same resources)]



Intriguing Energy Solutions: Thinking out of the box

VALVES (Preserve energy, but destroy exergy):

Practically, the **best** invention of engineers (*easily control flow rate*).
Thermodynamically, the **worst** invention of engineers (*destroy exergy*).

Throttling valves are *any kind of flow-restricting* devices that cause a significant pressure drop in the fluid.

Q: What is the difference between a turbine and a throttling valve?

Energy balance for a valve:

$$h_2 \cong h_1 \quad (\text{kJ/kg})$$

$$u_1 + P_1 v_1 = u_2 + P_2 v_2$$

Internal energy + Flow energy = Constant

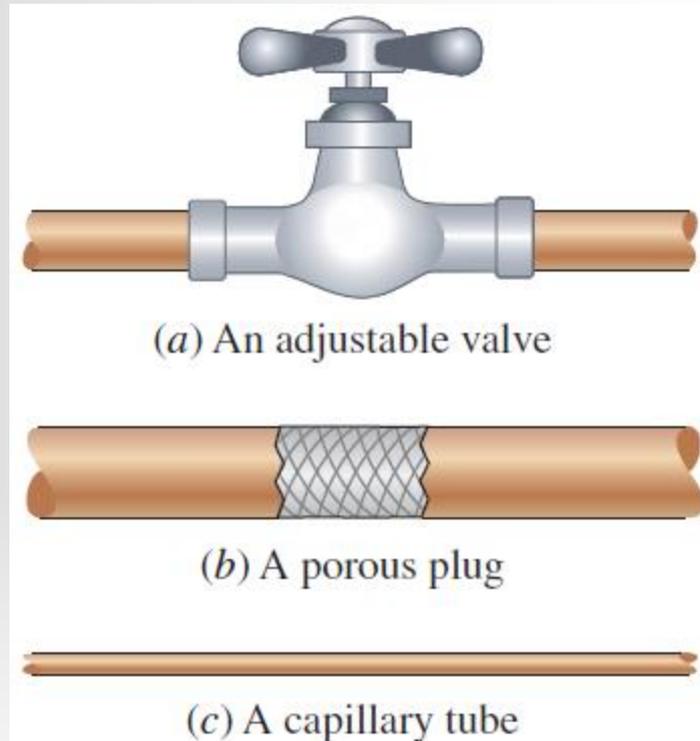


FIGURE 5-32

Throttling valves are devices that cause large pressure drops in the fluid.

Replacing a valve by a turbine:

LNG Turbine at -150°C ve 50 Bar

- At $0.28\text{ m}^3/\text{s}$ and -150°C , replacing a valve that drops LNG pressure from 50 to 10 Bar by a turbine:
- 900 kW power production
- \$800,000/yr savings
- Turbine cost: \$1 million
- Payback: ~ 1 year



POWER RECOVERY THROUGH THERMODYNAMIC EXPANSION OF LIQUID METHANE

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Utilization of 'coldness' of LNG at -162°C : Generating electricity from 'cold' (instead of 'heat')

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TECHNICAL NOTE

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Power generation potential of liquified natural gas regasification terminals

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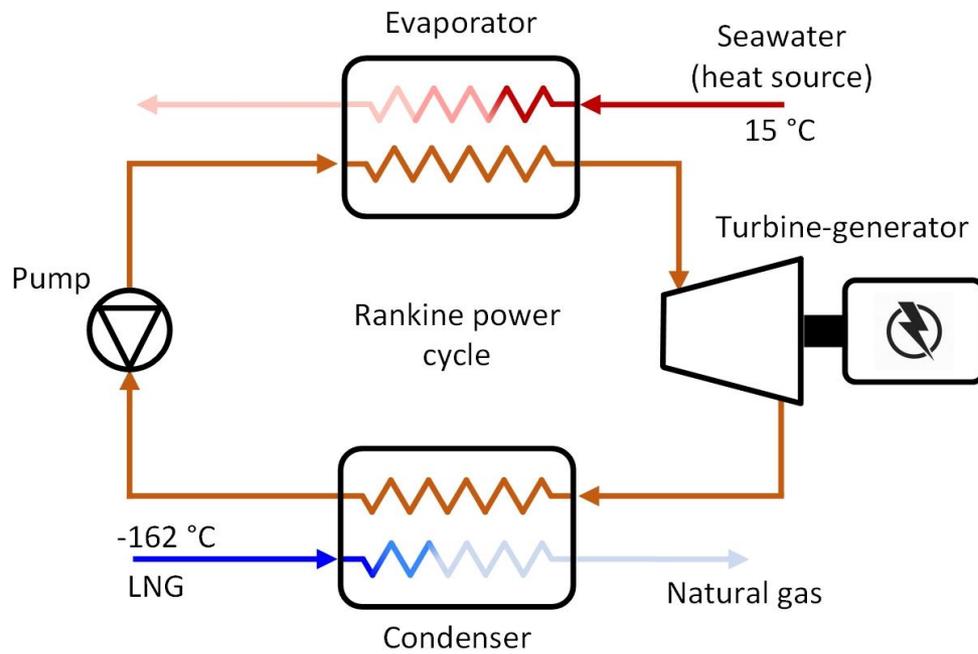
Summary

The share of liquified natural gas (LNG) in the international trade of natural



Energy resource: LNG at -162°C (serves as 'sink' of engine)
Energy source: Sea water at 15°C (serves as 'source' of engine)

LNG Regasification power plant: Basic Rankine cycle



Negishi Terminal
4 MW, year 1985 (Japan)

The power of 'low temperature' resource:

The **lower** the 'cold' resource temperature, the **higher** the efficiency
Maximum power that can be produced from LNG at -162°C

The reversible work of LNG between 1 atm, 15°C and 1 atm, -162°C is the exergy difference:

$$w_{\text{rev}} = ex_2 - ex_1 = (h_2 - h_1) - T_0 (s_2 - s_1) = \mathbf{0.281 \text{ kWh/kg}}$$

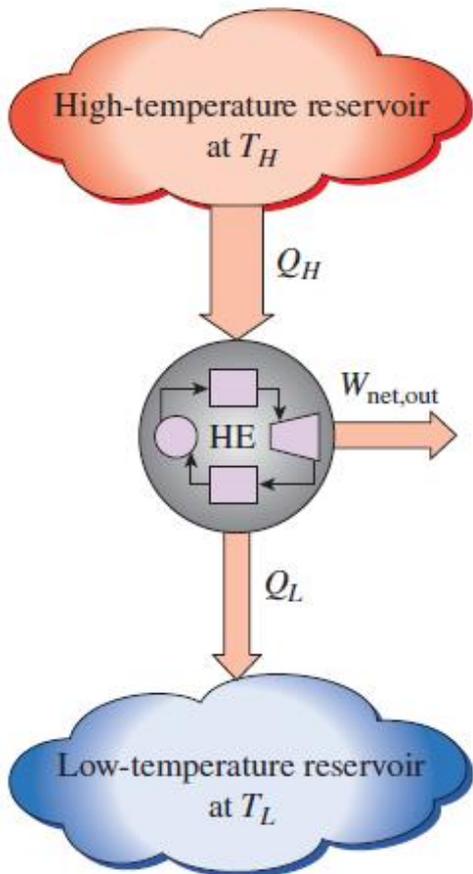
Reversible heat engine operating between seawater at 288 K and liquid methane at 111.5 K:

$$\eta_{\text{th, rev, liq}} = 1 - \frac{T_{\text{low}}}{T_{\text{high}}} = 1 - \frac{111.5 \text{ K}}{288 \text{ K}} = 0.613 \text{ or } 61.3\%$$

