The Energy to Sustain Civilizations for Nearly Eternity

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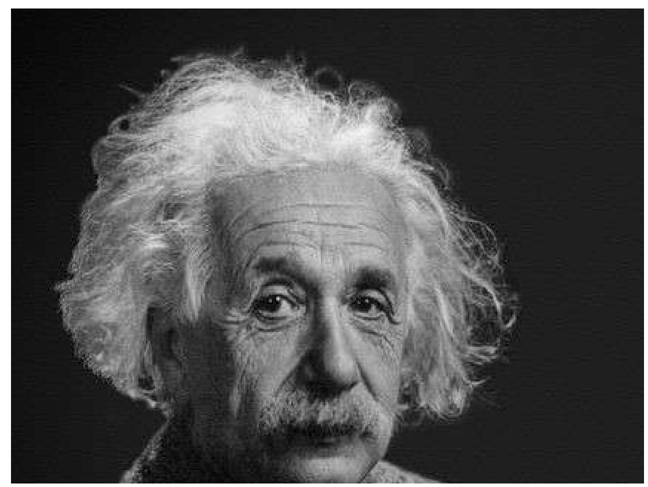
Presentation agenda: Follows video timestamps

1. Energy Production: What is it? E=mc^2
2. Efficiency: Wood coal oil fission fusion & antimatter
3. Efficiency: Gas food glucose protein fat & alcohol
4. Efficiency: Star fusion & 3 types black hole energy
5. The efficiency of converting light into food or electricity in order to sustain a biological civilization
6. Global electricity production by source
7. Cost of electricity production by source
8. Dealing with intermittency of solar and wind power
9. When will production become fully sustainable?
10. Conclusions and best future use of nuclear fuels

Chapter 1

Energy Production: What is it? $E=mc^2$



Energy Production: What is it?

- **This presentation is based on an idea promoted by Elon Musk about First Principles Thinking which is to "***boil things down to their fundamental truths and reason up from there, as opposed to reasoning by analogy"*
- **So with that principle in mind** we should start this presentation by answering the question of: **What is energy production?**
- **Most people would answer** that energy production is what happens at a power plant
- **That answer is true but not at a fundamental level**
- **What really happens when energy is produced** is that *mass is converted into energy*

Energy Production: What is it? E=mc^2

- ✓ **Specifically, Albert Einstein** discovered the world famous equation for this: **E=mc^2**, where E is energy, m is mass and c is a constant equal to the speed of light
- ✓ **For instance, Einstein's equation can be used to calculate that 1 kilo or 2.2 pounds** of mass can power a typical American household using 11,000 kWh per year for 2.3 million years
  - ✓ **Specifically, energy E in Joule is 89,880,000,000,000,000**=1kilo(m)*299,792,458m/s (c)^2
  - ✓ **In kWh we get 24,965,441,604** = (89,880,000,000,000,000* 0.00028)/1000 knowing 1 J = 0.00028 Wh
  - ✓ **Years to power typical household with 1kg of mass:** 2.3 million years = 24,965,441,604kWh/11,000kWh
- ✓ **I made a spreadsheet (see download link below video)** that you can use to easily make alternative calculations for yourself
- ✓ **E=mc^2 assumes a 100% efficient conversion of mass into energy** or energy into mass
- ✓ **Unfortunately, the commercial technology humanity currently have** to make such conversions is grossly inefficient

Chapter 2

Efficiency: Wood oil coal fission fusion & antimatter

Efficiency: Wood coal oil fission fusion & antimatter

Energy Technology and applied fuel	Year first done	Mass of fuel used	Energy produced in kWh	Mass of energy converted calc. using E=mc^2	Efficiency % of mass to energy conversion
Early humans learn to start a fire burning wood (chemical burn)	200,000 years ago	2.6 kg= 1 kg of dry wood + 1.6 kg of oxygen	5.28 kWh	0.000000211404 g	0.000000008131%
Mining of coal (chemical burn)	3000 years ago	3.7 kg= 1 kg of coal+ 2.7 kg of oxygen	8.14 kWh	0.000000326006 g	0.000000008811%
Oil wells and oil refining (chemical burn)	1850's	4.25 kg= 1 kg of oil + 3.25 kg of oxygen	11.63 kWh	0.000000465844 g	0.000000010961%
Nuclear fission (uranium-235 bomb)	1945	1 kg of uranium 235	24,000,000 kWh	0.961329648430 g	0.096132964843%
Nuclear fission (uranium power plant)	1957	1 kg of uranium 235	24,000,000 kWh	0.961329648430 g	0.096132964843%
Nuclear fusion (hydrogen-2 bomb)	1952	1 kg of deuterium and tritium mix	116,388,982 kWh	4.662003734865 g	0.466200373486%
Anti-protons (Berkeley Lab's Bevatron)	1955	1 kg (We are still only able to create a tiny amount of anti-matter particles for experimental use)	24,965,441,603 kWh	1000 g	100% (annihilation of 500g of matter with 500g of antimatter)

Sources for previous slides #1

- **Elon Musk on first principles thinking:** https://www.youtube.com/watch?v=NV3sBlRgzTI
- **E=mc^2:** https://www.calculatorsoup.com/calculators/physics/emc2.php
- **Convert joules to watt hours:** https://www.google.com/search?q=convert+joules+to+watt+hours&rlz=1C1CHBF_enDK866DK866&oq=convert+jous&aqs=chrome.3.69i57j0i13i512l8j0i13i30.12445j0j15&sourceid=chrome&ie=UTF-8
- **Spreadsheet used by HM experience (MS excel file that contains all calculations):** Download link is available below video at www.hmexperience.dk
- **Average household kWh use per year in the US:** https://shrinkthatfootprint.com/average-household-electricity-consumption/
- **1 kg in pounds:** Google 1 kg in pounds =2.2 pounds
- **Ounce to gram:** Google 1 ounce to gram =28 grams
- **For great YouTube video explaining E=m*c^2:** https://www.youtube.com/watch?v=KZ8G4VKoSpQ (video also explains general version. E=m*c^2 is a special case of the generalized Einstein equation that also account for the kinetic energy of mass as well as for the momentum in mass-less particles like photons but that is much more complicated than the ultra simple rest mass equation of E=m*c^2. Fortunately we do not need any of the complicated stuff for this presentation)
- **Early humans start using fire:** https://www.smithsonianmag.com/smart-news/evidence-of--fire-artificial-intelligence-180980319/#:~:text=Most%20evidence%20of%20fire%20dates,years%2C%20according%20to%20the%20statement.
- **1.6 kg of oxygen is needed to burn 1 kg of dry wood:** https://physics.stackexchange.com/questions/681929/how-much-oxygen-does-it-take-to-burn-a-log-of-wood
- **Energy in 1 kg of dry wood 19 MJ:** https://www.cs.mcgill.ca/~rwest/wikispeedia/wpcd/wp/w/Wood_fuel.htm#:~:text=Energy%20Content&text=%22Green%22%20wood%20is%20about%2010,19%20to%2020%20MJ%2Fkg.
- **First mining of coal 3000 years ago:** https://www.dyballassociates.co.uk/a-brief-history-of-energy-coal#:~:text=The%20earliest%20references%20of%20coal,began%20to%20flourish%20around%20120BC.
- **Energy in 1 kg of coal 29.3 MJ or 8.141 kWh:** https://www.euronuclear.org/glossary/coal-equivalent/#:~:text=1%20kg%20coal%20equivalent%20corresponds,MJ%2Fkg%20(anthracite).
- **2.7 kg of oxygen needed to burn 1 kg of coal:** https://www.quora.com/How-much-air-is-required-to-burn-1kg-of-carbon

Sources for previous slides #2

- **First oil wells and refining 1850s:** https://en.wikipedia.org/wiki/History_of_the_petroleum_industry#Oil_wells
- **Energy in 1 kg of crude oil 41.9 MJ or 8.141 kWh:** https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Kilograms_of_oil_equivalent_(kgoe)#:~:text=By%20convention%20it%20is%20equivalent,the%20energy%20from%20different%20sources.
- **3.25 kg of oxygen needed to burn 1 kg of oil (furnace oil):** http://www.opexworks.com/KBase/Energy_Management/Termal_Energy_Management/Fuel_and_Combution/Combution_of_Oil.htm#:~:text=Stoichiometric%20Combustion&text=For%20ideal%20combustion%20process%20for,burner%20and%20combustion%20is%20perfect.
- **First nuclear fission bomb 1945 using U235:** https://en.wikipedia.org/wiki/Trinity_(nuclear_test)
- **Energy in 1 kg of uranium 235 is 24,000,000 kWh:** https://www.euronuclear.org/glossary/fuel-comparison/#:~:text=With%20a%20complete%20combustion%20or,three%20million%20times%20the%20energy
- **First nuclear fission commercial power plant 1957 using U235:** https://www.energy.gov/sites/prod/files/The%20History%20of%20Nuclear%20Energy_0.pdf
- **First fusion in 1952 detonating a hydrogen nuclear bomb:** https://en.wikipedia.org/wiki/Operation_Ivy
- **1 kg of Deuterium and tritium fusion fuel is 10 million * 41.9 MJ:** https://ccfe.ukaea.uk/fusion-energy/fusion-in-brief/ To quote source "***Energy efficiency.*** One kilogram of fusion fuel could provide the same amount of energy as 10 million kilograms of fossil fuel." Source also describe that fuel as a deuterium and tritium mix and I have used MJ in 1kg of crude oil to finish the calculation.
- **First anti-matter protons 1955:** https://newscenter.lbl.gov/2010/11/17/antimatter-atoms/#:~:text=The%20first%20antiprotons%20were%20deliberately,physics%20in%20the%20same%20way.

Chapter 3

Efficiency: Gas food glucose protein fat & alcohol

Efficiency: Gas food glucose protein fat & alcohol

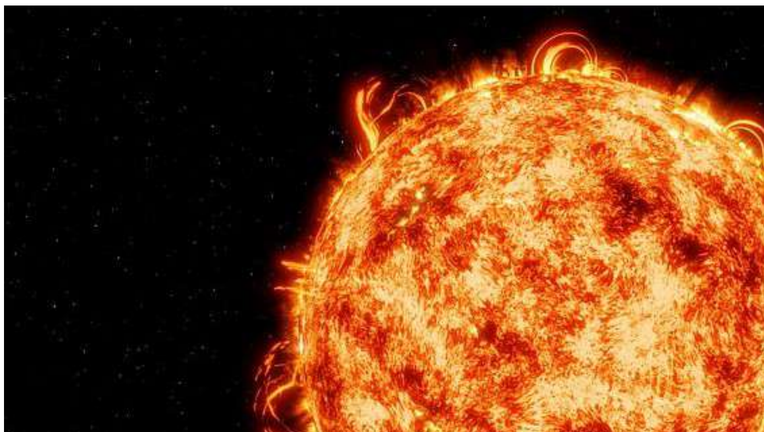
Energy Technology and applied fuel	Year first done	Mass of fuel used	Energy produced in kWh	Mass of energy converted calc. using E=mc^2	Efficiency % of mass to energy conversion
Natural gas, CH_4 (chemical burn)	1823 first gas well drilled	5 kg = 1 kg of gas + 4 kg of oxygen	15.44 kWh	0.000000618633 g	0.000000012373%
Homo sapiens/human using cellular respi-ration to digest food	300,000 years ago first HS	1.71 kg = 1 kg of food adult man + 0.71 kg oxygen	3.37 kWh	0.000000135005 g	0.000000007895%
Aerobic respiration using oxygen (1 glucose = 38 ATP)	2.4 billion years ago bacteria	1.91 kg = 1 kg of glucose+ 0.91 kg oxygen	4.33 kWh	0.000000173240 g	0.000000009070%
Anaerobic respiration not using oxygen (1 glucose only makes 2 ATP)	3.5 to 4 billion years ago bacteria	1 kg of glucose (early anaerobic life feed on hydrogen, CH_4 and sulfur S)	0.23 kWh	0.000000009118 g	0.000000000912%
Protein (aerobic metabolism)	2.4 billion years ago	1.99 kg = 1 kg of protein + 0.99 kg of oxygen	4.72 kWh	0.000000189151 g	0.000000009505%
Fat (aerobic metabolism)	2.4 billion years ago	3.17 kg = 1 kg of fat + 2.17 kg of oxygen	10.28 kWh	0.000000411681 g	0.000000012987%
Alcohol (aerobic metabolism)	2.4 billion years ago	2.7 kg = 1 kg of alcohol + 1.7 kg of oxygen	8.06 kWh	0.000000322669 g	0.000000011951%

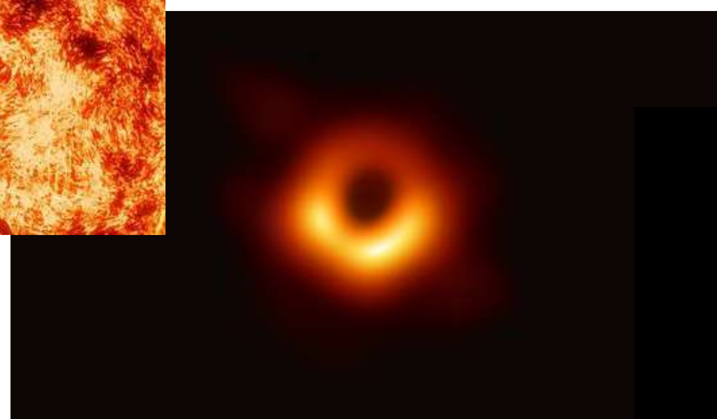
Sources for previous slide #1

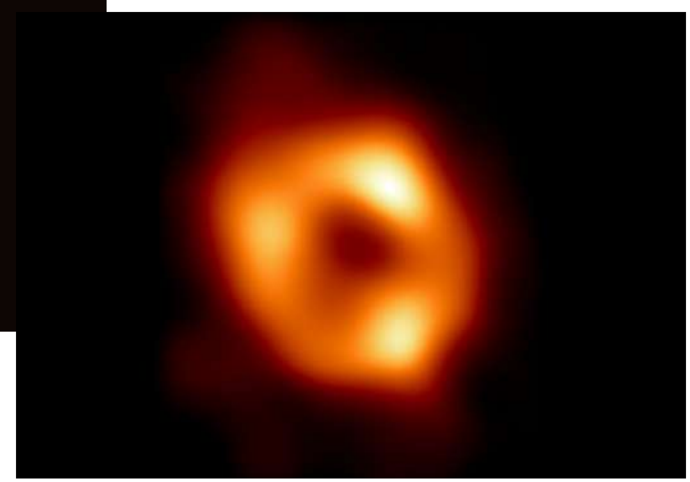
- **First commercial natural gas well drilled in 1821:** https://www.apga.org/apgamainsite/aboutus/facts/history-of-natural-gas
- **Energy in 1 kg of CH4 is 55.6 MJ or 15.44 kWh:** https://hypertextbook.com/facts/2004/BillyWan.shtml#:~:text=Methane%20is%20composed%20of%20CH,50%E2%80%9355.5%20MJ%2Fkg.
- **4 kg of oxygen needed to burn 1 kg of methane (CH4): https://www.aboutmech.com/2016/03/combustion-of-fuels.html#:~:text=Or%20in%20other%20words%2C%201%20kg%20of%20methane%20requires%204,kg%20of%20water%20or%20steam.**
- **First modern humans (homo sapiens) 300,000 years ago:** https://en.wikipedia.org/wiki/Human#:~:text=Homo%20sapiens%20emerged%20in%20Africa,local%20populations%20of%20archaic%20humans.
- **For men of reference body size, the average allowance is 2,900 kcal/day; for women, it is 2,200 kcal:** https://www.ncbi.nlm.nih.gov/books/NBK234938/#:~:text=For%20men%20of%20reference%20body,women%2C%20it%20is%202%2C200%20kcal.
- **Convert kcals into Joule:** https://convertilo.com/amp/2900-kilocalories-to-joules
- **Humans consume 500 liters of pure oxygen per day or 710 grams:** https://www.sharecare.com/health/air-quality/oxygen-person-consume-a-day#:~:text=The%20average%20adult%2C%20when%20resting,liters%20of%20air%20per%20day.
- **Convert m^3s of oxygen to kg:** https://www.aqua-calc.com/calculate/volume-to-weight
- **The origin of anaerobic respiration 3.5 to 4 billion years ago:** https://flexbooks.ck12.org/cbook/ck-12-biology-flexbook-2.0/section/2.30/primary/lesson/anaerobic-and-aerobic-respiration-bio/
- **The origin of early life 3.6 to 3.2 billion years ago and the chemicals available for early organisms to feed on using anaerobic respiration in hydrothermal vents and hydrothermal pools :** https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6789705/
- **Before plants discovered the power of photosynthesis, single-celled life survived on chemicals, not sunlight, burning through hydrogen, methane and sulfur, among other compounds:** https://www.livescience.com/44308-first-oxygen-breathers-on-earth.html
- **The origin of aerobic respiration 2.3 billion years ago:** https://www.science.org/doi/10.1126/science.aal3794
- **Aerobic respiration v. anaerobic respiration 38ATPs v. 2ATPs:** https://biologydictionary.net/aerobic-respiration/
- **Efficiency of aerobic respiration v. anaerobic respiration 40% v. 2.12% compared to energy in glucose:** http://www.biology.lifeeasy.org/3295/anaerobic-respiration-less-efficient-aerobic-respiration#:~:text=In%20anaerobic%20respiration%2C%202%20ATP%20molecules%20are%20used%20for%20breakdown.&text=2%20ATP%20x%2030.6%20kJ,respiration%20of%20each%20glucose%20molecule.&text=Thus%2C%20energy%20efficiency%20of%20anaerobic%20respiration%20is%20just%202.12%25.
- **Humans share 23% of genes with baking yeast:** https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5525645/
- **Humans share 98.8% of genes with chimpanzee:** https://www.amnh.org/exhibitions/permanent/human-origins/understanding-our-past/dna-comparing-humans-and-chimps
- **For energy content of fat (37 kJ/g), ethanol (29 kJ/g), protein (17 kJ/g), carbohydrates (17 kJ/g) and glucose (15.57 kJ/g):** https://en.wikipedia.org/wiki/Food_energy

