Nuclear Energy / The Hydrogen Economy
AOSC / CHEM 433 & AOSC 633

Ross Salawitch & Walt Tribett

Class Web Site: http://www.atmos.umd.edu/~rjs/class/spr2019

Topics for today:

- Nuclear Energy Production
  - History
  - Reactor Technology
  - Waste
- Hydrogen Economy
  - Overview
  - Source?
  - An Interesting Unintended Consequence

Lecture 22

7 May 2019

Course Logistics

- Problem Set #4 due today
  - Review will be held on Mon, 13 May, 6:30 pm
- Energy Plan (assigned only to 433 students) has also been posted
  - Due Thurs, 9 May
  - Several will be selected for presentation in class on 14 May
- Presentations/Paper (assigned to 633 students; 433 students can participate)
  - Mon, 13 May, 2 pm
- Final Exam
  - Mon, 20 May, 10:30 am to 12:30 pm
  - **Please return *Chemistry in Context* to receive refund of your $20**
- Course evaluation website http://CourseEvalUM.umd.edu
  open until 15 May, 11:59 pm
  - No evaluations submitted as of last night
  - 70% of students must submit, in order for future students to see evaluations
  - ***Please complete evaluations for all of your classes***

Energy and Power

Simple equation connects energy and power:

Energy = Power $\times$ Time

Size of a **power** plant is commonly measured in units of power:

kW (kilo: 10^3 Watts): Home solar

MW (mega: 10^6 Watts) Industrial

GW (giga: 10^9 Watts): Massive Hydroelectric

TW (terra: 10^{12} Watts): Large Nation and/or Global

Output of a **power** plant in units of energy:

kWh (kilo: 10^3 W hour)

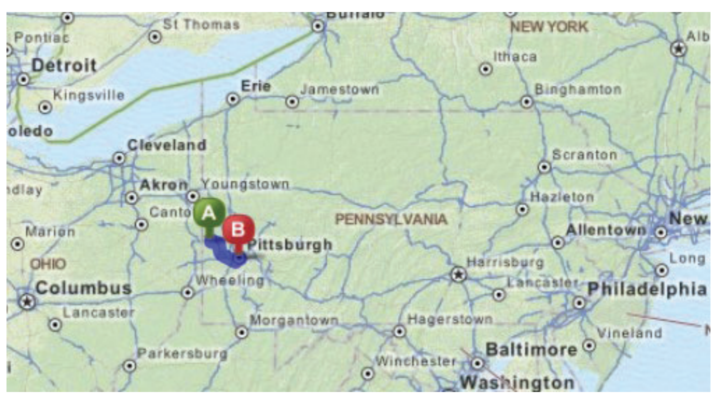
MWh (mega: 10^6 W hour)

GWh (gig: 10^9 W hour)

Capacity Factor: actual output of a power plant (energy) divided by maximum output if plant could run 24/7/365 at full capacity

Nuclear Power History

- Use of nuclear power developed by military; currently around 150 ships, globally
  - – allowed submarines to stay underwater for extended periods of time
  - – 1954: *U.S.S. Nautilus*, first nuclear powered submarine
- 1956: first commercial nuclear power plant, U.K.
- 1957: first U.S. commercial nuclear power plant, Shippingport, Pa



Using a crane rated for 125 tons, technicians and contractors lowered the 153-ton reactor vessel for installation at the Shippingport Atomic Power Station. The nuclear reactor core would be installed later.

http://www.phmc.state.pa.us/portal/communities/pa-heritage/atoms-for-peace-pennsylvania.html

Pros and Cons of Nuclear Energy

Discussions about nuclear energy evoke strong emotions. Climate change concerns have led some to reassess their views regarding this power source.

To those influencing environmental policy but opposed to nuclear power:

As climate and energy scientists concerned with global climate change, we are writing to urge you to advocate the development and deployment of safer nuclear energy systems. We appreciate your organization's concern about global warming, and your advocacy of renewable energy. But continued opposition to nuclear power threatens humanity's ability to avoid dangerous climate change.