A heat engine that absorbs 100 kJ of heat from the seawater will produce 61.3 kJ of work and reject the remaining 38.7 kJ of waste heat to liquid methane. Their ratio is:

$$\text{Ratio}_{\text{rev, liq}} = \frac{w_{\text{rev, liq}}}{q_{\text{low, liq}}} = \frac{61.3}{38.7} = 1.58$$

That is, for each 1 kJ of cold energy, up to 1.58 kJ of work is produced by engine.

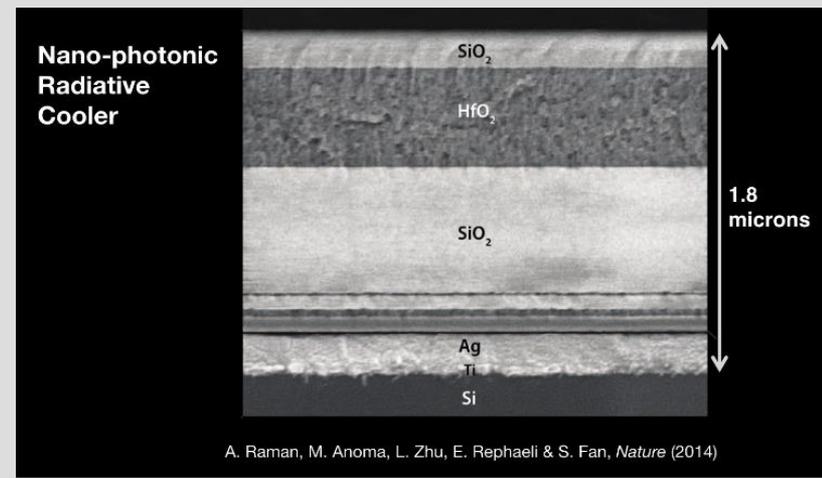
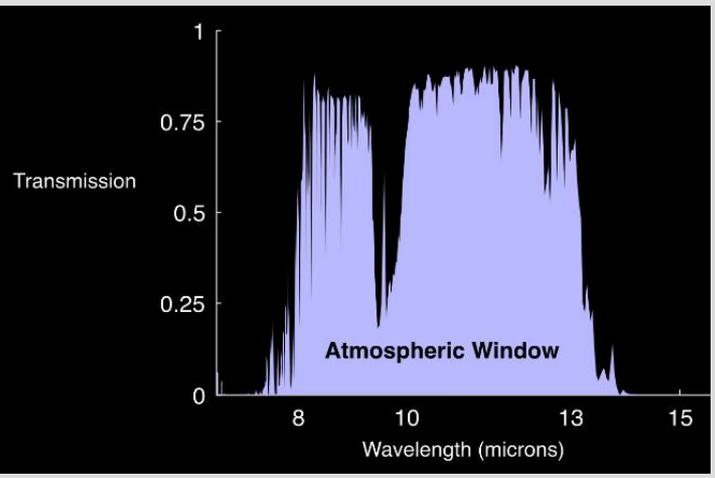
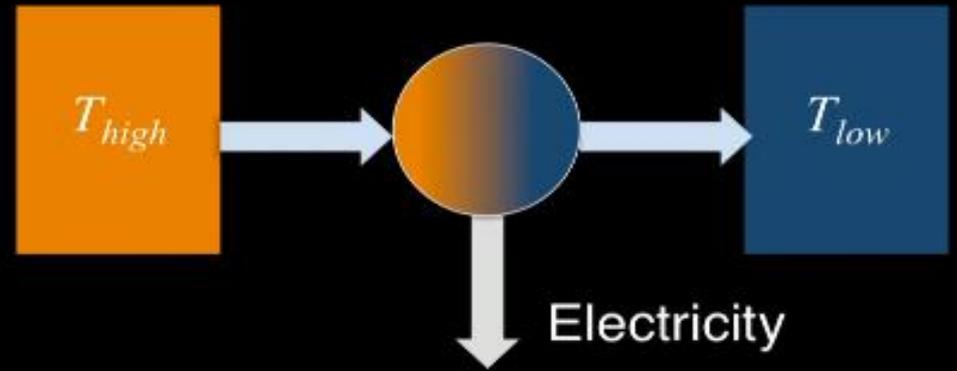


Atmosphere as energy source for power generation: Empty space at ~0 K as an infinite power source