Chapter 4

Efficiency: Star fusion & 3 types black hole energy



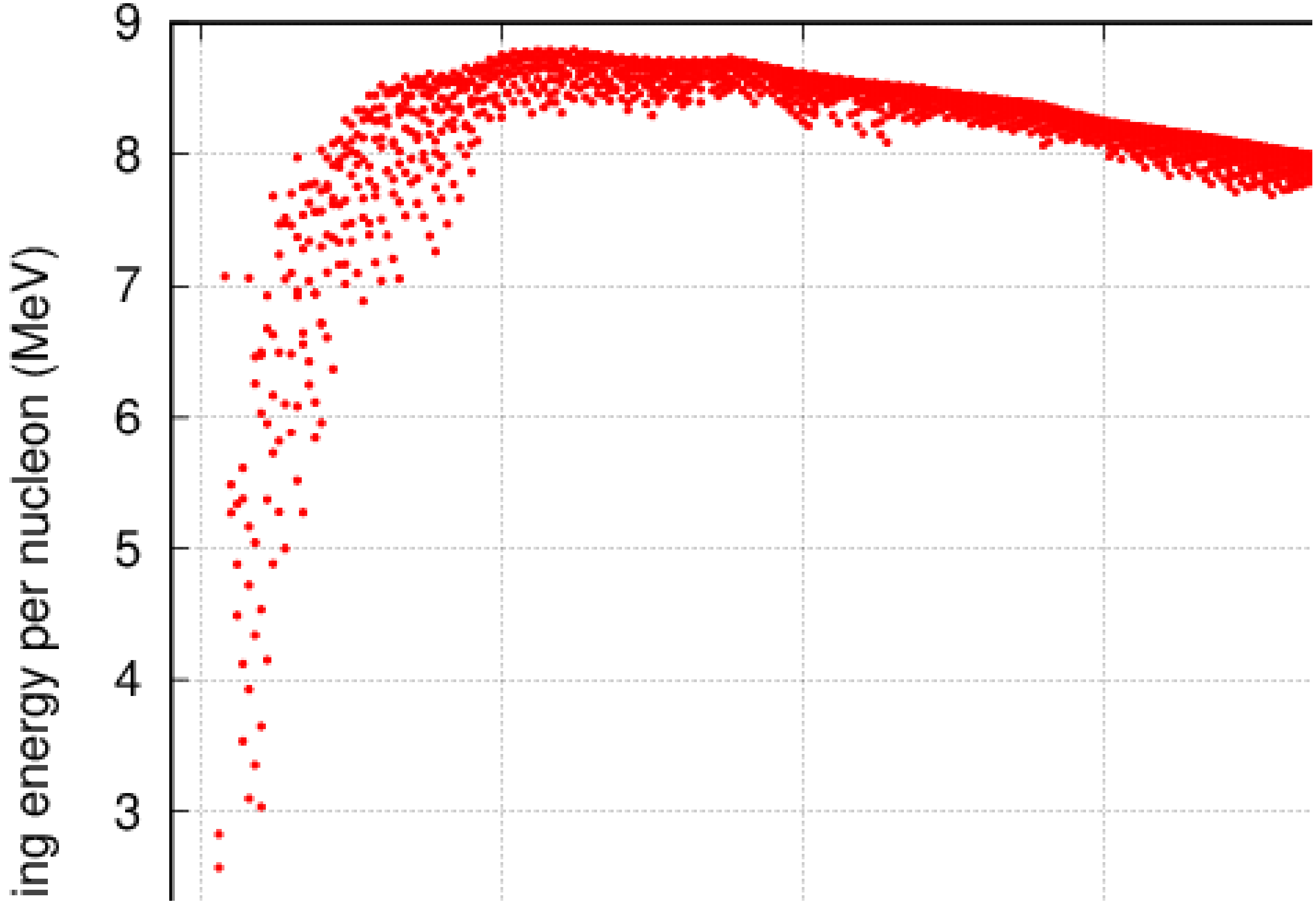




Efficiency: Star fusion & 3 types black hole energy

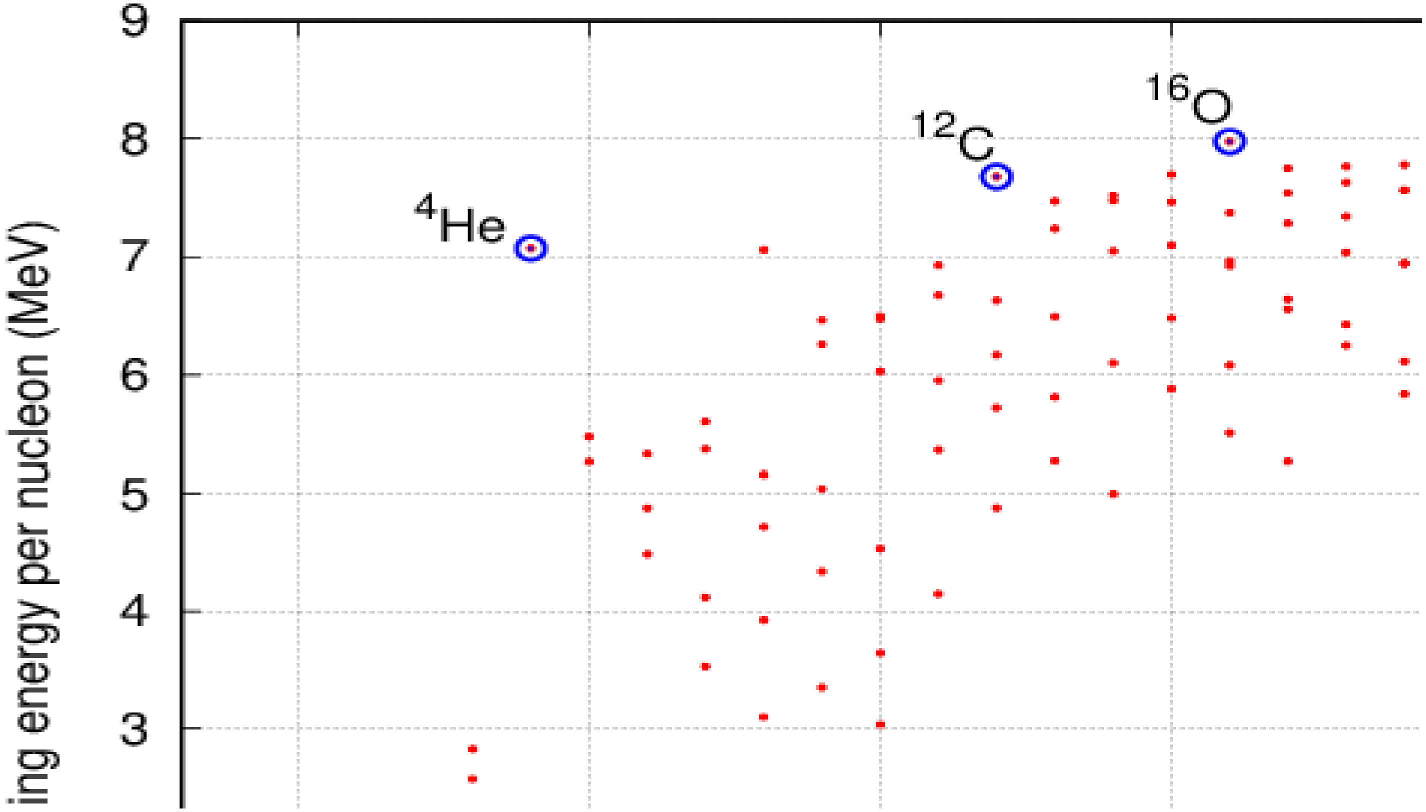
Energy Technology and applied fuel	Year first done	Mass of fuel used	Energy produced in kWh	Mass of energy converted calc. using E=mc^2	Efficiency % of mass to energy conversion
Nuclear fission, **slide 4** (uranium power plant)	1957	1 kg of uranium 235	24,000,000 kWh	0.961329648430 g	0.096132964843%
Nuclear fusion, **slide 4** (hydrogen-2 bomb)	1952	1 kg of deuterium H-2 and tritium H-3 mix	116,388,982 kWh	4.662003734865 g	0.466200373486%
Fusion in our sun (4H-1 to 1He)	4.6 billion years ago	1 kilo of hydrogen-1	174,758,091 kWh	7.000000000000 g	0.700000000000%
Fusion in our sun (3He to 1C)	7 billion years in the future	1 kilo of helium-4	15,728,228 kWh	0.630000000000 g	0.063000000000%
Black hole accretion (fuel is anything falling onto BH circling it at extreme speed and temperature radiating light)	13 billions years ago	1 kg of mass that are thrown onto black hole	9,986,176,641 kWh	400 g	40% (other source say accretion process is 6% for non-rotating BH and 32% for rotating BH)
Rotating black hole (fuel is kinetic energy harvested by PVs exploiting super radiant scattering of light by mirrors)	Doable future technology	1 kg of mass of black hole itself	7,239,978,065 kWh	290 g	Max 29% (kinetic energy in rotating BH can be at most be 29% of its total energy)
Black hole Hawking radiation (fuel is mass of black hole itself)	Pending empirical validation	1 kg of mass of black hole itself	24,965,441,603 kWh	1000 g	100% (black holes radiates mostly photons)

Why fusion of hydrogen is by far the most efficient type of fusion that exist



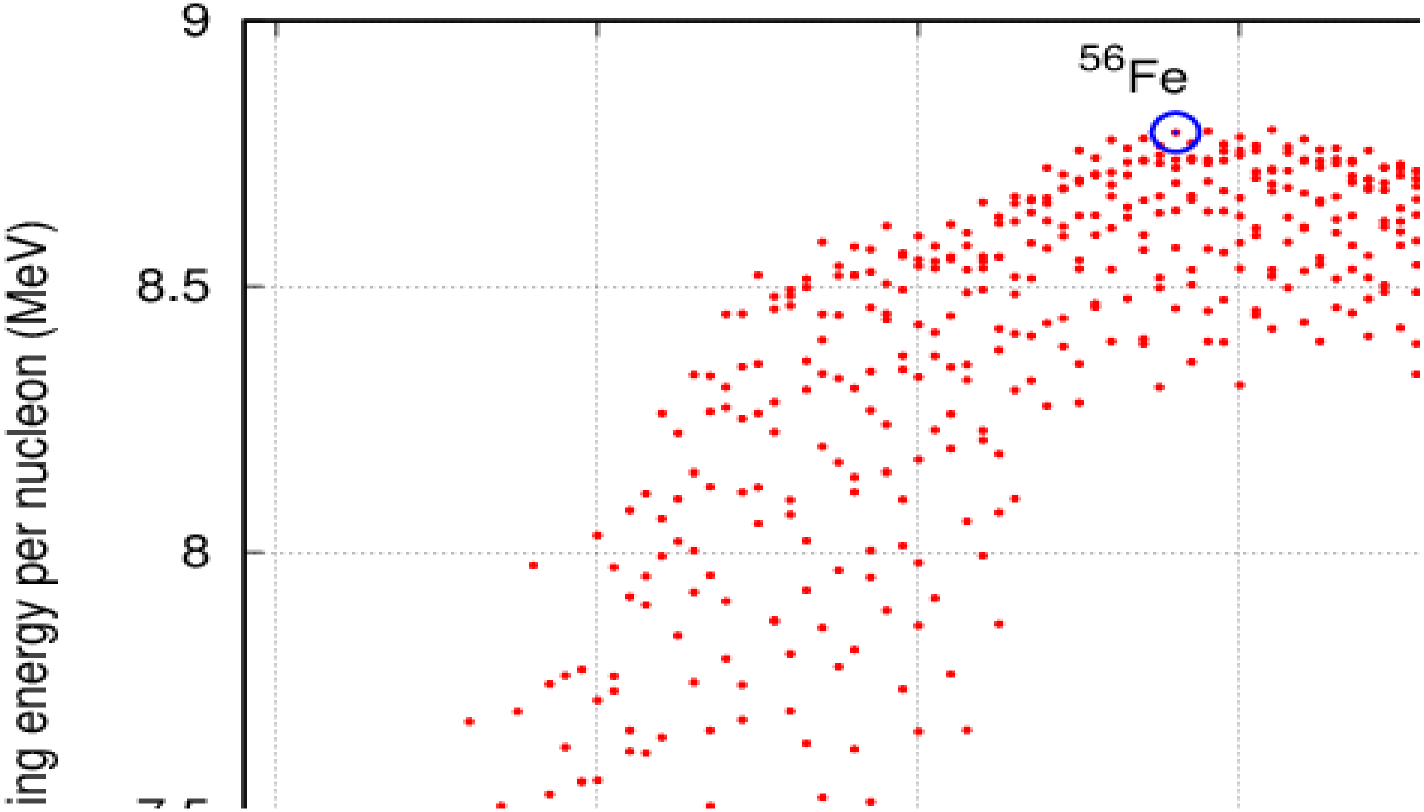
- **Source: Curve of nuclear binding energy:** http://spiff.rit.edu/classes/phys370/lectures/fusion/fusion.html

Why fusion of hydrogen is by far the most efficient type of fusion that exist



- **This curve of nuclear binding energy showing that hydrogen-1 fusion is by far the most efficient kind of fusion process that exist.** Fx graph show energy released **is (7-0)*4=28 MeV** when 4H fusion into 1He
- Reality of that process is more complex but calculation is still a good approximation
- **Next is fusion of 3He into 1C that only release (7.7-7)*3=2.1 MeV using this quick and dirty calculation method that is almost correct.** Note that is only 7.5% as efficient as H fusion 7.5%=2.1*100/28
- True number is He fusion is 9% as efficient as H-1 fusion but that is beyond this presentation to explain

Why fusion of hydrogen is by far the most efficient type of fusion that exist



- **This curve of nuclear binding energy also shows that fusion beyond Iron (Fe) will not release energy but instead consume energy because the curve slopes downwards after iron**
- **Heavier elements than Fe requires** that the star go supernova or other energy intense events that the universe has such as a hypernova for stars over 30 times the mass of our sun or a kilonova when two neutron and or neutron star and black hole collide
- **The fact that the heaviest kinds of fusion consume energy** is also the reason that it is possible to make energy by splitting atoms in nuclear fission, such as, Uranium 235 fission