Earth,
300 K

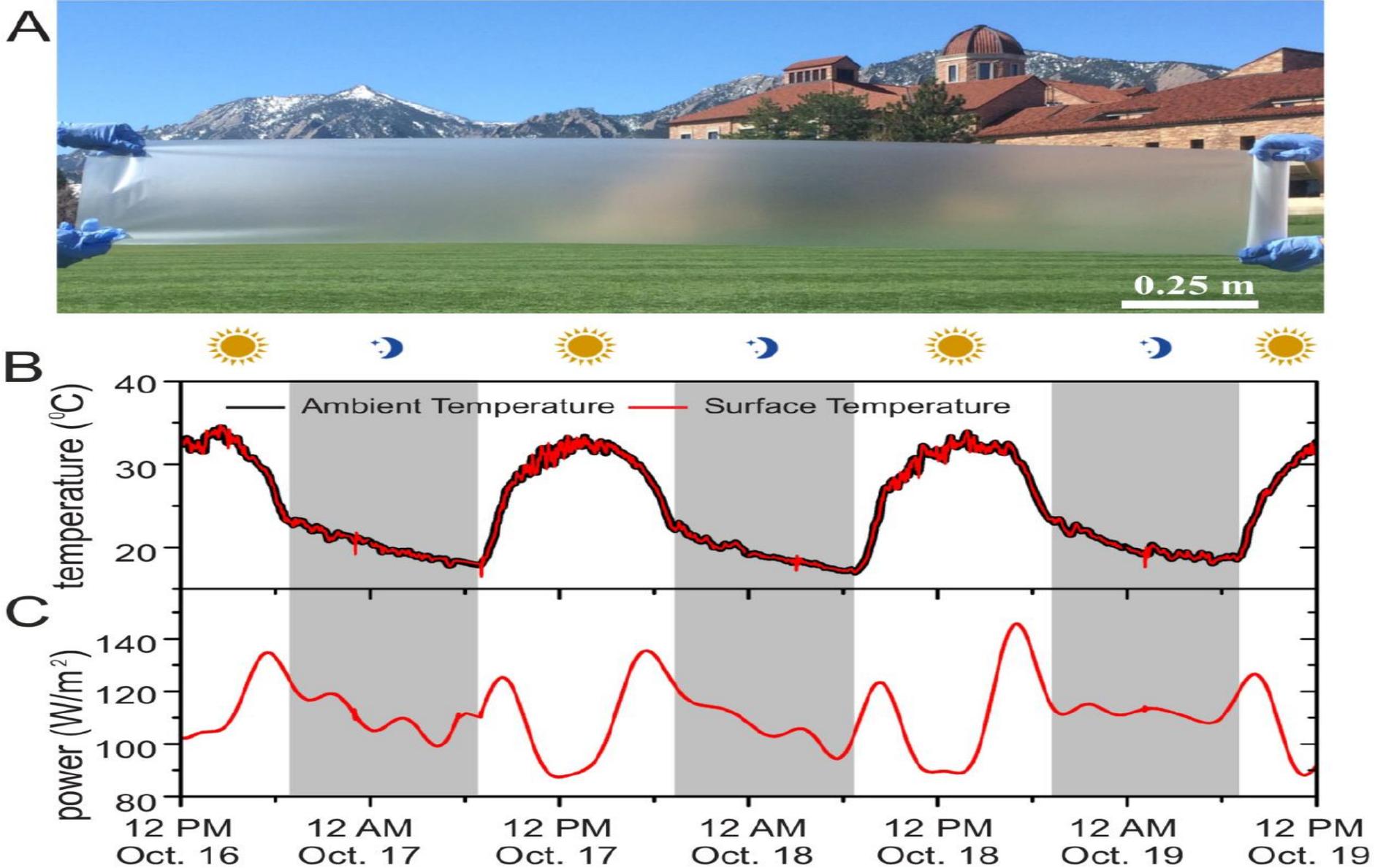


Space,
3 K



Low-T sky as an 'energy sink' (hybrid metamaterials)

Average radiative cooling power of 110 W/m^2



Sustainability in energy:

The big picture: Sustainability at global societal level



SUSTAINABLE DEVELOPMENT GOALS

17 GOALS TO TRANSFORM OUR WORLD

1 NO POVERTY



2 ZERO HUNGER



3 GOOD HEALTH AND WELL-BEING



4 QUALITY EDUCATION



5 GENDER EQUALITY



6 CLEAN WATER AND SANITATION



7 AFFORDABLE AND CLEAN ENERGY



8 DECENT WORK AND ECONOMIC GROWTH



9 INDUSTRY, INNOVATION AND INFRASTRUCTURE



10 REDUCED INEQUALITIES



11 SUSTAINABLE CITIES AND COMMUNITIES



12 RESPONSIBLE CONSUMPTION AND PRODUCTION



13 CLIMATE ACTION



14 LIFE BELOW WATER



15 LIFE ON LAND



16 PEACE, JUSTICE AND STRONG INSTITUTIONS



17 PARTNERSHIPS FOR THE GOALS



Sustainability in energy:

Renewable energy + energy efficiency + storage

- **Sustainability:** Renewable energy + Energy Efficiency + Storage
- **Definition:** Energy system that serves **the needs of the present** without compromising the ability of **future generations** to meet their needs.
- **Venue:** Low-carbon technologies.



Towards the goal of carbon-free energy: Paris Agreement (Entered into force in 2016)

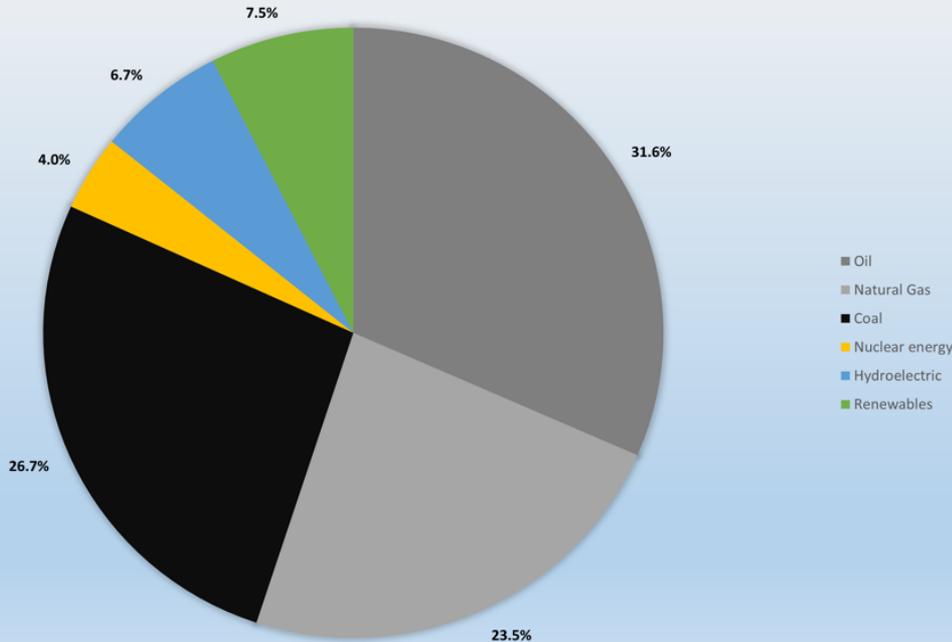
“Holding the increase in the global average temperature to **well below 2°C** above pre-industrial levels and pursuing efforts to limit the temperature increase to **1.5°C above pre-industrial levels**, recognizing that this would significantly reduce the risks and impacts of climate change;” **(Article 2)**



Percentage of fossil fuel use:

2022: 82% of energy; 61% of electricity.
(2019: 84% of energy; 64% of electricity)