Sources for previous slides #1

- **First image made of Black hole in 2019 named Messier 87 and its mass is 6.5 billion suns and it is 50 million lights years from Earth:** https://www.nationalgeographic.com/science/article/first-picture-black-hole-revealed-m87-event-horizon-telescope-astrophysics
- **First image of black-hole in center of our milky way taken in 2022 named Sagittarius A* and it mass is 4.3 million solar masses:** https://www.space.com/milky-way-monster-black-hole-first-image-eht
- **Efficiency of hydrogen-1 fusion in our solar system is 0.7%:** https://www.quora.com/How-efficient-is-the-sun-in-turning-matter-into-energy
- **Age of sun in our solar system is 4.6 billion years:** https://en.wikipedia.org/wiki/Sun#:~:text=It%20formed%20approximately%204.6%20billion,of%20a%20large%20molecular%20cloud.
- **7 billion years into the future the sun will start to fusion He into C and shortly after that it will become a white dwarf that has no fusion occurring but steadily cools to lower temperatures:** https://en.wikipedia.org/wiki/Formation_and_evolution_of_the_Solar_System#Timeline_of_Solar_System_evolution
- **No scientific consensus about how long time our sun will live as a white dwarf before it becomes a black dwarf with no visible light. NASA say 10 billion years others say 10^15 years:** https://www.smithsonianmag.com/science-nature/four-types-stars-will-not-exist-billions-or-even-trillions-years-180971299/#:~:text=NASA%20estimates%20that%20the%20sun,these%20exotic%20objects%20exist%E2%80%94yet.
- **Helium fusion only produce 9% as much energy as hydrogen fusion:** https://faculty.wcas.northwestern.edu/infocom/The%20Website/end.html
- **Curve of nuclear binding energy showing that hydrogen-1 fusion is by far the most efficient kind of fusion process that exist (fx graph show energy released per nucleon is (7-0)*4=28 MeV when 4H fusion into 1He. Reality of that process is more complex but it is still a good approximation. Next is fusion of 3He into 1C that only release (7.7-7)*3=2.1 MeV using this quick and dirty calculation method that is almost correct. Note that is only 7.5% as efficient as H fusion 7.5%=2.1*100/28. True number is 9% but that is beyond this presentation to demonstrate:** http://spiff.rit.edu/classes/phys370/lectures/fusion/fusion.html
- **Why both fusion and fission are able to release energy:** https://www.euro-fusion.org/faq/top-twenty-faq/how-do-both-fission-and-fusion-generate-energy/#:~:text=While%20it%20might%20seem%20confusing,energy%20when%20they%20fuse%20together.
- **Accretion (of matter) onto a black hole is the most efficient process for emitting energy from matter in the Universe, (except Hawking radiation if true) releasing up to 40% of the rest mass energy of the material falling onto.** https://web.stanford.edu/~wilkinsd/docs/posters/BlackHolesPoster.pdf
- **TED YouTube video on black hole accretion say matter/energy production from it is 6% efficient for non-rotating black holes and 32% efficient for rotating black holes (problem with source is that they do not give a reference to where they got these numbers from but otherwise video seams credible and also get other facts right about energy of fission and sun radiation):** https://www.youtube.com/watch?v=Q6ZEf6UZyco (the important takeaway IMO is that 6% or 40% is still much higher than the efficiency of fusion that max out at 0.7% or fission that max out at 0.1%. Different physicists may have gotten different results calculating these efficiencies because our knowledge of black holes is still incomplete and making such calculations could not have been done without making some assumptions that is not know with certainty to be true)

Sources for previous slides #2

- **Harvesting energy from rotating black holes, see Penrose process, can be max 29% of original mass of black hole:** https://en.wikipedia.org/wiki/Penrose_process
- **Harvesting energy from rotating black holes using a Dyson sphere PV solar panels combined with mirrors around black hole and have the rotating black hole increase the energy level exponentially of low energy photons beamed at the black hole that kind of "slingshot" (superradiant scattering) between the warped space-time outside the event horizon of the black hole and the mirrors surrounding the black hole:** https://www.youtube.com/watch?v=ulCdoCfw-bY&t=215s (see time 5.25)
- **Nuclear fusion may happen when small black hole devour a white dwarf but only at a rate 10^-4 times the rate of an average star so nuclear fusion in the accretion of black holes are not important relative to star fusion in the universe:** https://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=8912003&fileOId=8912097#:~:text=Black%20hole%20accretion%20disks%20also,nuclear%20fusion%20to%20take%20place.
- **Dyson sphere:** https://en.wikipedia.org/wiki/Dyson_sphere
- **Black hole Hawking radiation (if true to exist which most physicists believe it is) is a 100% efficient mass to energy converter:** https://www.quora.com/Would-a-tiny-black-hole-say-a-billionth-of-a-billionth-of-a-meter-in-diameter-created-on-Earth-start-sucking-up-all-the-mass-on-Earth-and-quickly-spiral-into-a-larger-black-hole-Or-would-there-be-a-way-of-keeping-it-tiny
- **To geek out calculating properties of a black hole and Hawkins radiation see:** https://www.vttoth.com/CMS/physics-notes/311-hawking-radiation-calculator
- **When energy particles like photons are absorbed into a black hole its mass increases by the photon energy divided by c2:m=E/c^2:** https://physics.stackexchange.com/questions/34604/why-do-photons-add-mass-to-a-black-hole#:~:text=Yes%2C%20the%20mass%20of%20the,energy%20divided%20by%20c2.

Chapter 5

The efficiency of converting light into food or electricity in order to sustain a biological civilization

Food & electricity power all biological civilizations

- ✓ **Chapters 2 to 4 discussed the key methods that exist** for producing energy from various forms of fuels that all according to Einstein's E=mc^2 convert mass into energy at different efficiencies
- ✓ **The big takeaway is that**

1. **Chemical fuels** like fossils and food are grossly inefficient (<0.000000013%)
2. **Nuclear** fission and fusion are much better but still not great at less than 0.7% efficiency whereas
3. **Black hole technology** has great potential at efficiencies from 6% to 40% but require we become a space-faring civilization

- ✓ **The only two kinds of energy** that are needed to sustain a modern civilization of biological beings are **A) food** and **B) electricity**
- ✓ **Food and electricity are ultimately made from converting** the energy in light into chemical or electric energy (this is not E=mc^2)
- ✓ **How efficient is that energy conversion** using different technology?

Efficiency: Photosynthesis PVs and electric generators

Energy to energy conversion technology	Year first done	Key part of energy conversion chain and efficiency	End efficiency of photons to fuel or electric energy
Photosynthesis in typical food plants	420 million years ago	Plants use photons from sun to make **chemical energy** in this case typical food plants at **1.5% efficiency**	**1.5%**
Photosynthesis in most efficient plants, C4	420 million years ago	Most efficient plants use photons to make **chemical energy** in bio fuels say wood pellets or ethanol at **4.3% efficiency**	**4.3%**
Typical photovoltaic PV cell (1-junction, non-concentrator)	1883 year first PV cell	Direct conversion of energy in photons to **electric energy** at **23.3% efficiency** (multi crystalline Si)	**23.30%**
Most efficient solar PV cell made (4-junction, concentrator)	2022	Direct conversion of energy in photons to **electric energy** at **47.1% efficiency**	**47.10%**
Typical electric generator	1844	Converts mechanical energy to electric energy at **95% efficiency**	NA
Steam engine (powered the early industrial revolution)	1712	Chemical energy from say wood are burned to make steam that steam engine use to make mechanical energy at **15% efficiency**	**0.61%** =95%*15%*4.3%
Internal combustion engine (partly power current civilization)	1876	Chemical energy from gasoline/ethanol are combusted in a combustion engine to make mechanical energy at **20% efficiency**	**0.82%** =95%*20%*4.3%
Steam turbine fuel powered (partly power current civilization)	1884	Chemical energy from coal/wood are burned to make steam that steam turbine use to make mechanical energy at **40% efficiency**	**1.63%** =95%*40%*4.3%
Steam turbine sun powered (also called concentrated solar power plant)	1866 steam engine	Mirrors are used to concentrate sun light to make steam that a steam turbine use to make mechanical energy at **40% efficiency**	**38.00%** =95%*40%
Gas turbine combined cycle (partly power current civilization)	1936	Chemical energy from gas/biogas are combusted in a gas turbine and exhaust heat from that is subsequently used to power a steam turbine to make mechanical energy at **60% efficiency**	**2.45%** =95%*60%*4.3%

Photosynthetic efficiency

From Wikipedia, the free encyclopedia

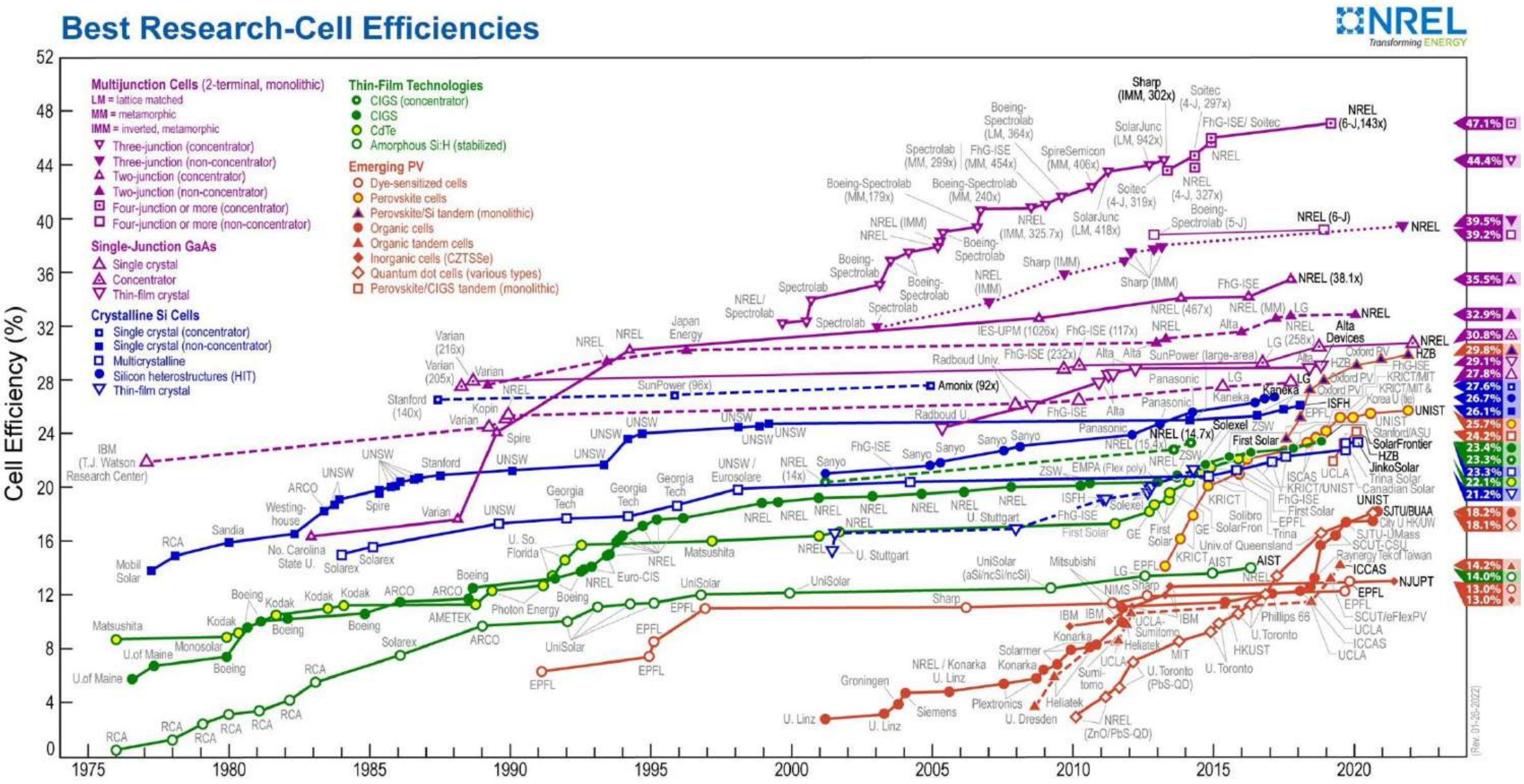
The **photosynthetic efficiency** is the fraction of light energy converted into chemical energy during photosynthesis in green plants and algae. Photosynthesis can be described by the simplified chemical reaction

$$6\ H_2O + 6\ CO_2 + \text{energy} \rightarrow C_6H_{12}O_6 + 6\ O_2$$

where $C_6H_{12}O_6$ is glucose (which is subsequently transformed into other sugars, starches, cellulose, lignin, and so forth). The value of the photosynthetic efficiency is dependent on how

- **Glucose and oxygen** is what humans and other animals use to power their bodies and brains and the exhaust product (what we breathe out) is H2O and CO2
- **So quite a beautiful symbiosis of life** between algae/plants and animals
- **Should be noted that evolution of photosynthesis started 3.4 billion years ago.** However, oxygen creating photosynthesis first appeared 2.7 billion years ago in Cyanobacteria. Green algae photosynthesis is 0.75B years old and green plant photosynthesis is 0.42B years old

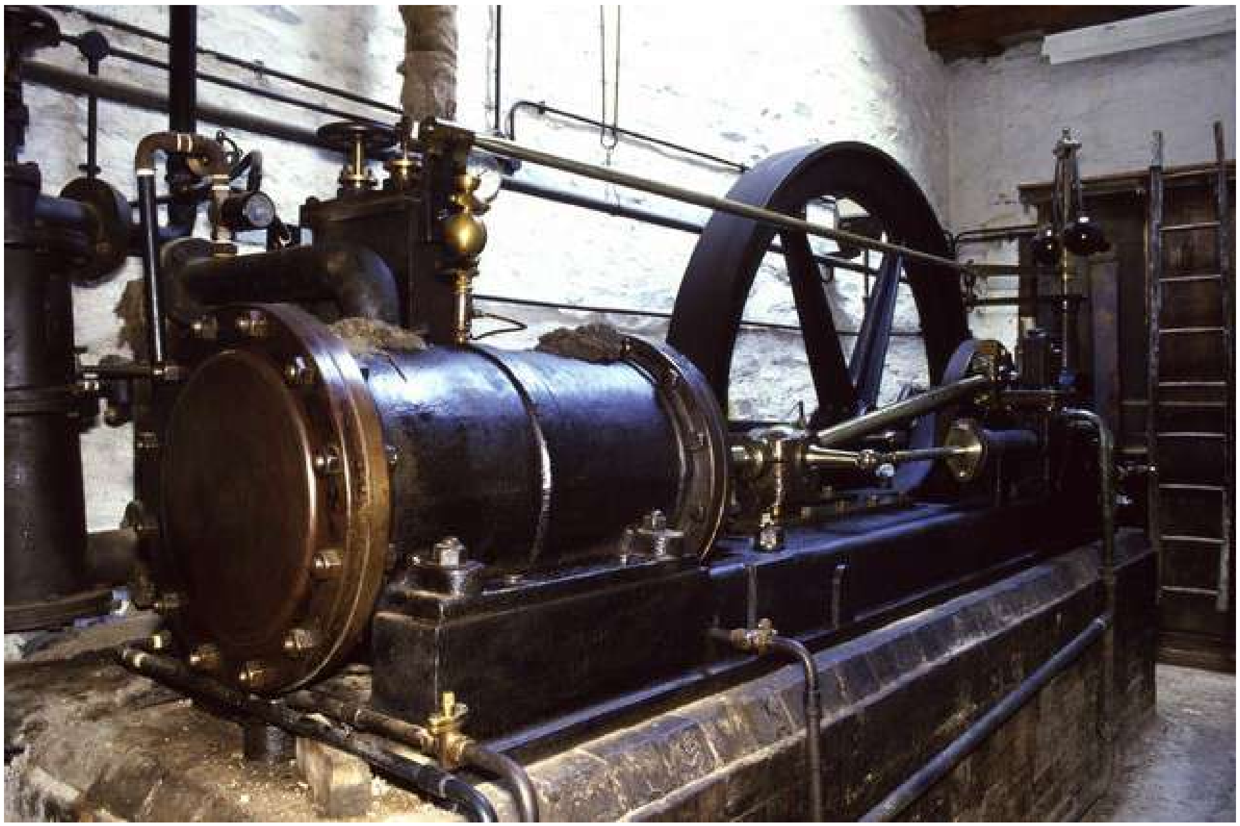
PV/solar cell efficiencies



- **Source:** By National Renewable Energy Laboratory, Golden, CO - https://www.nrel.gov/pv/cell-efficiency.html, CC0, https://commons.wikimedia.org/w/index.php?curid=115930082

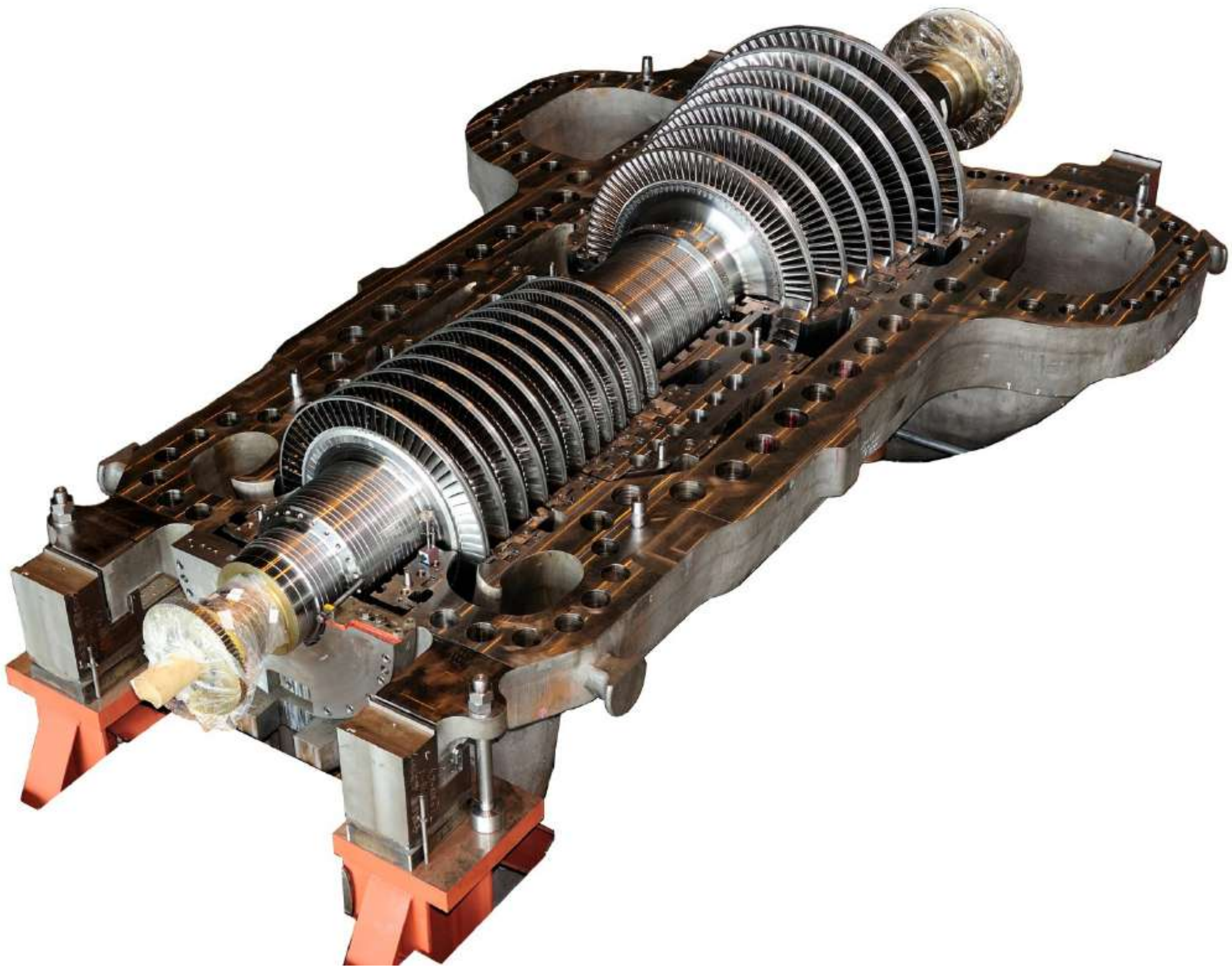
Stott Park Bobbin Mill Steam Engine

Steam engine, Stott Park Bobbin Mill (near to Lakeside, Cumbria, Great Britain)
By W Bradley, Gooder Lane Ironworks, Brighouse. Restored to steam and a very pleasant sight.



- **Source:** https://commons.wikimedia.org/wiki/File:JamesWattEngine.jpg

Steam turbine – On the inside



- **Source:** https://www.global.toshiba/ww/news/corporate/2015/04/pr2301.html

Steam turbine & generator

English: Steam turbine generator set with multistage steam turbine (right) and cylindrical AC generator (left). A tube condenser for the exhaust steam is set beneath the turbine. Turbine: System Melma-Pfenninger, made 1910 by Maschinenbau A.G., Prague, rating 331 kW, rotational speed 2000 rpm. Generator: made 1910 by Elektro Akt. Ges., Prague, rating 250 kW.

- **Source:** https://commons.wikimedia.org/wiki/File:TMW_773_-_Steam_turbine_generator_set.jpg

Concentrated solar power - tower

- **Source:** https://commons.wikimedia.org/wiki/File:Crescent_Dunes_Solar_December_2014.JPG
- Location USA, Nevada. Operational 2014: https://en.wikipedia.org/wiki/Crescent_Dunes_Solar_Energy_Project
- **Note:** In future we may combine multi-junction concentrator PV cells with steam turbine to reach 60% efficiency from photons to kWh

Sources for previous slides

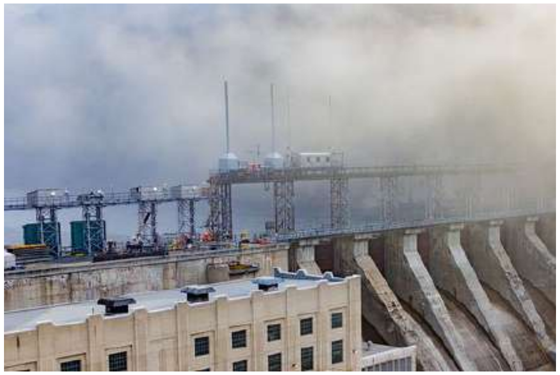
- **Evolution of photosynthesis started 3.4 billion years ago. However, oxygen creating photosynthesis first appeared 2.7 billion years ago in Cyanobacteria. Green algae photosynthesis is 0.75B years old and green plant photosynthesis is 0.42B years old:** https://en.wikipedia.org/wiki/Evolution_of_photosynthesis
- **Photosynthesis:** https://en.wikipedia.org/wiki/Photosynthesis
- **Photosynthetic efficiency 1.5% for typical food plants and 4.3% for most efficient C4 plants:** https://en.wikipedia.org/wiki/Photosynthetic_efficiency#:~:text=From%20Wikipedia%2C%20the%20free%20encyclopedia%20The%20photosynthetic%20efficiency,H%2012%20O%206%20%2B%206%20O%202
- **Origin of solar cells. First PV cell made in 1883:** https://www.smithsonianmag.com/sponsored/brief-history-solar-panels-180972006/
- **Photovoltaics efficiency is 20% for typical commmercial solar panels and recort is 47.1%:** https://en.wikipedia.org/wiki/Photovoltaics and https://www.bostonsolar.us/solar-blog-resource-center/blog/how-efficient-are-commercial-solar-panels/#:~:text=How%20to%20Measure%20the%20Efficiency,they%20were%20averaging%201%25%20efficiency.
- **Origin of electric generators for industrial use in 1844:** https://yorator.com/history-of-generators/
- **Modern electric generator efficiency typical 95%:** https://www.linquip.com/blog/generator-efficiency/#:~:text=The%20power%20of%20the%20load%20circuit%20and%20the,commercial%20electricity%20generators%2C%20this%20ratio%20may%20reach%2095%25.
- **First commercial steam engines in 1712:** https://en.wikipedia.org/wiki/History_of_the_steam_engine
- **Modern steam engines efficiency at 15%:** https://en.wikipedia.org/wiki/Steam_engine#Efficiency
- **First modern internal combustion engine in 1876:** https://en.wikipedia.org/wiki/Internal_combustion_engine#:~:text=The%20first%20commercially%20successful%20internal,in%201876%20by%20Nicolaus%20Otto.
- **Efficiency of typical internal combustion engine is 20%:** https://en.wikipedia.org/wiki/Internal_combustion_engine#Energy_efficiency
- **First steam turbine in 1884:** https://en.wikipedia.org/wiki/Steam_turbine
- **Efficiency of steam turbine is 29%:** https://www.linquip.com/blog/steam-turbine-efficiency-complete-explanation/#Why_Is_Steam_Turbine_Efficiency_So_Low
- **Efficiency of single cycle steam turbine is 35-42%:** https://en.wikipedia.org/wiki/Combined_cycle_power_plant#Historical_cycles
- **Efficiency of average global steam turbine coal power plant is 33% but modern off the shelf plants are 40% efficient:** https://www.ge.com/power/transform/article.transform.articles.2018.mar.come-hele-or-high-water
- **First use of concentrated solar power to run steam engine in 1866:** https://www.aalborgcsp.com/business-areas/solar-district-heating/csp-parabolic-troughs/history-of-csp
- **First commercial gas turbine in 1936:** https://www.britannica.com/technology/gas-turbine-engine/Development-of-gas-turbines
- **Efficiency of typical gas turbine is 38%:** https://www.sciencedirect.com/topics/materials-science/turbine-efficiency
- **Efficiency of new combined cycle gas power plant is 60%:** https://en.wikipedia.org/wiki/Combined_cycle_power_plant#Efficiency
- **Future of expanding universe no more stars in trillions of years into the future:** https://en.wikipedia.org/wiki/Future_of_an_expanding_universe#:~:text=By%201014%20(100%20trillion,making%20this%20era%20last%20longer.

Chapter 6

Global electricity production by source



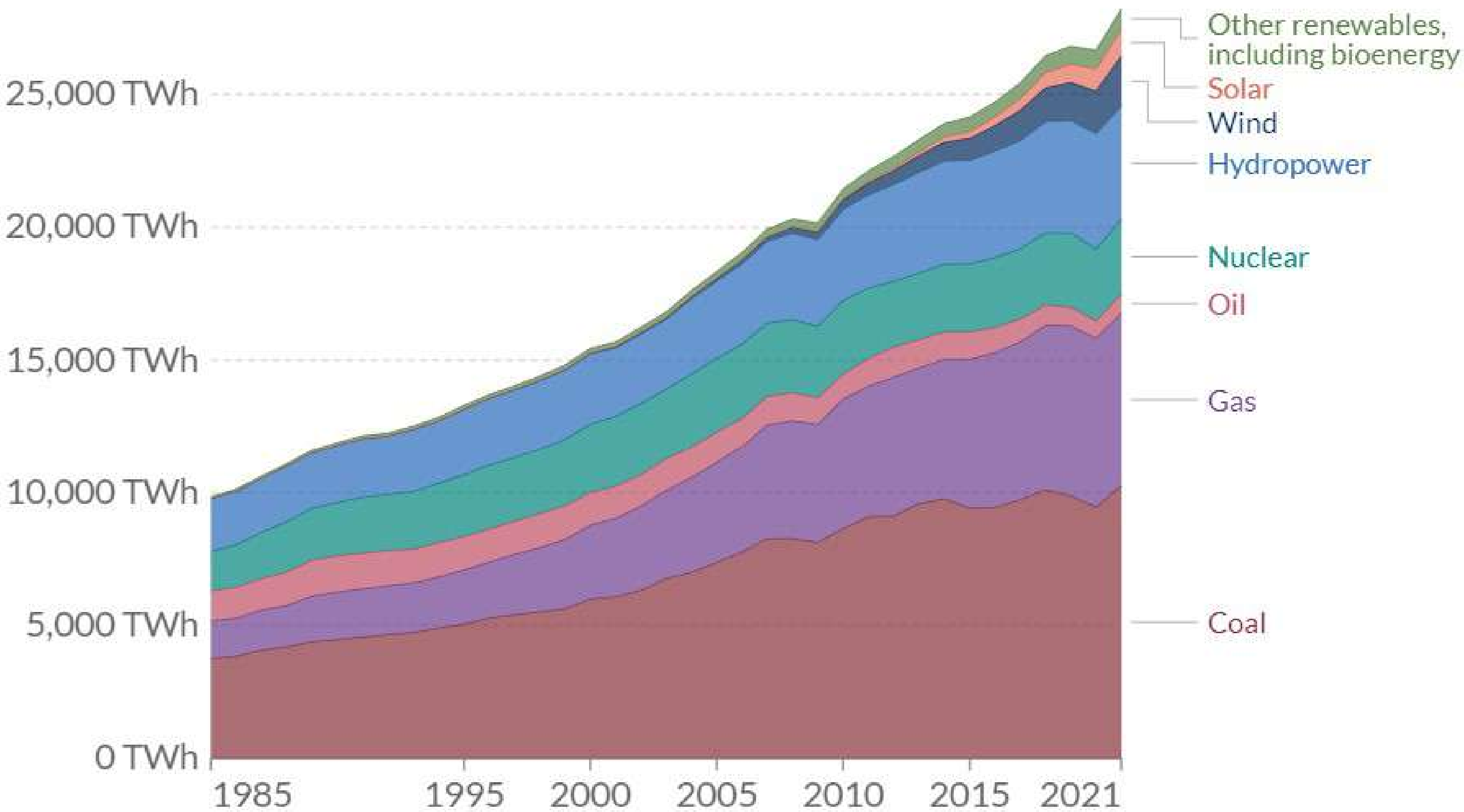





Electricity production by source, World

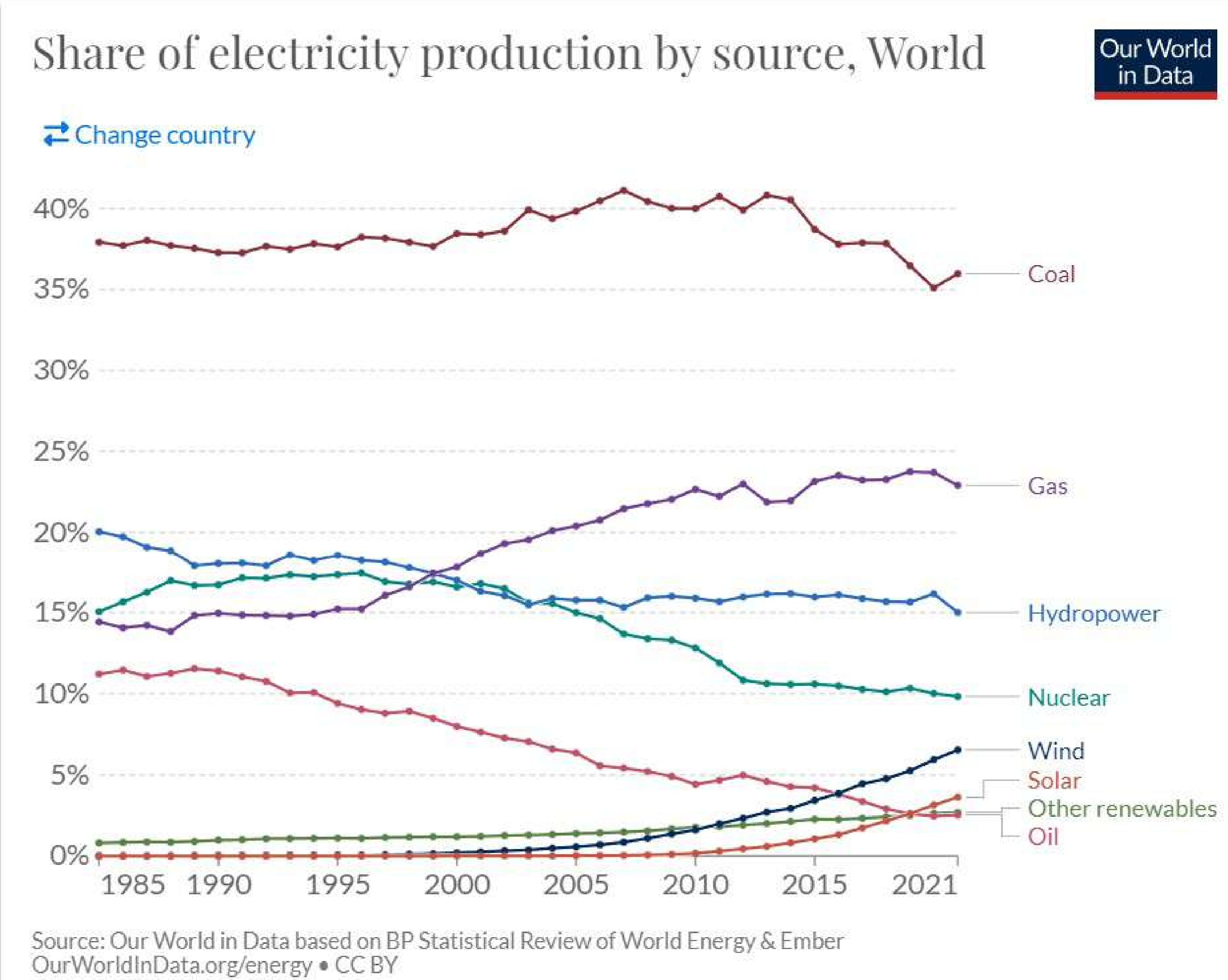
Our World in Data

Change country   ☐ Relative



Source: Our World in Data based on BP Statistical Review of World Energy (2022); Our World in Data based on Ember's Global Electricity Review (2022); Our World in Data based on Ember's European Electricity Review (2022)
Note: 'Other renewables' includes biomass and waste, geothermal, wave and tidal.
OurWorldInData.org/energy • CC BY