PRIMARY GLOBAL ENERGY CONSUMPTION 2022



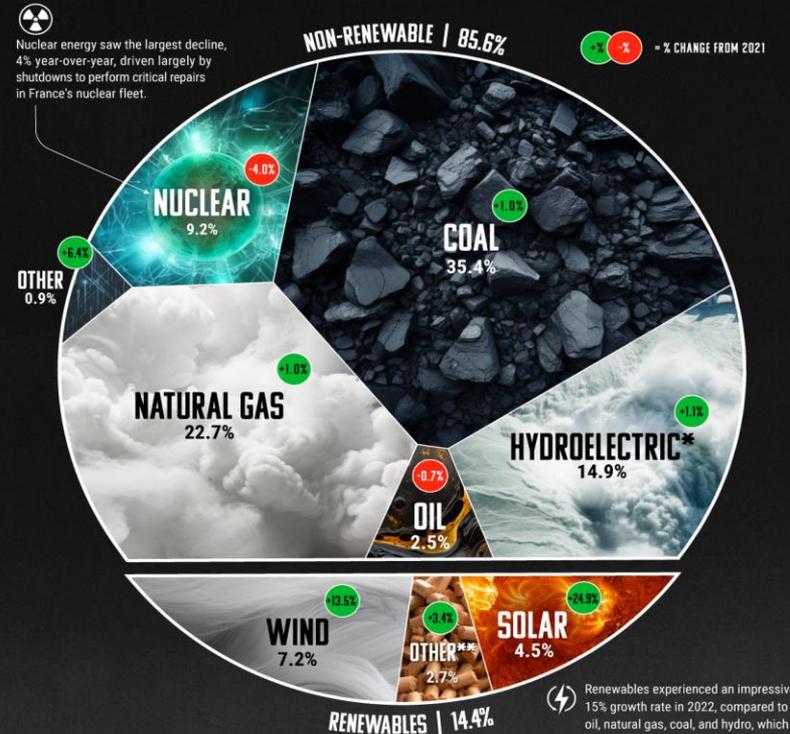
Data source: 2023 Statistical Review of World Energy

© Robert Rapier

WHAT POWERED THE WORLD ⚡ 2022?

Coal still leads the charge when it comes to electricity, representing 35% of global power generation in 2022, followed by natural gas at 23%, and hydroelectric at 15%.

ELECTRICITY SOURCES BY FUEL 2022



*The Statistical Review excludes hydroelectric energy in their renewable calculations; renewables, including hydro, represented 29% of global electricity generation in 2022.
 ** Other Renewables includes geothermal, biomass, and other renewable fuels.

<https://www.forbes.com/sites/rrapier/2023/08/06/global-energy-trends-insights-from-the-2023-statistical-review-of-world-energy/?sh=51ad6d9e3502>

<https://www.visualcapitalist.com/electricity-sources-by-fuel-in-2022/>

Sustainable development:

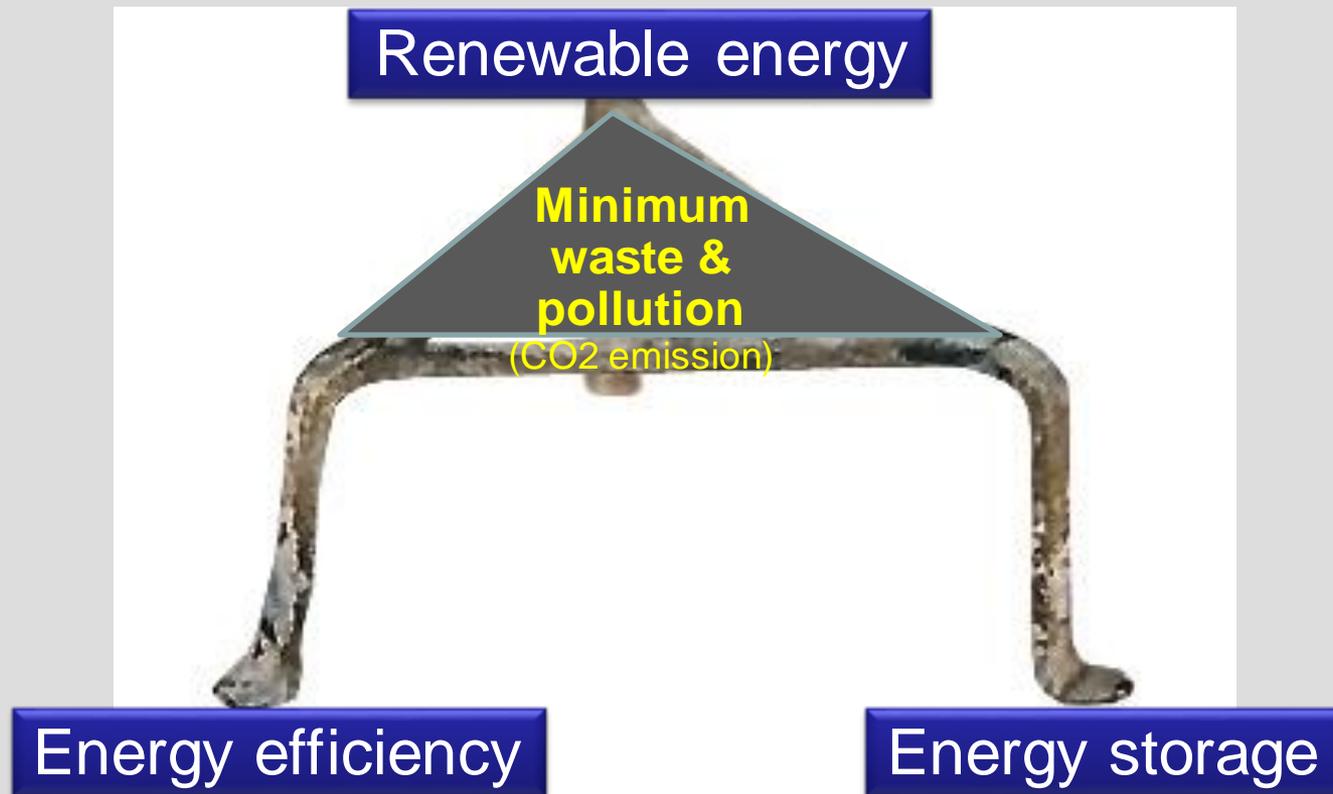
Related to ethics, climate change and green practices

- **Sustainable development:** *“Development that meets the needs of the present without compromising the ability of future generations to meet their own needs”*. (World Commission on Environment and Development, 1987).
- Closely tied to **ethics**. Do not consume resources that belong to future generations.
- **Green/sustainable practices** allow humans to exploit nature, but to do so **without inflicting irreversible damage**.
- **Global warming** and the associated **climate change** are closely **related to inefficient use of energy**.
- **Entropy generation** or **exergy destruction** is a measure of inefficiencies/imperfections/waste associated with energy conversion processes.