- **Source:** https://ourworldindata.org/electricity-mix



- **Source:** https://ourworldindata.org/electricity-mix

Global electricity production by source - 2021

Electricity production technology	Data year	Installed capacity in GW	Capacity factor	Annual growth rate in produced kWh	kWh produced	% of global kWh produced
Global power	2021	-	-	2.45%	28,214,000,000,000	100.00%
Solar power	2021	849.5	13.48%	24.96%	1,002,900,000,000	3.55%
Wind power	2021	824.9	25.88%	14.63%	1,870,300,000,000	6.63%
Biomass power	2019	140.0	53.41%	6.46%	655,000,000,000	2.32%
Geothermal power	2019	15.4	68.20%	3.30%	92,000,000,000	0.33%
Hydro power	2021	1360.0	36.32%	1.31%	4,327,400,000,000	15.34%
Total sustainable power	-	-		-	**7,947,600,000,000**	**28.17%**
Gas power	2021	1,800.0	41.36%	1.81%	6,180,000,000,000	23.11%
Coal power	2021	2,201.0	52.08%	0.69%	10,042,200,000,000	35.59%
Nuclear power, fission	2020	396.6	76.96%	-0.30%	2,673,900,000,000	9.48%
Nuclear power, fusion	-	0.0	-	-	-	0.00%
Oil power & other	-	-	-	-	-	3.65%
Total non-sustainable power	-	-	-	-	-	**71.83%**
Potential solar power, 1% of Earth PVs 25% efficiency	-	NA	"0.25%"	-	21,374,400,000,000,000	7688.63%
Potential wind power 10MW turbine per 10 mi2 of Earth	-	196,900.0	25.88%	-	446,432,379,682,386	1605.87%

Sources for previous slides 1

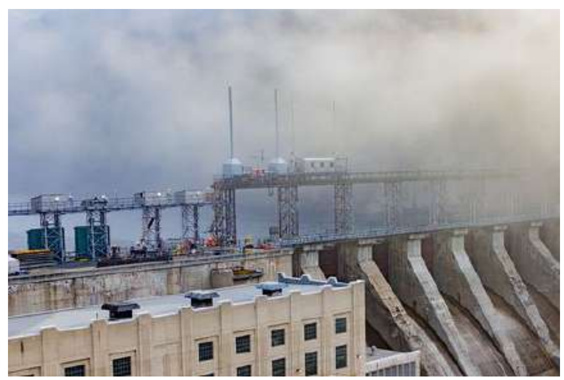
- **Spreadsheet used by HM experience (MS excel file that contains all calculations):** Download link is available below video at www.hmexperience.dk
- **Global electricity production in 2020 is 26,823,200 GWh and 22,158.5 GWh in 2011:** https://en.wikipedia.org/wiki/List_of_countries_by_electricity_production
- **Global electricity production in 2021 is 28,214,000 GWh:** https://ourworldindata.org/electricity-mix
- **Global electricity production in 1985 is 9,831,000 GWh:** https://ourworldindata.org/electricity-mix
- **Global solar power capacity 849,4 GW capacity in 2021 and 306.5 GW in 2016:** https://en.wikipedia.org/wiki/Solar_power_by_country
- **Global solar power generation was 1002.9 TWh in 2021 and 329.1 TWh in 2016:** https://www.iea.org/reports/solar-pv
- **Wind power capacity 369,6 GW in 2014 and 824,9 GW in 2021:** https://en.wikipedia.org/wiki/Wind_power_by_country
- **Wind power generation in 2021 is 1870.3 TWh and in 2014 it was 719.1 TWh:** https://www.iea.org/reports/wind-electricity
- **Biomass electricity production of 655TWh in 2019 and it was 510TWh in 2015:** https://www.statista.com/statistics/481743/biomass-electricity-production-worldwide/
- **Biomass power generation capacity in 2019 was 140 GW:** https://www.statista.com/statistics/264637/world-biomass-energy-capacity/
- **Global geothermal power capacity (15.4 GW capacity in 2019 and 9.7 GW in 2007):** https://en.wikipedia.org/wiki/Geothermal_power#Worldwide_production
- **Global geothermal power generation in 2019 was 92 TWh and in 2007 it was 62.3 TWh:** https://www.iea.org/reports/geothermal-power
- **Global hydropower generation was 4231 TWh in 2018 and 4327.4 in 2021:** https://www.iea.org/reports/hydroelectricity
- **Global hydropower capacity 1360 GW in 2020:** https://www.statista.com/statistics/1179170/global-hydropower-capacity/
- **Global nuclear capacity in 2021 was 396.6 GW:** https://www.statista.com/statistics/263947/capacity-of-nuclear-power-plants-worldwide/
- **Global nuclear power generation in 2020 was 2673.9 TWh and in 2010 it was 2756.3 TWh:** https://www.iea.org/fuels-and-technologies/nuclear

Sources for previous slides 2

- **Global coal power generation was 10,042.2 TWh in 2021 and it was 9837.7 TWh in 2018:** https://www.statista.com/statistics/1082201/coal-fired-electricity-generation-globally/
- **Global coal power capacity was 2201 GW in 2020 and 2104 GW in 2018:** https://www.statista.com/statistics/217256/global-installed-coal-power-generation-capacity/
- **Global gas power generation was 6521 TWh in 2021 and it was 6180 TWh in 2018:** Natural Gas-Fired Electricity – Analysis - IEA
- **Global gas power capacity was 1800 GW in 2021:** https://www.statista.com/statistics/1304427/global-gas-power-capacity/
- **Earth is radiated with 122 PetaW of solar energy at its surface (Earth receives 174 PW of incoming solar radiation but 30% is reflected back into space):** https://en.wikipedia.org/wiki/Solar_energy
- **Convert Peta watt to giga watt:** https://www.unitconverters.net/power/petawatt-to-gigawatt.htm
- **196.9 million square miles on surface of Earth:** https://www.universetoday.com/25756/surface-area-of-the-earth/

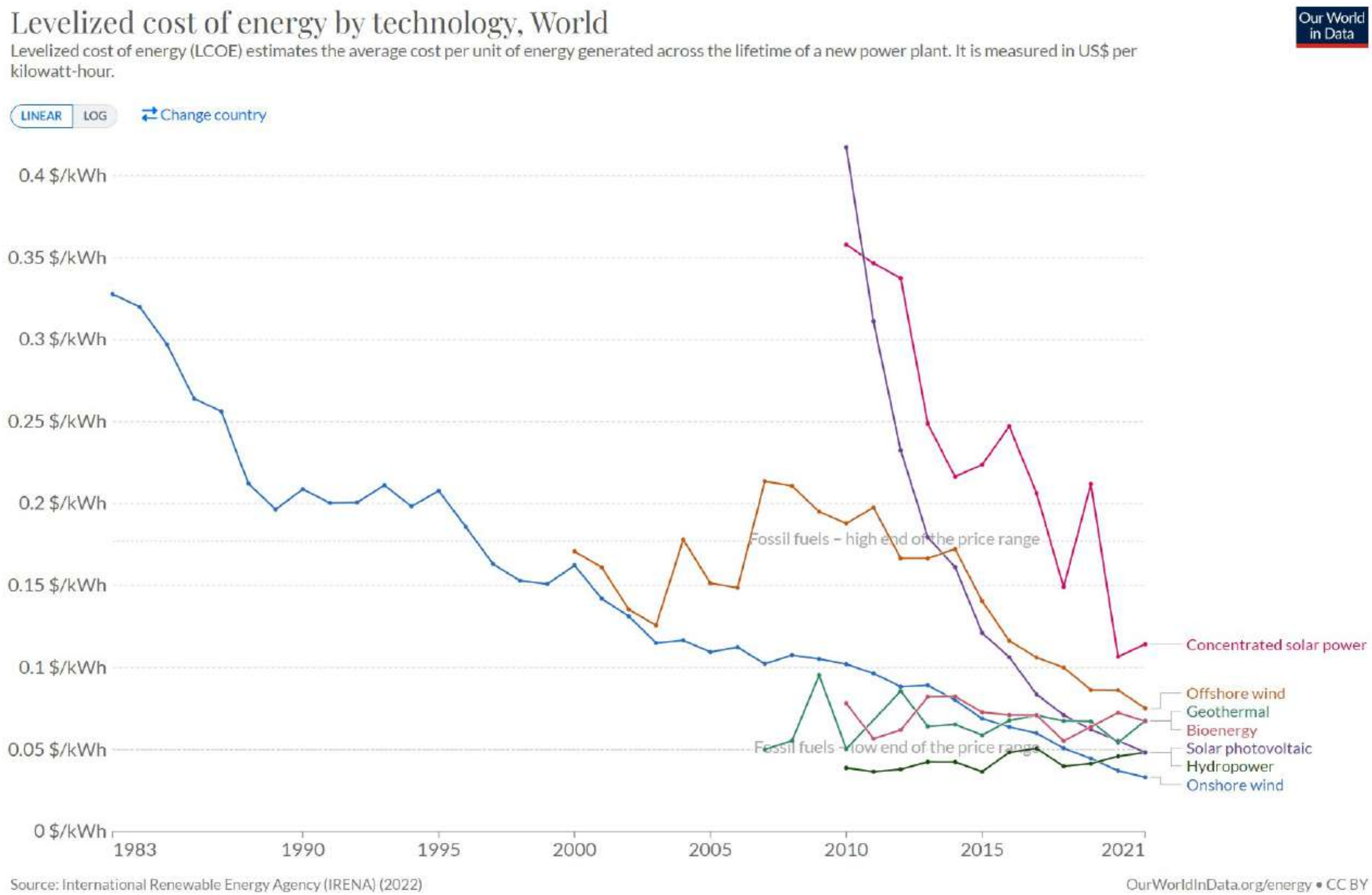
Chapter 7

Cost of electricity production by source



Global cost of electricity production by source

Electricity production technology	Data year	Capital cost per GW in billion USD	Capacity factor	Fuel costs (Yes/No)	Maintenance & operating cost (Yes/No)	Annual growth rate in produced kWh	Levelized cost of generation (USD per kWh)
Sustainable power sources below							
Solar power (PV fixed)	2021	0.83B	13.48%	N	Y	24.96%	0.039 USD
Solar power (PV tracking)	2021	0.86B	-	N	Y	-	0.047 USD
Solar (PV residential)	2020	3.00B	-	N	Y	-	0.189 USD
Onshore wind power	2021	1.60B	25.88%	N	Y	14.63%	0.041 USD
Offshore wind power	2021	6.50B	36.00%	N	Y	-	0.079 USD
Biomass power, see coal	2019	3.65B	53.41%	Y	Y	6.46%	0.088-0.112 USD
Geothermal power	2020	2.80B	68.20%	N	Y	3.30%	0.080-0.099 USD
Hydro power	2020	2.75B	36.32%	N	Y	1.31%	0.068 USD
Non-sustainable power sources below							
Gas combined cycle	2020	1.00B	41.36%	Y	Y	1.81%	0.059 USD
Gas single cycle, peak	2020	0.71B	10%?	Y	Y		0.175 USD
Coal power	2020	3.65B	52.08%	Y	Y	0.69%	0.088-0.112 USD
Nuclear power	2020	6.00B	76.96%	Y	Y	-0.30%	0.069-0.164 USD



- **Source:** https://ourworldindata.org/grapher/levelized-cost-of-energy

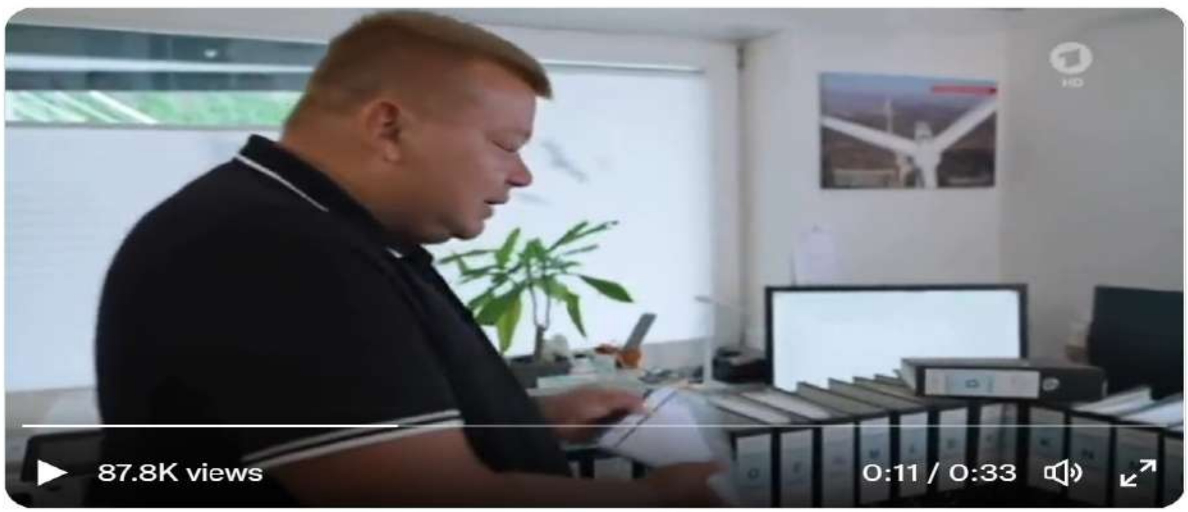
Why do solar and wind not grow faster than 25% & 15%?

Thomas C. Theiner
@noclador

A German engineer shows the files needed to build one wind turbine in 2002 - a single, thin folder.

Then he shows 55 thick folders it takes in 2022 to build one wind turbine.

Merkel sabotaged wind energy in favor of russian gas.