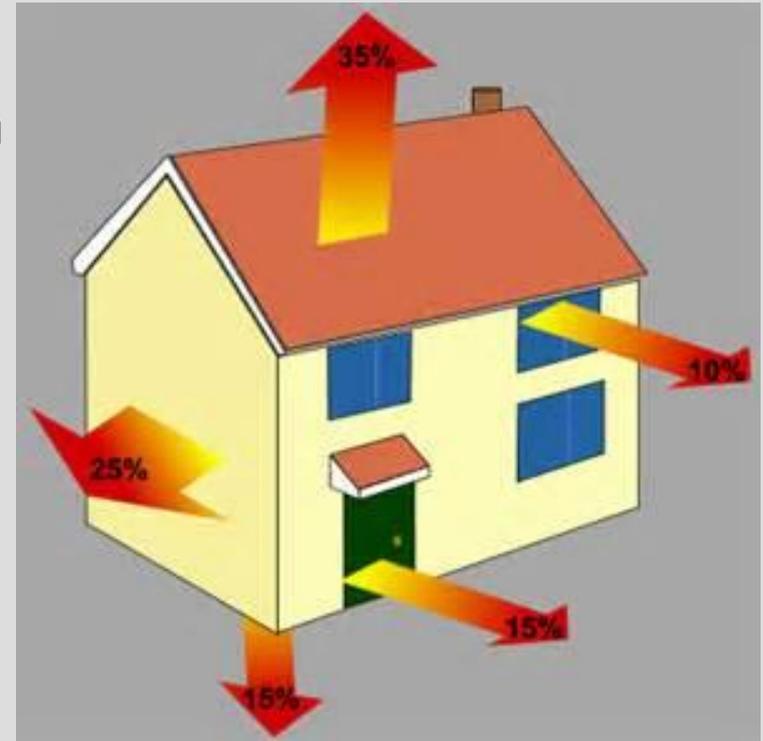
The 3 legs of sustainability:

Renewable energy, energy efficiency, and energy storage



Energy conservation: A 2nd Law concept

- **1st law:** Energy is always **conserved**, even when heat is lost from a building (conservation of energy principle).
- **2nd law:** Degraded energy is **wasted energy**.
- Conserving energy is preserving it at the most useful form.
- Energy converted to a useless form is lost forever.



Sustainability in a nutshell:

Make 'best resource utilization' a basic pillar of life

- The 2nd law of thermodynamics is an effective tool for assessing the **best utilization of resources** by comparing current practice to the best possible practice.
- It leads the way to achieve **sustainability and prosperity** by:
 - reduced waste,
 - enhanced effectiveness, and
 - Improved efficiency.



ENERGY EFFICIENCY:

Largest, cleanest & cheapest energy source

Energy efficiency: Minimizing energy waste

- Energy efficiency is to **reduce energy use to the minimum level**, but do so without:
 - reducing the standard of living,
 - the production quality, and
 - the profitability.
- **Energy efficiency** is associated with the most efficient use of energy at all stages **from production to end use**. It is a broader term that includes **energy conservation**.



- Most domestic,
- Cleanest,
- Cheapest,
- Most environment friendly,
- Most accessible,
- Largest energy source ...

... is energy efficiency.

1. Oil
2. Coal
3. Natural Gas
4. Nuclear
5. Renewable energy (Hydro, wind, solar, geothermal, ...)

6. Energy efficiency

- The cost of electricity obtained from energy efficiency is usually below **5 cents (US) per kWh**.
- Further, energy efficiency is **local** and **labor intensive** with significant benefits to the **environment** by displacing pollution.
- Over the past 50 years, energy efficiency has been the **greatest domestic source of energy** of the US.

US VISION 2025 for ENERGY EFFICIENCY



National Action Plan for Energy Efficiency **Vision for 2025:** Developing a Framework for Change

A RESOURCE OF THE NATIONAL ACTION PLAN FOR
ENERGY EFFICIENCY

NOVEMBER 2007

*“U.S. plans to meet **at least 50%** the expected future load growth by energy efficiency.*”

*As in construction of new power plants, **serious funds should be budgeted for energy efficiency.**”*

Energy-efficient LED lamps: %80 savings compared to incandescent lamps



Use of low-e coating on window glass: 50% savings energy relative to double-pane windows

ISICAMsinerji®



ISICAMkonfor®

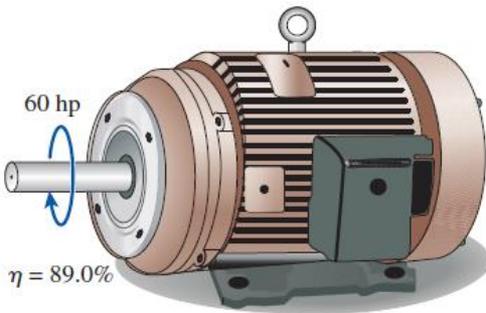


Low-e glass greenhouses:
Minimize energy use.

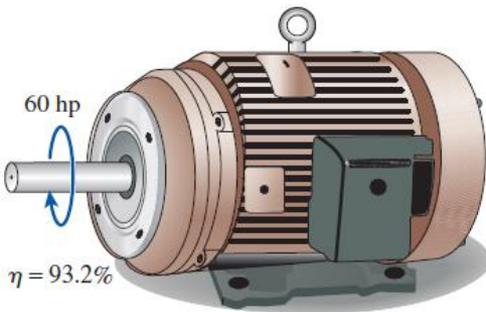


Cost Savings with high-efficiency motors:

Is the higher price tag justified?



Standard motor



High-efficiency motor

A 60-hp electric motor (a motor that delivers 60 hp of shaft power at full load) that has an efficiency of 89.0 percent is worn out and is to be replaced by a 93.2 percent efficient high-efficiency motor (Fig. 2–61). The motor operates 3500 hours a year at full load. Taking the unit cost of electricity to be \$0.08/kWh, determine the amount of energy and money saved as a result of installing the high-efficiency motor instead of the standard motor. Also, determine the simple payback period if the purchase prices of the standard and high-efficiency motors are \$4520 and \$5160, respectively.

$$\dot{W}_{\text{electric in, standard}} = \dot{W}_{\text{shaft}} / \eta_{\text{st}} = (\text{Rated power})(\text{Load factor}) / \eta_{\text{st}}$$

$$\dot{W}_{\text{electric in, efficient}} = \dot{W}_{\text{shaft}} / \eta_{\text{eff}} = (\text{Rated power})(\text{Load factor}) / \eta_{\text{eff}}$$

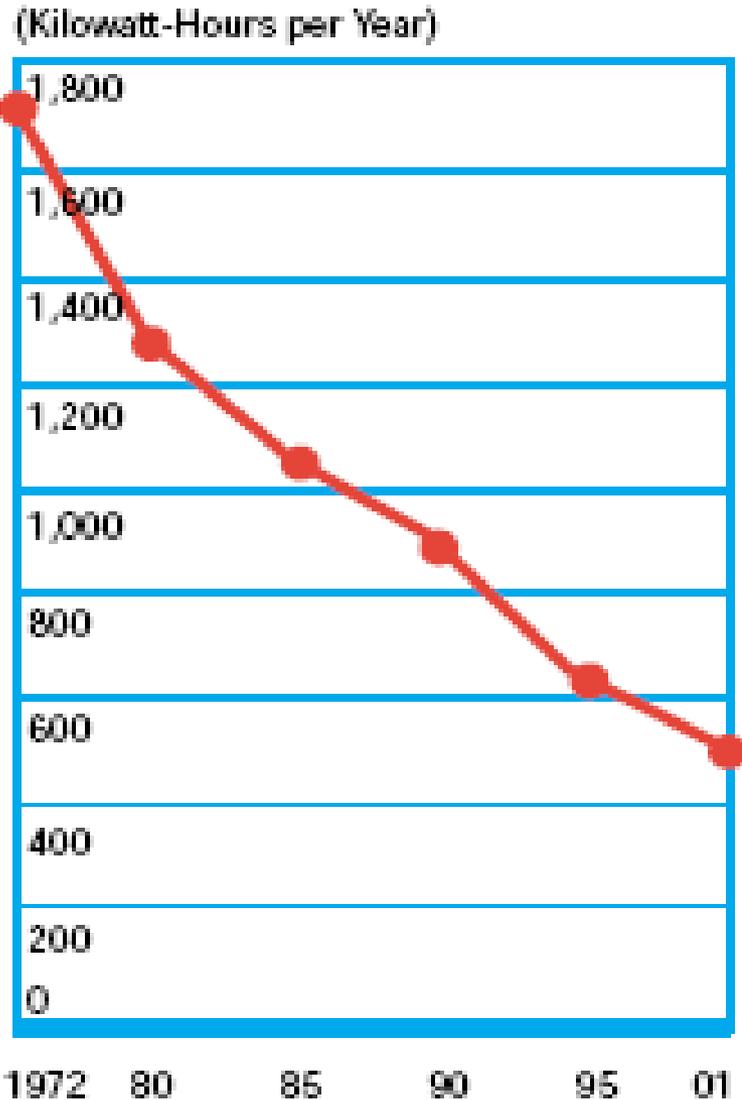
$$\begin{aligned} \text{Power savings} &= \dot{W}_{\text{electric in, standard}} - \dot{W}_{\text{electric in, efficient}} \\ &= (\text{Rated power})(\text{Load factor})(1/\eta_{\text{st}} - 1/\eta_{\text{eff}}) \end{aligned}$$

where η_{st} is the efficiency of the standard motor, and η_{eff} is the efficiency of the comparable high-efficiency motor. Then the annual energy and cost savings associated with the installation of the high-efficiency motor become

$$\begin{aligned} \text{Energy savings} &= (\text{Power savings})(\text{Operating hours}) \\ &= (\text{Rated power})(\text{Operating hours})(\text{Load factor})(1/\eta_{\text{st}} - 1/\eta_{\text{eff}}) \\ &= (60 \text{ hp})(0.7457 \text{ kW/hp})(3500 \text{ h/year})(1)(1/0.89 - 1/0.93.2) \\ &= \mathbf{7929 \text{ kWh/year}} \end{aligned}$$

$$\begin{aligned} \text{Cost savings} &= (\text{Energy savings})(\text{Unit cost of energy}) \\ &= (7929 \text{ kWh/year})(\$0.08/\text{kWh}) \\ &= \mathbf{\$634/\text{year}} \end{aligned}$$

Energy efficiency on refrigerators (Importance of tech. development): Equivalent of 30 nuclear plants (USA)



Energy efficiency of refrigerators-freezers has increased by nearly 70% over the last 30 years due to better insulation and higher efficiency compressors.

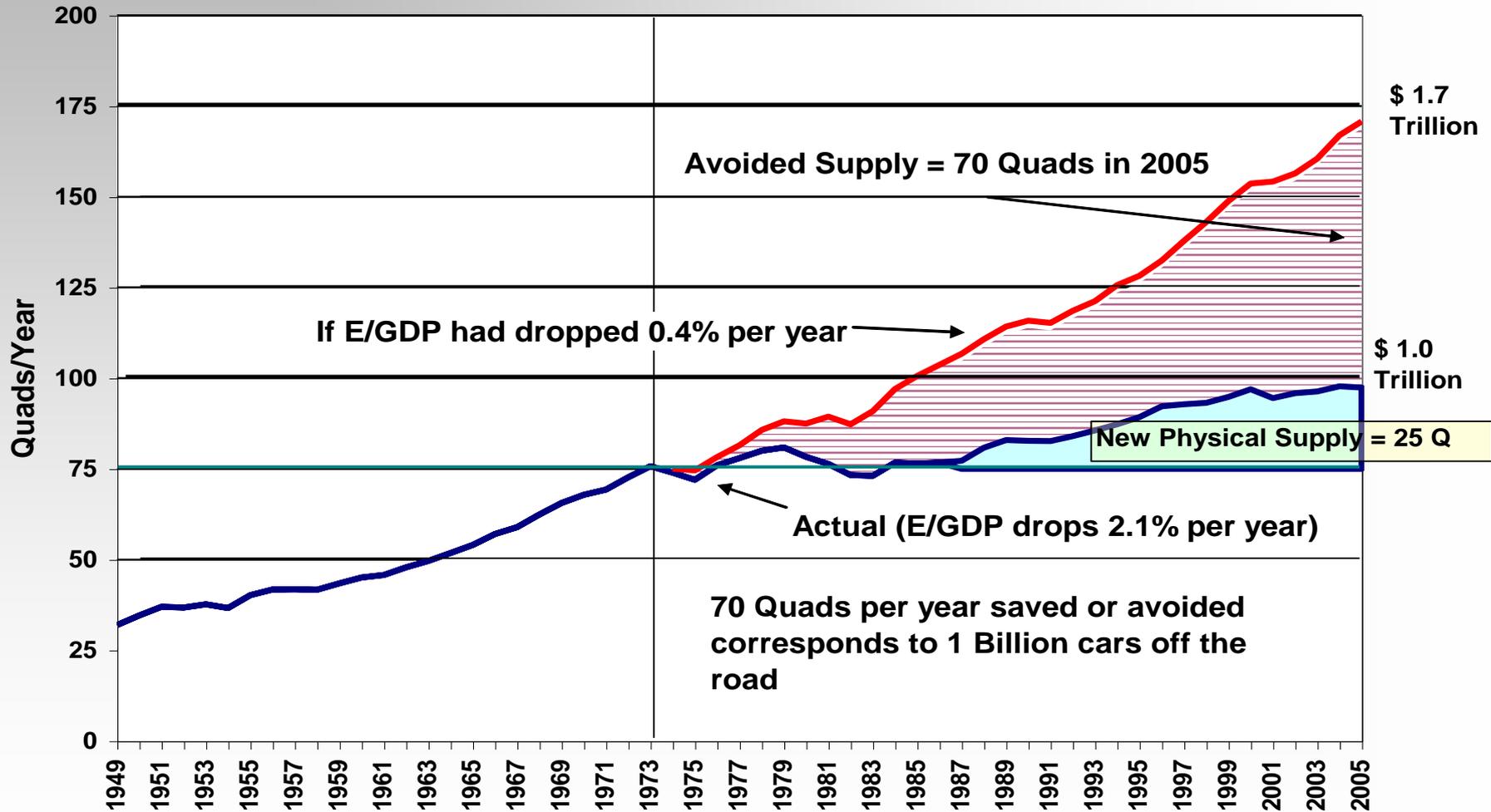
In the US, energy-efficient refrigerators has eliminated the need to build 30,000 MW of power plants since 1973.