From **Wolf Maahn** 🇺🇦

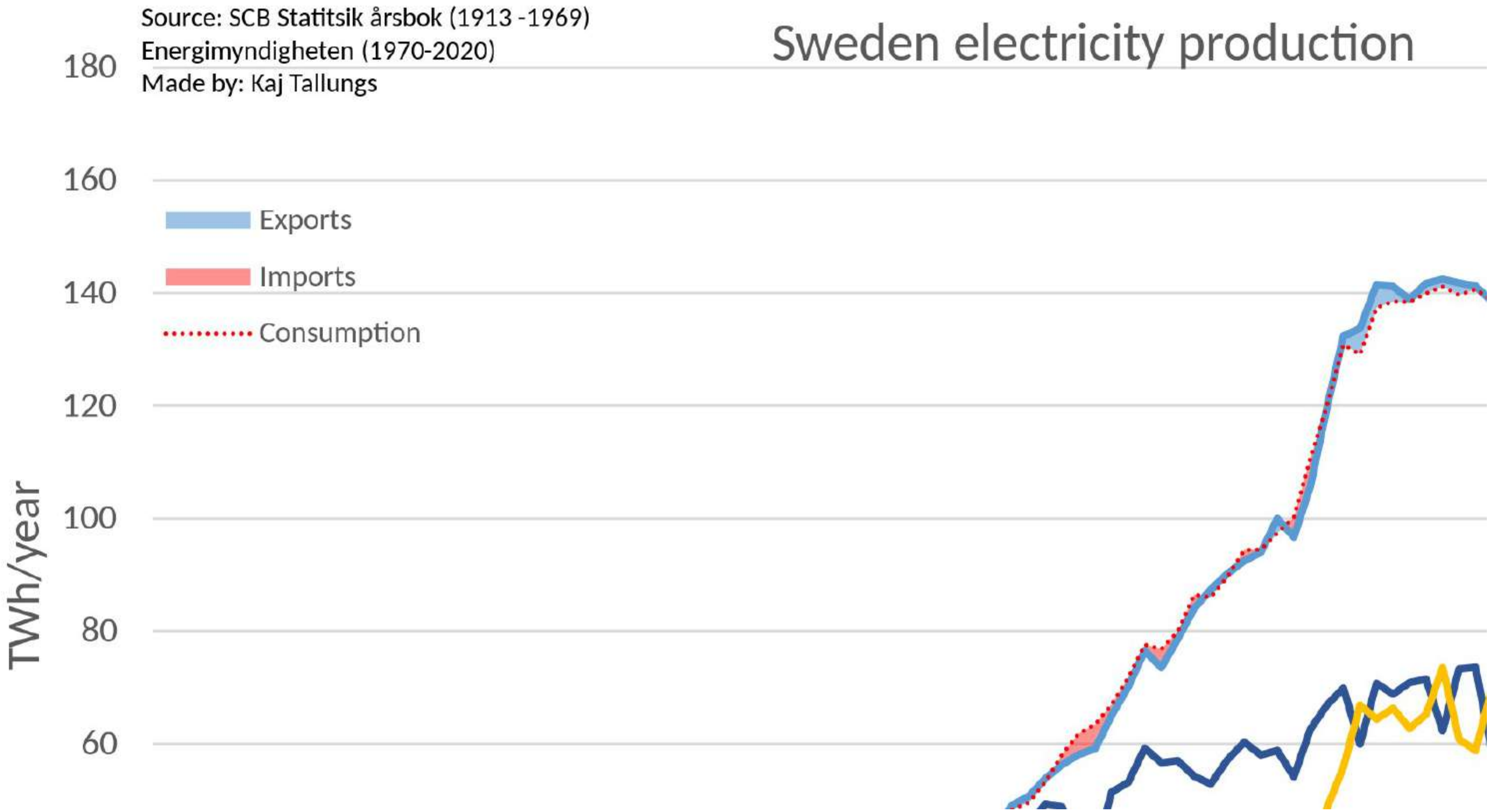
1:41 PM · Nov 3, 2022

- **Source:** https://twitter.com/noclador/status/1588149281562714113

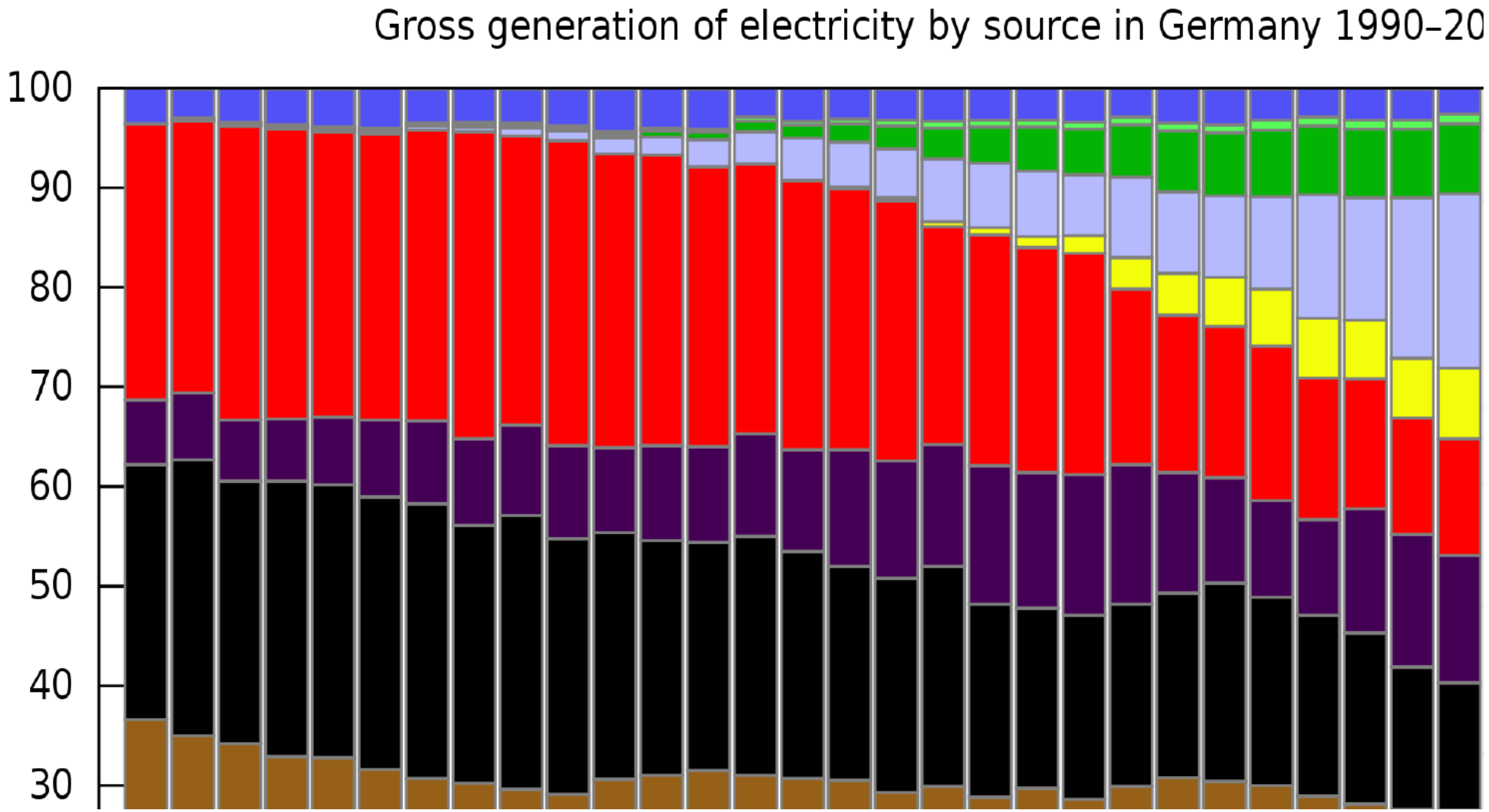
Main article: ***Nuclear power in Sweden***

Name	Unit No.	Reactor		Status	Net capacity (MW)	Construction start	Commercial operation	Closure
		Type	Model					
Ågesta	1	PHWR	R3	Decommissioned	10	1 December 1957	1 May 1964	2 June 1974
Barsebäck	1	BWR	ASEA-II	Shut down/in decommissioning	600	1 February 1971	1 July 1975	30 November 1999
	2	BWR	ASEA-II	Shut down/in decommissioning	600	1 January 1973	1 July 1977	31 May 2005
Forsmark	1	BWR	ASEA-III, BWR-2500	Operational	986	1 June 1973	10 December 1980	
	2	BWR	ASEA-III, BWR-2500	Operational	1116	1 January 1975	7 July 1981	
	3	BWR	ASEA-IV, BWR-3000	Operational	1167	1 January 1979	18 August 1985	
Oskarshamn	1	BWR	ASEA-I	Shut down/in decommissioning	473	1 August 1966	6 February 1972	19 June 2017
	2	BWR	ASEA-II	Shut down/in decommissioning	638	1 September 1969	1 January 1975	22 December 2016
	3	BWR	ASEA-III, BWR-3000	Operational	1450	1 May 1980	15 August 1985	
R4	1			Unfinished	130			1970
Ringhals	1	BWR	ASEA-I	Shut down	881	1 February 1969	1 January 1976	31 December 2020[17]
	2	PWR	WH 3-loops	Shut down	904	1 October 1970	1 May 1975	30 December 2019
	3	PWR	WH 3-loops	Operational	1062	1 September 1972	9 September 1981	
	4	PWR	WH 3-loops	Operational	1104	1 November 1973	21 November 1983	

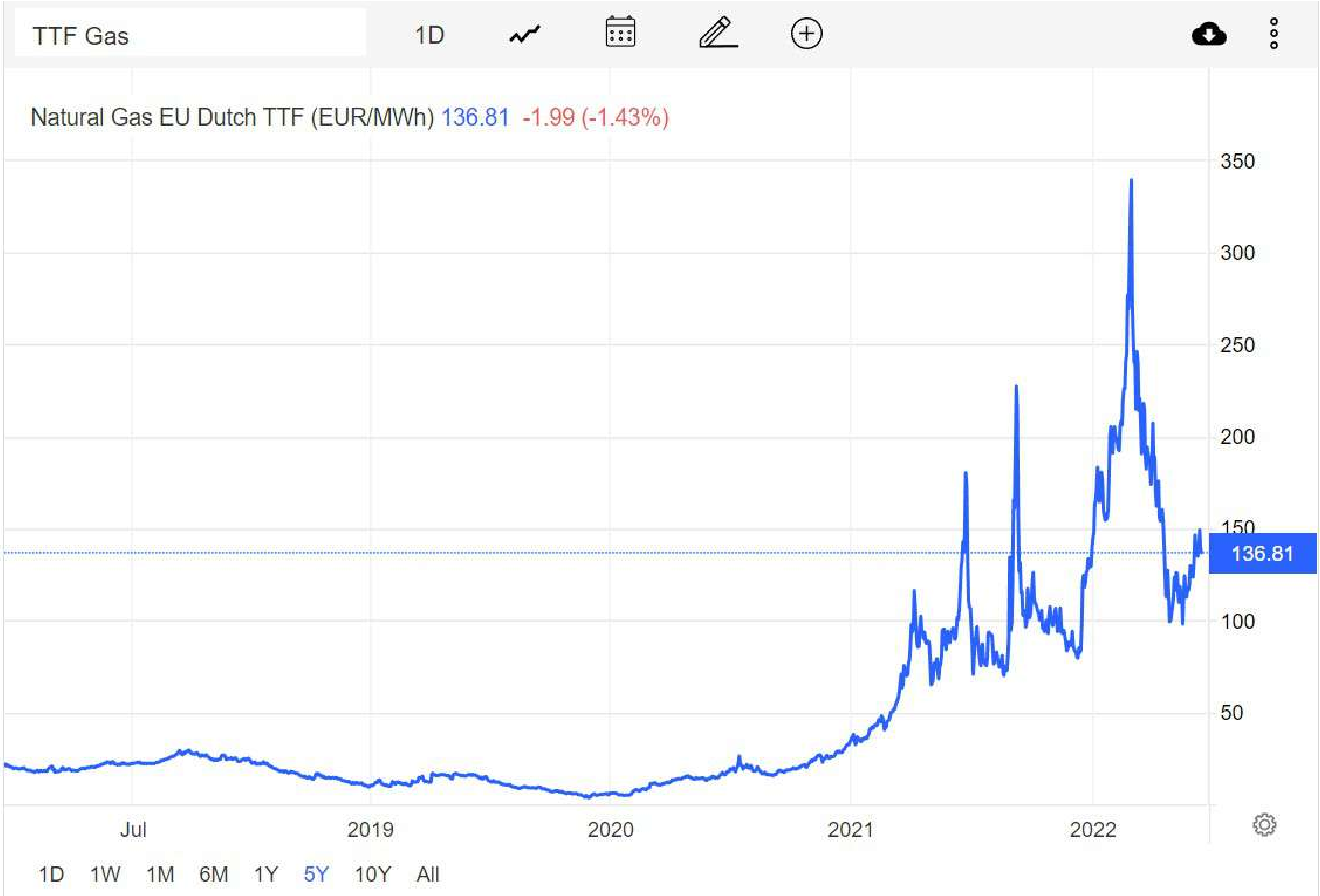
- **Note:** Sweden has closed nuclear reactors for economic reasons and age as they scrapped a political phase out of nuclear in 2009 that would have ended nuclear in Sweden in 2010. Ringhals 1 and 2 will be restarted as decided in October 2022 because of the very high electricity prices that Russia's war in Ukraine has caused in Europe so at current prices they are economical to restart.
- **Source:** https://en.wikipedia.org/wiki/Nuclear_power_in_Sweden



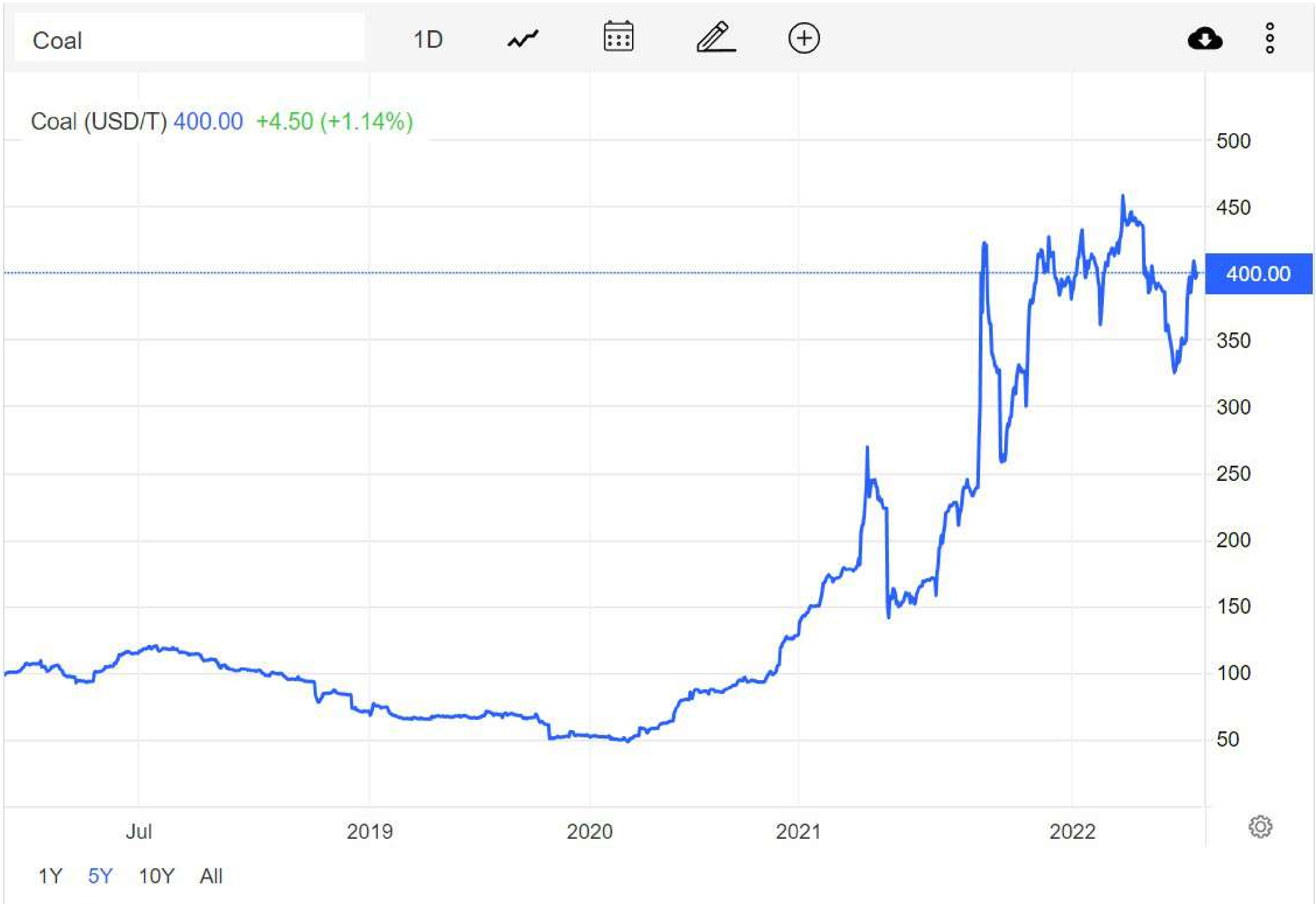
- **Note:** As this graph shows Sweden are not dependent on fossil fuel for electricity. Electricity is made by hydro, nuclear, wind and biomass.
- **Source:** https://en.wikipedia.org/wiki/Electricity_sector_in_Sweden