The drop in the electricity consumption of new refrigerators-freezers over the years (per unit)

(National Energy Policy Report USA 2001)

The power of energy efficiency (USA): \$700 billion/yr savings; Pulling 1 billion cars off the road

Energy Consumption in the United States 1949 - 2005



Source: California Energy Commission,

<http://www.energy.ca.gov/commission/commissioners/rosenfeld.html>

Renewable energy:

Replacing fossil fuels with zero-carbon alternatives

Renewable energy:
Use it or lose it



“Unused renewable energy ...

... is wasted energy.”

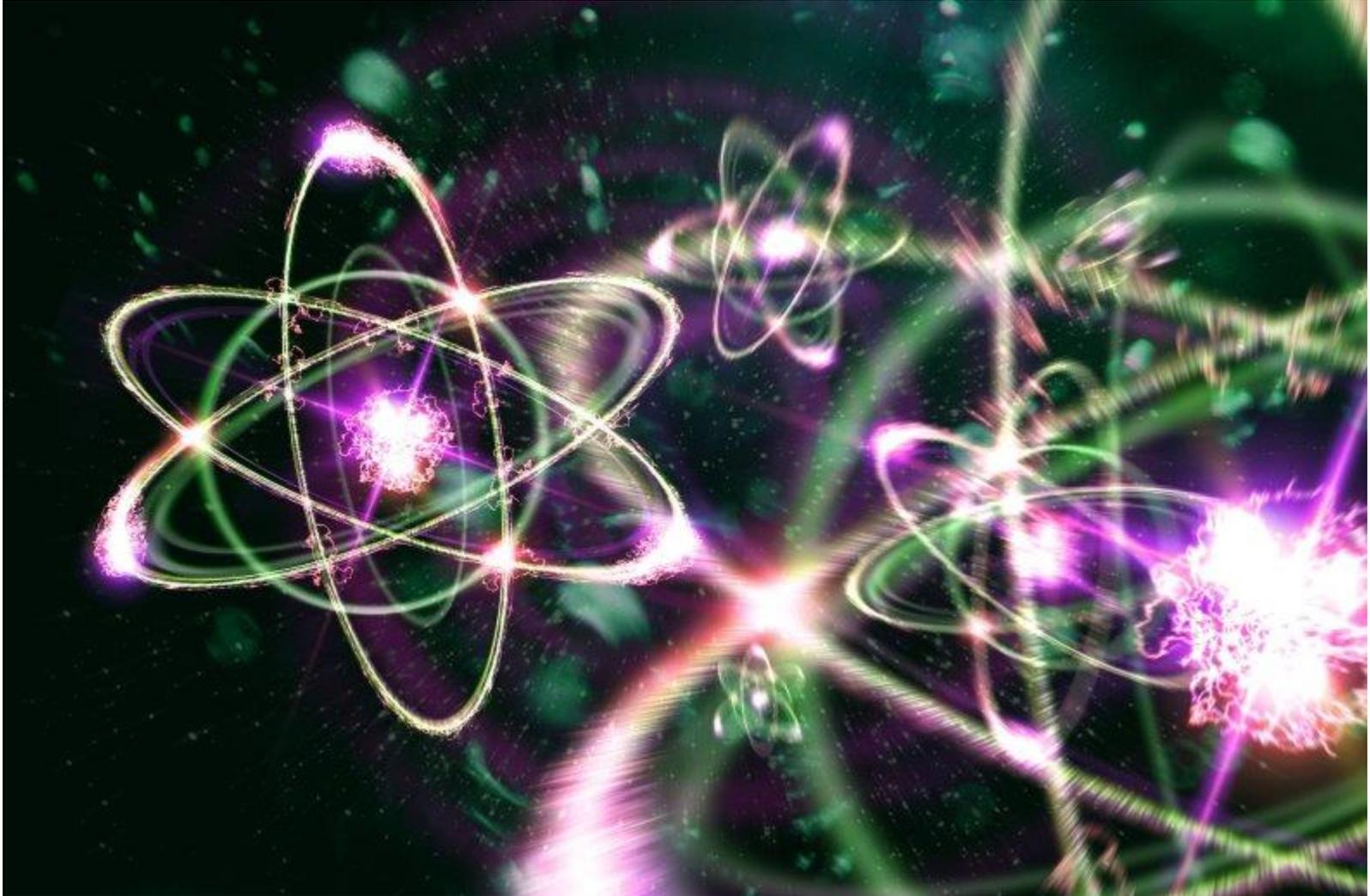
Nuclear (fusion) energy:
A zero-carbon technology

Korean nuclear fusion reactor: Achieves 100 million°C for 30 seconds



- A sustained, stable experiment is the latest demonstration that nuclear fusion is moving from being a physics problem to an engineering one.

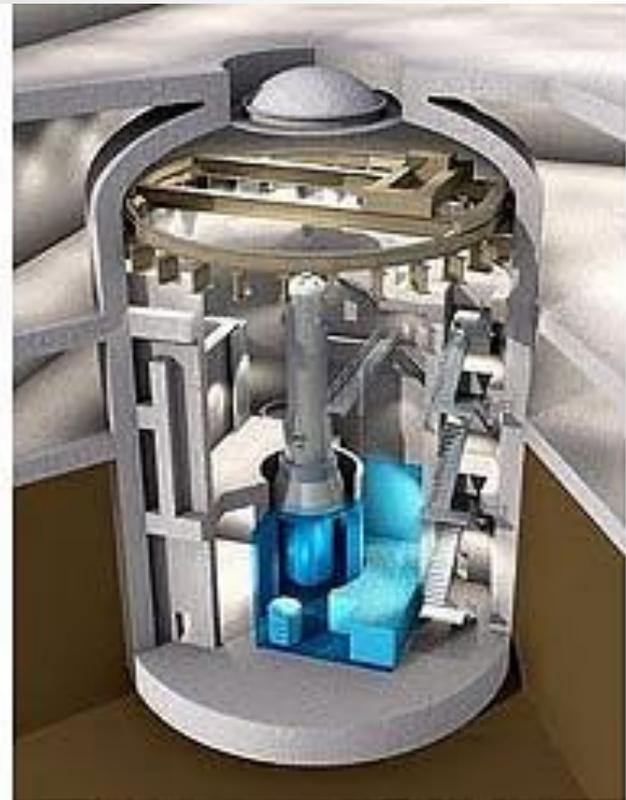
First fusion plant (100 MW) is planned to be built in UK: Construction to begin in early 2030s and end by 2040



Small Modular Nuclear Reactors (SMR): US developing 50-MW SMR's

- SMRs are smaller, lower capital cost, factory produced units designed to provide electricity in the range of 50 to 300 MW.
- In 2012, the US Department of Energy launched a 6-year \$452-million SMR support program aimed at promoting the development and investment in US-based SMR projects.
- Uranium or thorium as fuel.

Modular: To be assembled from standardized, mass-produced subcomponents.



Detailed Report:

<http://trade.gov/publications/pdfs/the-commercial-outlook-for-us-small-modular-nuclear-reactors.pdf>

Molten-salt nuclear reactors: Safer, cheaper, faster, more efficient



CONSTRUCTION COST IN \$ BN

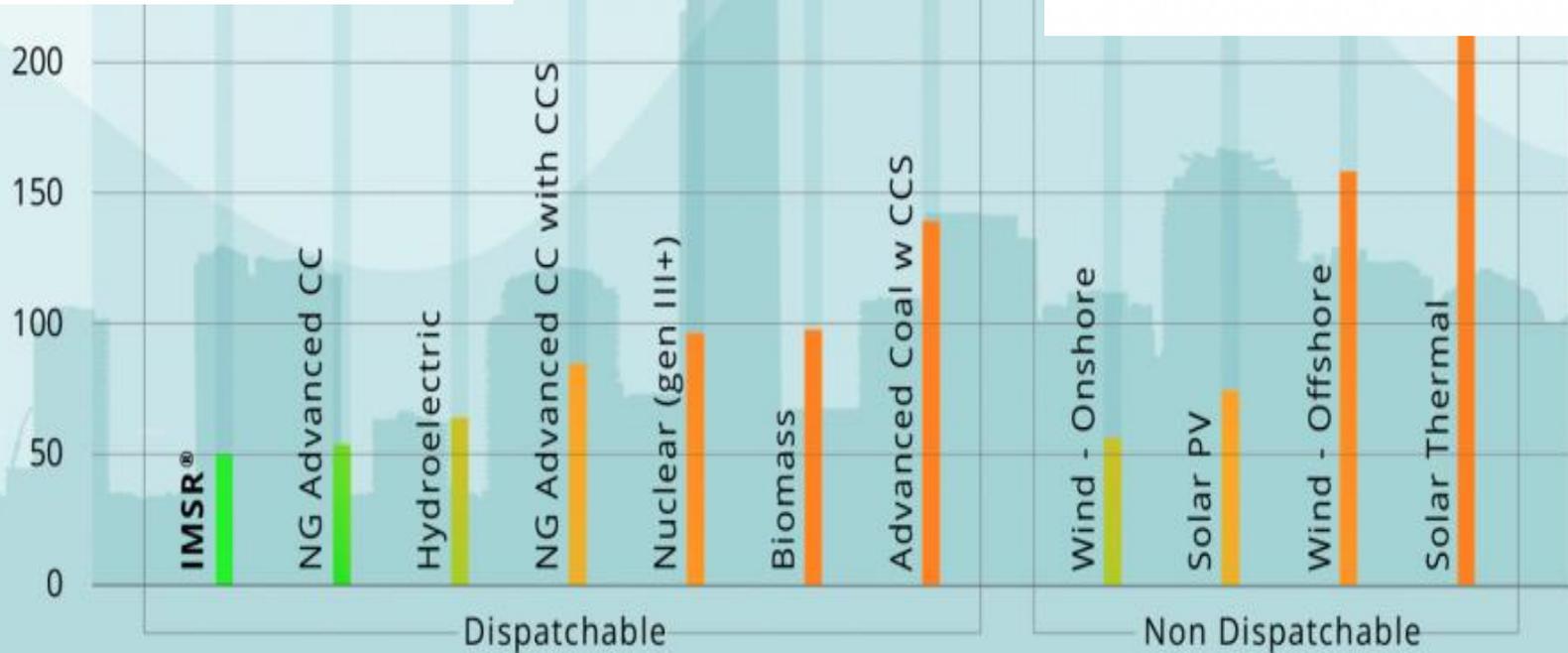


TIME TO BUILD IN YEARS



TOTAL SYSTEM COST

\$/MWh



Source: US Energy Information Agency: Capacity-Weighted Average LCOE (2016 \$/MWh)

Philosophical depth:
Deep understanding

Sir E. S. Eddington on ENTROPY: Although nonphysical, secured a place in physics

Q: Arrange the following in two categories:

Distance, mass, electric force, entropy, beauty, melody.

Answer 1 (An ordinary physicist):

Category 1: Distance, mass, electric force, **entropy** (physical)

Category 2: Beauty, melody (nonphysical)

Answer 2 (E. S. Eddington):

Category 1: Distance, mass, electric force,

Category 2: Beauty, melody, **entropy** (*features of arrangement; emergent*)

“The reason why this stranger can pass itself off among the aborigines of the physical world is that it is able to **speak their language**, viz., the language of **arithmetic**. It has a measure-number associated with it and so is made quite at home in physics. Beauty and melody have not the arithmetical password and so are barred out.”

*Weaver in 1949 Theory of Information: “I feel sure that Eddington would have been willing to include the word ‘**meaning**’ along with beauty and melody.”*

Sir E. S. Eddington, from his 1928 book ‘The Nature of the Physical World’.

Weaver, W. (1949). “Recent Contributions to the Mathematical Theory of Information.

Do living beings violate the 2nd law?:

Orderly structures out of disorderly materials (Reduced entropy?)

Does a chemical factory violate the 2nd law?

- Does an air-conditioner or heat pump violate the 2nd law since it transports heat from a cold medium to a warm medium?
- How about a car climbing a hill?



Temperature (a thermophysical property of mass):

A measure of magnitude of sensible heat (thermal energy) content

Is it the temperature or is it the heat flow that burns?

- Sensible heat is ontologically objective (tangible). It is physical existence.
 - Temperature is ontologically subjective (intangible). It is mental existence (a nonphysical entity) since temperature is not made of matter-energy.
-
- A 200°C-oven will not burn the hand, but 100°C-water will (higher heat transfer rate).
 - Liquid N₂ at 25°C will not burn you, but liquid N₂ at -196°C will.



What is the temperature and entropy of light?

Temperature is a property of mass (a measure of activity of molecules)

Entropy is a property of mass as well.

A light beam of $0.7 \mu\text{m}$ wavelength is emitted by the filament of an incandescent light bulb at 3000°C . Can we tell it apart from a light beam of the same wavelength emitted by the sun?



(Temperature represents the average vibrational kinetic energy of a substance.)

- What is the **entropy of light**? (For black body radiation, entropy is given as $s=4E/3T=4\sigma T^3/3$ and entropy flux as E/T where T is the temperature of the blackbody and $E=\sigma T^4$).
- Can things **without mass** have entropy?
- What is the temperature and entropy of **space**?

<https://asmedigitalcollection.asme.org/IMECE/proceedings-abstract/IMECE2006/47640/217/320872>

Closure

The final word in thermodynamics:

Make 'best resource utilization' a basic pillar of life

Minimize waste via minimizing entropy generation & exergy destruction

Achieve sustainability and prosperity at

- personal,
- national, and
- global levels

via

- reduced waste,
- improved efficiency, and
- enhanced effectiveness.



Sustainability in a nutshell:

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