- **Note:** Germany has decided to not shut down there remaining nuclear reactors because of the current energy crisis in Europe with extremely high electricity prices caused by Russia's war in Ukraine.
- **Source:** https://en.wikipedia.org/wiki/Nuclear_power_in_Germany



- **Note:** Graph shows gas in Europe used to cost 0.025 EUR per kWh of gas energy. Now it cost 0.137 EUR per kWh. To convert to electricity you lose efficiency because even a combined cycle gas plant is only 60% efficient. Add cost of operation and taxes and current EU electricity prices are about 1 EUR per kWh at peak consumption hours.
- **Source:** https://tradingeconomics.com/commodity/eu-natural-gas



- **Note:** Graph shows coal used to cost about 80 USD per ton. Now it is 400 USD per ton.
- **Source:** https://tradingeconomics.com/commodity/coal

Sources for previous slide

- **Capital costs for various energy sources:** https://en.wikipedia.org/wiki/Cost_of_electricity_by_source#Capital_costs
- **Global levelized cost of generation (US$ per MWh):** https://en.wikipedia.org/wiki/Cost_of_electricity_by_source#Additional_cost_factors
- **Another source for Global levelized cost of generation:** https://ourworldindata.org/grapher/levelized-cost-of-energy
- **I did a few searches for cost of residential solar and most sources said about 3 USD per Watt:** https://modernize.com/solar/panel-cost-calculator
- **Capacity factor for offshore wind is 36% in Europe that has the most offshore wind in the world:** https://windeurope.org/about-wind/daily-wind/capacity-factors

Chapter 8

Dealing with intermittency of solar and wind power

Key ways to deal with intermittency of solar and wind 1

1. **Hydropower can be turned on and off** and thereby offset the intermittency of wind and solar
   - Problem is not all countries have enough hydropower
2. **Coal, oil and gas power plants** can also be turned on and off and thereby offset the intermittency of wind and solar
   - But, they are not sustainable so only a temporary solution
3. **Biomass power** are like coal power plants that burn wood pellets instead of coal and they can therefore also be turned on and off to deal with the intermittency of solar and wind
4. **Battery storage power** can obviously be used to deal with the intermittency of solar and wind power but the solution is too expensive for long-term storage of large amounts of power
   - Because of high cost battery storage power is most suited for dealing with daily grid intermittency

Key ways to deal with intermittency of solar and wind 2

5. **Smart grids** where the price of electricity is communicated in real time to enable consumers to increase or decrease their consumption whenever price decrease and increase
   - When production of solar and wind electricity is low prices will be high and the smart grid can therefore reduce demand
6. **High voltage transmission lines** can be used to deal with the intermittency of solar and wind
   - They do so by transferring energy from geographic locations that produce much solar and wind to other areas that produce less solar and wind because of different weather systems
   - Fact is the sun hit Earth with same energy at all times so with enough global scale transmission lines the intermittency of solar power could be close to eliminated

Key ways to deal with intermittency of solar and wind 3

7. **Overbuilding capacity for solar and wind** is an obvious way to deal with the intermittency of solar and wind

- The problem is too little production (not too much) when solar and wind make the least energy due to unfavorable weather conditions (little sunlight and little wind)
- So doubling the capacity of wind and solar will also double the production of electricity when production are at a minimum
- An electric grid with high capacity for solar and wind could have many periods during the year where electricity prices are close to zero cents per kWh and still electricity needs to be wasted because there are not enough demand to take all of the electricity supply
- Denmark that makes over 50% of its electricity from wind turbines wasted 4.3% of its 2020 electric production on that account
- Thermal energy storage could be a great solution to spend excess supply of electricity in a grid with much capacity for solar and wind

Key ways to deal with intermittency of solar and wind 4

8. **High temperature thermal energy storage (HT-TES)** can be used to store solar and wind energy in large quantities over long time (many months) at much less cost than using batteries

- Fx 1 cubic meter (m3) of granite rock cooled from 600 degrees Celsius to 200 degrees Celsius will emit 211 kWh of energy
- For comparison a good lithium battery is 400 Wh/liter or 400 kWh/m3 but rock cost nearly nothing
- The 211 kWh heat in 1 m3 of rock could be used to generate electricity in a steam turbine power plant at 40% electric conversion rate with the rest 60% used for district heating
- **High temperature thermal energy storage and subsequent electric generation** is not economically viable unless there are large amounts of electricity available at very low cost frequently during the year and that will happen when we get much more solar/wind
- Technology scales extremely well and can be build anywhere

Sources for previous slide

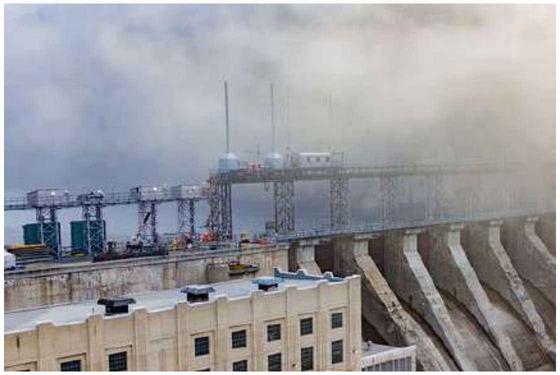
- **In 2020 1.46 TWh wind energy in Denmark was curtailed due to lack of demand and grid flexibility, equivalent of 4.3% of the total Danish electricity consumption:** https://www.danfoss.com/en/about-danfoss/insights-for-tomorrow/integrated-energy-systems/thermal-energy-storage/#:~:text=Thermal%20energy%20storage%20can%20also,of%20water%20deep%20below%20ground.
- **Web calculator for calculating the energy stores in different materials as sensible heat:** https://www.engineeringtoolbox.com/sensible-heat-storage-d_1217.html
- **From Joule to kWh:** https://www.rapidtables.com/convert/energy/Joule_to_kWh.html
- **Storing energy by heating stones to 600 degrees can power Denmark for hours:** https://cleantechnica.com/2019/03/19/storing-energy-by-heating-stones-to-600-degrees-could-power-whole-country-for-hours/
- **Academic paper investigating which kind of rocks would be most suited for storing heat at 600 degrees Celsius:** https://backend.orbit.dtu.dk/ws/portalfiles/portal/147556283/Pedersen_et_al_LASDEWES2018_0250_1_12.pdf
- **First commercial scale high temperature thermal energy storage is in Finland:** https://www.renewableenergymagazine.com/storage/first-commercial-sandbased-thermal-energy-storage-is-20220707#:~:text=As%20a%20material%2C%20sand%20is,8%20MWh%20of%20energy%20capacity.

Chapter 9

When will global electricity production become fully sustainable?








Assumptions behind sustainability prediction - 1

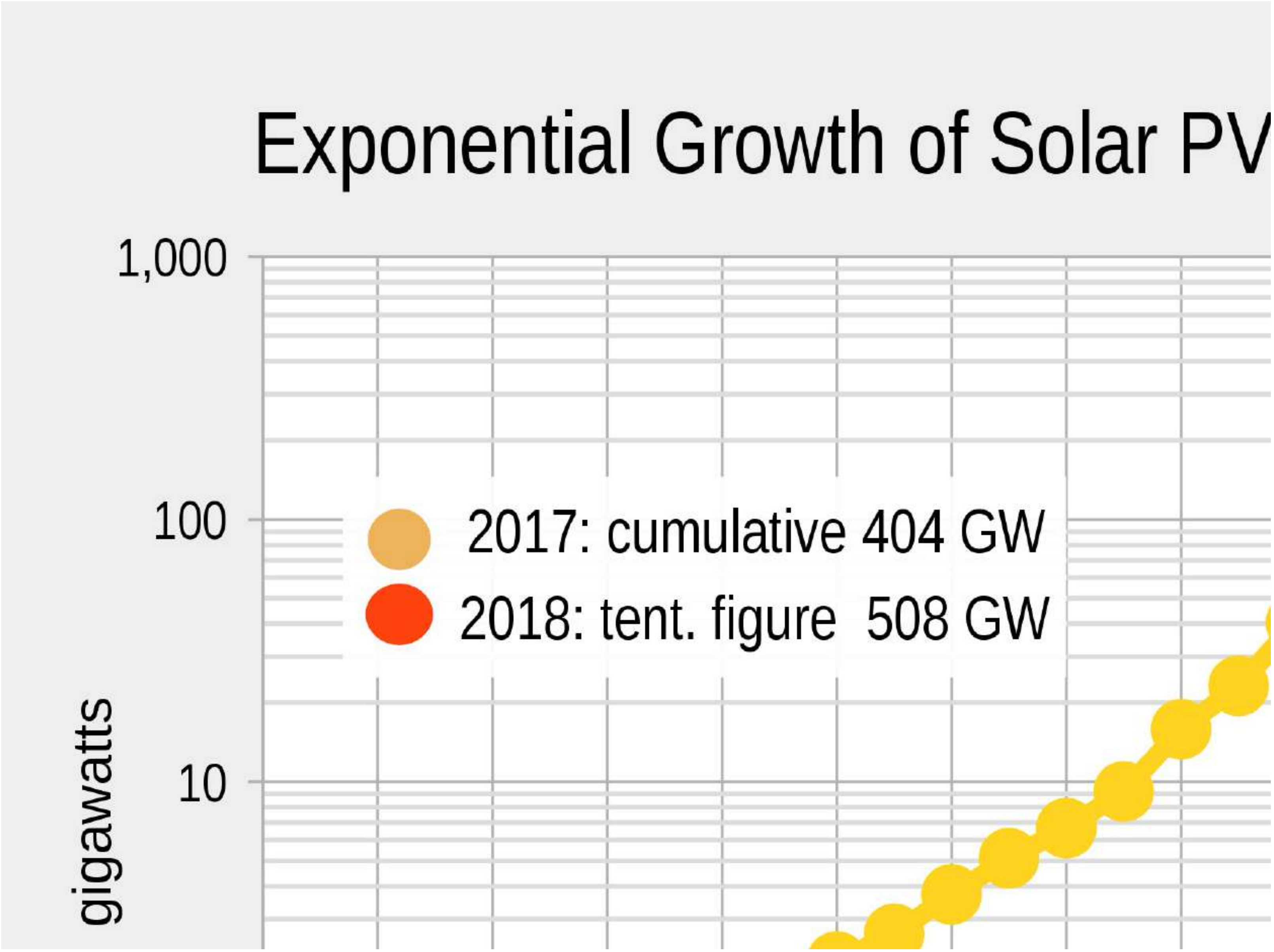
✓ **Growth in global electricity consumption will increase** from currently 2.45% annually to 3.00% starting from 2031, 3.50% starting from 2033 and 4.00% starting from 2039

✓ **3 reasons for this increase in growth rate**

1. **Most heating services will become electrified** using electric heat pumps as electricity prices drops and make that option for heating more economic versus the mostly fossil alternatives
2. **Transportation will transition to battery electric** with regard to land vehicles, ships and short- to mid-range airplanes
   - Rockets and long-distance airplanes will eventually use renewable fuels
3. **Datacenters will consume ever more electricity** especially for AI powered services

Assumptions behind sustainability prediction - 2

- ✓ **All non-sustainable sources of electricity** (gas, oil, coal, nuclear) are currently growing below the total global growth rate of 2.45% and that low growth rate is expected to continue and even amplify to outright negative growth
- ✓ **The reason for this expectation** is that solar and wind power unlike all other power sources continue to fall in price so they will keep growing at a higher rate than the average growth rate for electricity production/comsumption
- ✓ **Consequently, the growth for non-sustainable electricity is not specified individually** but rather calculated as a residual share of global electricity when the individual growth of sustainable sources has been considered and summed up
- ✓ **Solar, wind, biomass, geothermal and hydro** are expected to keep growing at their current 2021 growth rates into the future



- **Note:** Graph shows the installed capacity of PV solar power grows exponentially at a constant growth rate as we can fit a straight line on the data points in the graph that has a logarithmic Y axis. It is therefore reasonable to assume this growth will continue for some time in the future as well. The 25% annually growth rate for solar that are used for prediction in the following is calculated as annual growth in kWh produced globally growing from level in 2016 to level in 2021, see excel spreadsheet at hmexperience.dk
- **Source:** https://en.wikipedia.org/wiki/Solar_power

Assumptions behind sustainability prediction - 3

- **2032 will be the last year that global electricity production equals global electricity consumption** with sustainable power being 72.58% of production and non-sustainable sources the remaining 27.42%
- **Starting in 2033 total power consumption at 100% (by definition) will be less than total power production at 105.03%**
- **Power production will be higher than consumption because** one of the most economic ways to deal with the intermittency of ever more solar and wind power production is to build more capacity for wind and solar than possible to consume on average
- **Starting in 2042 non-sustainable sources of energy are no longer needed to help with the intermittency of solar and wind power** as they have got enough alternative remedies for the problem such as extensive over capacity for wind and solar resulting in production being 170% of total consumption

When will global electricity production become fully sustainable? 2042

	Global electric power Consumption, kWh	Global share	Solar power Production, kWh	Solar share	Wind power Production, kWh	Wind share	Biomass power Production, kWh	Biomass share	Geothermal power Production, kWh	Geothermal share	Hydro power Production, kWh	Hydro share	Sustainable power share Production (Sum of shares)	Non-sustainable power share Production (residual share or given share)	Total global power Production	Year
Growth % next years	2.45%		25.88%		14.63%		6.46%		3.30%		0.75%					
2019	26,811,000,000,000						655,000,000,000	2.44%	92,000,000,000	0.34%						
2020	26,659,000,000,000						697,283,006,230	2.62%	95,037,749,230	0.36%						
2021	28,214,000,000,000	100.00%	1,002,900,000,000	3.55%	1,870,300,000,000	6.63%	742,295,558,439	2.63%	98,175,801,942	0.35%	4,327,400,000,000	15.34%	28.50%	71.50%	100.00%	2021
2022	28,903,943,020,632	100.00%	1,262,475,378,170	4.37%	2,143,948,824,209	7.42%	790,213,860,305	2.73%	101,417,470,059	0.35%	4,360,018,973,692	15.08%	29.95%	70.05%	100.00%	2022
2023	29,610,757,855,672	100.00%	1,589,235,298,120	5.37%	2,457,635,973,282	8.30%	841,225,490,196	2.84%	104,766,174,858	0.35%	4,392,883,821,914	14.84%	31.70%	68.30%	100.00%	2023
2024	30,334,857,087,193	100.00%	2,000,568,784,519	6.59%	2,817,219,566,514	9.29%	895,530,135,453	2.95%	108,225,450,586	0.36%	4,425,996,398,015	14.59%	33.78%	66.22%	100.00%	2024
2025	31,076,663,386,518	100.00%	2,518,365,572,629	8.10%	3,229,414,841,024	10.39%	953,340,374,074	3.07%	111,798,948,186	0.36%	4,459,358,569,311	14.35%	36.27%	63.73%	100.00%	2025
2026	31,836,609,760,944	100.00%	3,170,181,003,763	9.96%	3,701,919,559,054	11.63%	1,014,882,506,862	3.19%	115,490,439,150	0.36%	4,492,972,217,195	14.11%	39.25%	60.75%	100.00%	2026
2027	32,615,139,806,494	100.00%	3,990,702,424,561	12.24%	4,243,557,763,969	13.01%	1,080,397,443,291	3.31%	119,303,819,504	0.37%	4,526,839,237,241	13.88%	42.80%	57.20%	100.00%	2027
2028	33,412,707,966,855	100.00%	5,023,595,126,742	15.03%	4,864,444,569,601	14.56%	1,150,141,644,552	3.44%	123,243,113,915	0.37%	4,560,961,539,313	13.65%	47.06%	52.94%	100.00%	2028
2029	34,229,779,798,645	100.00%	6,323,826,061,825	18.47%	5,576,175,060,379	16.29%	1,224,388,127,487	3.58%	127,312,479,941	0.37%	4,595,341,047,669	13.42%	52.14%	47.86%	100.00%	2029
2030	35,066,832,243,171	100.00%	7,960,588,990,807	22.70%	6,392,040,829,966	18.23%	1,303,427,533,323	3.72%	131,516,212,418	0.38%	4,629,979,701,073	13.20%	58.22%	41.78%	100.00%	2030
2031	35,924,353,904,822	100.00%	10,020,986,735,090	27.89%	7,327,278,202,269	20.40%	1,387,569,265,403	3.86%	135,858,747,994	0.38%	4,664,879,452,901	12.99%	65.52%	34.48%	100.00%	2031
Growth % next years	3.00%		21.50%	5.01%	14.63%	2.30%	6.46%	0.13%	3.30%	0.00%	0.00%	-0.38%	7.07%	-7.07%	0.00%	
2032	37,002,084,521,967	100.00%	12,175,498,883,135	32.90%	8,399,352,770,362	22.70%	1,477,142,700,356	3.99%	140,344,669,810	0.38%	4,664,879,452,901	12.61%	72.58%	27.42%	100.00%	2032
Growth % next years	3.00%		19.00%	5.11%	14.63%	2.56%	6.46%	0.13%	3.30%	0.00%	0.00%	-0.37%	7.44%	-2.42%	5.03%	
2033	38,112,147,057,626	100.00%	14,488,843,670,930	38.02%	9,628,285,567,095	25.26%	1,572,498,477,459	4.13%	144,978,712,338	0.38%	4,664,879,452,901	12.24%	80.03%	25.00%	105.03%	2033
Growth % next years	3.50%		17.00%	4.96%	14.63%	2.72%	6.46%	0.12%	3.30%	0.00%	0.00%	-0.41%	7.38%	-2.00%	5.38%	
2034	39,446,072,204,643	100.00%	16,951,947,094,988	42.97%	11,037,026,958,629	27.98%	1,674,009,871,229	4.24%	149,765,766,379	0.38%	4,664,879,452,901	11.83%	87.40%	23.00%	110.40%	2034
Growth % next years	3.50%		16.00%	5.19%	14.63%	3.01%	6.46%	0.12%	3.30%	0.00%	0.00%	-0.40%	7.92%	-2.00%	5.92%	
2035	40,826,684,731,805	100.00%	19,664,258,630,186	48.17%	12,651,885,243,394	30.99%	1,782,074,252,626	4.36%	154,710,884,221	0.38%	4,664,879,452,901	11.43%	95.32%	21.00%	116.32%	2035
Growth % next years	3.50%		16.00%	5.82%	14.63%	3.33%	6.46%	0.12%	3.30%	0.00%	0.00%	-0.39%	8.89%	-2.00%	6.89%	
2036	42,255,618,697,418	100.00%	22,810,540,011,016	53.98%	14,503,017,960,544	34.32%	1,897,114,644,575	4.49%	159,819,284,975	0.38%	4,664,879,452,901	11.04%	104.21%	19.00%	123.21%	2036
Growth % next years	3.50%		16.00%	6.52%	14.63%	3.69%	6.46%	0.13%	3.30%	0.00%	0.00%	-0.37%	9.97%	-2.00%	7.97%	
2037	43,734,565,351,828	100.00%	26,460,226,412,779	60.50%	16,624,995,083,139	38.01%	2,019,581,377,913	4.62%	165,096,360,081	0.38%	4,664,879,452,901	10.67%	114.18%	17.00%	131.18%	2037
Growth % next years	3.50%		16.00%	7.31%	14.63%	4.09%	6.46%	0.13%	3.30%	0.00%	0.00%	-0.36%	11.17%	-4.00%	7.17%	
2038	45,265,275,139,142	100.00%	30,693,862,638,823	67.81%	19,057,444,613,688	42.10%	2,149,953,854,225	4.75%	170,547,679,002	0.38%	4,664,879,452,901	10.31%	125.34%	13.00%	138.34%	2038
Growth % next years	3.50%		15.00%	7.53%	14.63%	4.53%	6.46%	0.14%	3.30%	0.00%	0.00%	-0.35%	11.85%	-4.00%	7.85%	
2039	46,849,559,769,012	100.00%	35,297,942,034,647	75.34%	21,845,792,638,588	46.63%	2,288,742,422,490	4.89%	176,178,995,094	0.38%	4,664,879,452,901	9.96%	137.19%	9.00%	146.19%	2039
Growth % next years	4.00%		15.00%	7.97%	14.63%	4.77%	6.46%	0.12%	3.30%	0.00%	0.00%	-0.38%	12.47%	-4.00%	8.47%	
2040	48,723,542,159,772	100.00%	40,592,633,339,844	83.31%	25,042,111,661,991	51.40%	2,436,490,376,856	5.00%	181,996,251,688	0.37%	4,664,879,452,901	9.57%	149.66%	5.00%	154.66%	2040
Growth % next years	4.00%		14.00%	8.01%	14.00%	4.94%	6.46%	0.12%	3.30%	0.00%	0.00%	-0.37%	12.70%	-3.00%	9.70%	
2041	50,672,483,846,163	100.00%	46,275,602,007,422	91.32%	28,548,007,294,669	56.34%	2,593,776,083,398	5.12%	188,005,588,356	0.37%	4,664,879,452,901	9.21%	162.36%	2.00%	164.36%	2041
Growth % next years	4.00%		10.00%	5.27%	10.00%	3.25%	6.46%	0.12%	3.30%	0.00%	0.00%	-0.35%	8.28%	-2.00%	6.28%	
2042	52,699,383,200,010	100.00%	50,903,162,208,164	96.59%	31,402,808,024,136	59.59%	2,761,215,244,152	5.24%	194,213,347,391	0.37%	4,664,879,452,901	8.85%	170.64%	0.00%	170.64%	2042
Growth % next years	4.00%		4.50%	0.46%	4.00%	0.00%	4.00%	0.00%	3.30%	0.00%	0.00%	-0.34%	0.12%	0.00%	0.12%	
2043	54,807,358,528,010	100.00%	53,193,804,507,532	97.06%	32,658,920,345,102	59.59%	2,871,663,853,918	5.24%	200,626,080,504	0.37%	4,664,879,452,901	8.51%	170.76%	0.00%	170.76%	2043

- **Source:** Link to excel spreadsheet at www.hmexperience.dk

Comments regarding the 2042 prediction - 1

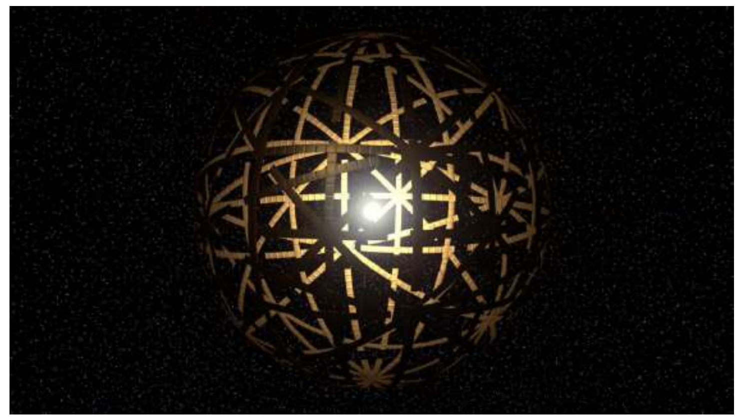
- ✓ **This prediction is not an attempt to be exact** with regard to which year Earth will go fully renewable
- ✓ **It could happen sooner or later dependent on whether political developments** will press to speed the process up or slow it down
- ✓ **Also different countries will have different opportunities** such as an abundance of hydropower or fossil fuels or have different weather systems that determine the economics of wind & solar
- ✓ **Therefore, the general global picture may look very different** for individual countries and their time to become fully renewable with electricity may differ much from global picture
- ✓ **Some countries will do it before 2042** and others will take longer
- ✓ **Indeed, Norway and Iceland** are already there being 100% renewable with regard to their electricity production

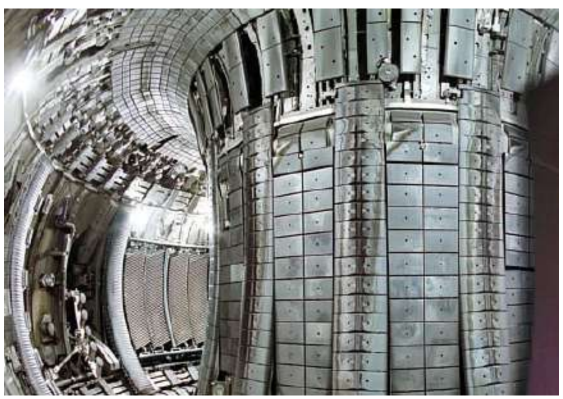
Comments regarding the 2042 prediction - 2

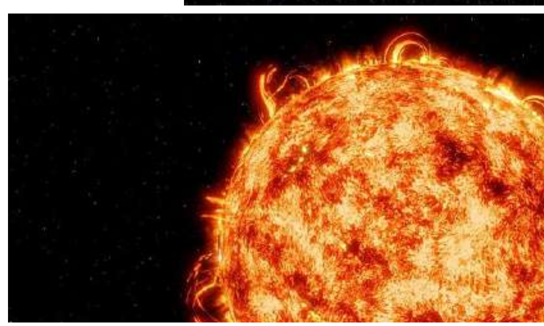
- ✓ **Also when electricity production from solar and wind** approaches 100% or more of electricity consumption the function of the electric grid will fundamentally change
- ✓ **In particular, during the year there will be many more and longer periods where prices for electricity approaches zero USD** per kWh because supply exceeds demand
- ✓ **In such a grid High Temperature - Thermal Energy Storage** (HT-TES) **will become economic** because it can buy electricity for heating at say 1 cents per kWh and sell regenerated electricity (at up to 38% efficiency) back at other times for much higher prices when solar and wind makes less energy than the grid demands
- ✓ **Indeed, it could be expected that such HT-TES systems** may consume say 20% to 40% of all electricity produced and thus no electricity need to be wasted in grid 100% based on solar and wind
- ✓ **Note that HT-TES systems scale much more affordable** than battery back-up but the backside is that they are only up to 38% efficient

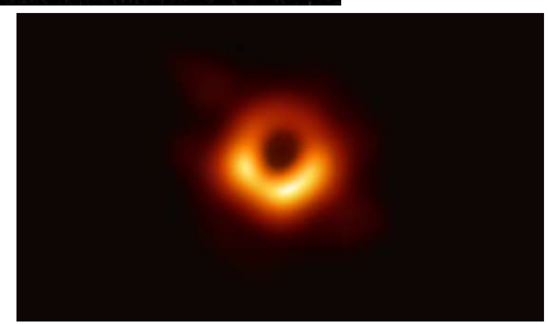
Chapter 10

Conclusions and best future use for nuclear fuels









Conclusions and best future use for nuclear fuels - 1

- ✓ **This presentation should have made it abundantly clear** that solar power in combination with wind power and a few remedies to deal with their intermittency is how the civilizations on Earth will power themselves in the not so distant future, say, around 2042
- ✓ **This power scenario is happening** not so much because of political promotion or obstruction but mostly because it is the lowest cost power production scenario
- ✓ **All other power scenarios are more expensive** including nuclear
- ✓ **This wind and solar power scenario also happens to solve environmental concerns and security concerns**
- ✓ Indeed, it makes nearly all nations fully self supplied with electric power that also do not contribute to global warming or air pollution
- ✓ **The future of humanity will be better** as a result of that and also because lower electricity prices will make everything else cheaper

Conclusions and best future use for nuclear fuels - 2

- ✓ **This presentation could end right here** but a few words on what to do with nuclear energy is warranted
- ✓ **As argued nuclear energy is not needed to power anything on Earth** and it is also more expensive per kWh than both solar and wind power
- ✓ **However, fact is ultra long-term survival of civilizations** (whether biological or not) critically depend on the finite fuels available in our solar system for nuclear fission and fusion (U235, thorium and LiH-2 lithium deuteride)
- ✓ We need these fuels to power large generational spaceships that are able to bring civilizations to other solar systems or black-holes
- ✓ **In order to survive a journey** to another solar system/black-hole you will have to bring your own power source because radiation from other stars and black-holes is too week in interstellar space to power anything meaningful on a large spaceship
- ✓ **Only nuclear fuels will contain enough energy to survive such journeys**
- ✓ **So IMO the best use of the finite nuclear fuels available in our solar system** would be to reserve it for interstellar journeys (colonization) and to power outposts beyond Saturn (<15W/m2) in our own solar system

Conclusions and best future use for nuclear fuels - 3

- ✓ **So how long can our civilization carry on** if we are able to expand to other solar systems and black holes using the nuclear fuel we got in our solar system and other solar systems that we colonize?
- ✓ **Answer:** Many trillions of years into the future. 1 trillion is 1000 billion
- ✓ It should be noted that going at 1/1000 the speed of light it will take about 5,000 to 10,000 years to travel to the nearest solar systems 5 to 10 light years away from our solar system
- ✓ It is not realistic go faster than about 1/1000 the speed of light because the kinetic energy of hitting stuff in interstellar space will destroy Starship if it goes faster
- ✓ **For, comparison Voyager 1 travel at 1/18,000 the speed of light**. So to get to 1/1000 we need a nuclear powered rocket engine. Chemical engine not possible
- ✓ Also nearest galaxy to our galaxy the Milky Way is Andromeda. That is 2.5 million light years away so will take 2.5 billion years to reach in a spaceship ceteris paribus
- ✓ Actually it will take less time because Andromeda and Milky way are on a collision course
- ✓ **Anyway my point is to make it crystal clear** that without nuclear fuels there is no way to make it alive to another solar system or galaxy
- ✓ **IMO that is a really good** argument for not wasting precious nuclear fuels on Earth

Sources/attribution for previous slides

- **Picture for Dyson sphere used in Chapter 10 slide:** https://commons.wikimedia.org/wiki/File:A_Dyson_Swarm_Superstructure_(21983905140).png
  Attribution: Author Kevin Gill from Los Angeles, CA, United States
- **Solar radiation is 15W/m2 at *Saturn:** https://www.pveducation.org/pvcdrom/properties-of-sunlight/solar-radiation-in-space
- **7 billion years into the future the sun will start to fusion He into C and the sun will end it nuclear fusion and become a white dwarf:** https://en.wikipedia.org/wiki/Formation_and_evolution_of_the_Solar_System#Timeline_of_Solar_System_evolution
- **Energy radiated from white dwarf will drop over very long time to zero Kelvin when it become a black dwarf. Potentially a white dwarf can start its life with radiating up to 100 times more than our active sun but that will drop to zero eventually I could not find any source for how much energy the white dwarf our own sun will become will radiate and how it will cool over time:** https://public.nrao.edu/ask/can-a-white-dwarf-star-be-used-as-an-energy-source/
- **Artificial nuclear fusion in a man made fusion reactor or hydrogen nuclear bomb is based on fusion of LiH-2 (lithium deuteride) not H-1 (H-2 is also called deuterium, the lithium is needed to crate H-3 or tritium that in turn is needed to make the fusion happen at the relative low temperature of 100 million degrees Celsius. The point I want to make here is that while our solar system has plenty of hydrogen we do not have plenty of lithium that will be lost forever if used for fusion. IMO for the sake of future civilizations we should conserve the lithium we have in our solar system for making batteries and for interstellar expansion:** https://www.iter.org/sci/FusionFuels see also https://www.atomicarchive.com/science/fusion/h-bomb-basics.html
- **Nearest solar system is Alpha Centauri is 4.35 light years away from Earth:** https://www.space.com/18090-alpha-centauri-nearest-star-system.html
- **Vojager 1 travel at 1/18000 the speed of light:** https://en.wikipedia.org/wiki/Interstellar_travel#:~:text=The%20fastest%20outward%2Dbound%20spacecraft,Centauri%20would%20take%2080%2C000%20years.
- **Nearest Galaxy Andromeda is 2.5 million light years away from Earth:** https://en.wikipedia.org/wiki/Andromeda_Galaxy