We call on your organization to support the development and deployment of safer nuclear power systems as a practical means of addressing the climate change problem. Global demand for energy is growing rapidly and must continue to grow to provide the needs of developing economies. At the same time, the need to sharply reduce greenhouse gas emissions is becoming ever clearer. We can only increase energy supply while simultaneously reducing greenhouse gas emissions if new power plants turn away from using the atmosphere as a waste dump.

Renewables like wind and solar and biomass will certainly play roles in a future energy economy, but **those energy sources cannot scale up fast enough to deliver cheap and reliable power at the scale the global economy requires**. While it may be theoretically possible to stabilize the climate without nuclear power, **in the real world there is no credible path to climate stabilization that does not include a substantial role for nuclear power.**

We understand that today's nuclear plants are far from perfect. Fortunately, passive safety systems and other advances can make new plants much safer. And modern nuclear technology can reduce proliferation risks and solve the waste disposal problem by burning current waste and using fuel more efficiently. Innovation and economies of scale can make new power plants even cheaper than existing plants. Regardless of these advantages, nuclear needs to be encouraged based on its societal benefits.

http://dotearth.blogs.nytimes.com/2013/11/03/to-those-influencing-environmental-policy-but-opposed-to-nuclear-power

Pros and Cons of Nuclear Energy

Discussions about nuclear energy evoke strong emotions. Climate change concerns have led some to reassess their views regarding this power source.

Quantitative analyses show that the risks associated with the expanded use of nuclear energy are orders of magnitude smaller than the risks associated with fossil fuels. No energy system is without downsides. We ask only that energy system decisions be based on facts, and not on emotions and biases that do not apply to 21st century nuclear technology.

While there will be no single technological silver bullet, the time has come for those who take the threat of global warming seriously to embrace the development and deployment of safer nuclear power systems as one among several technologies that will be essential to any credible effort to develop an energy system that does not rely on using the atmosphere as a waste dump.

With the planet warming and carbon dioxide emissions rising faster than ever, we cannot afford to turn away from any technology that has the potential to displace a large fraction of our carbon emissions. Much has changed since the 1970s. The time has come for a fresh approach to nuclear power in the 21st century.

We ask you and your organization to demonstrate its real concern about risks from climate damage by calling for the development and deployment of advanced nuclear energy.

Sincerely,

Dr. Ken Caldeira, Senior Scientist, Department of Global Ecology, Carnegie Institution
Dr. Kerry Emanuel, Atmospheric Scientist, Massachusetts Institute of Technology
Dr. James Hansen, Climate Scientist, Columbia University Earth Institute
Dr. Tom Wigley, Climate Scientist, University of East Anglia and the National Center for Atmospheric Research

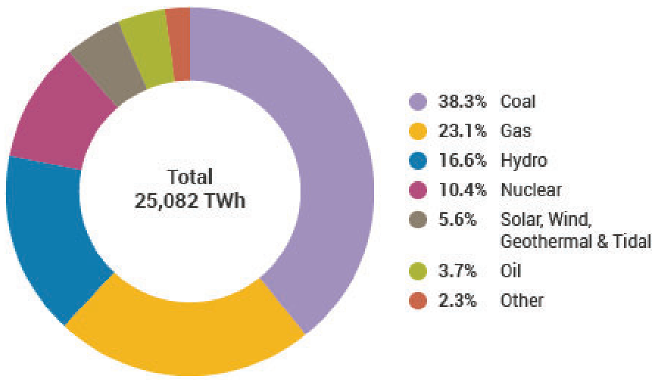
11 Nov 2013

http://dotearth.blogs.nytimes.com/2013/11/03/to-those-influencing-environmental-policy-but-opposed-to-nuclear-power

World Production: Nuclear

Electricity Generation Capacity via nuclear = 373.9 / 7015.5 x 100 = 5.3 %

Electricity Generation Production via Nuclear = 10.4 % in 2016



Source: IEA Electricity Information 2018

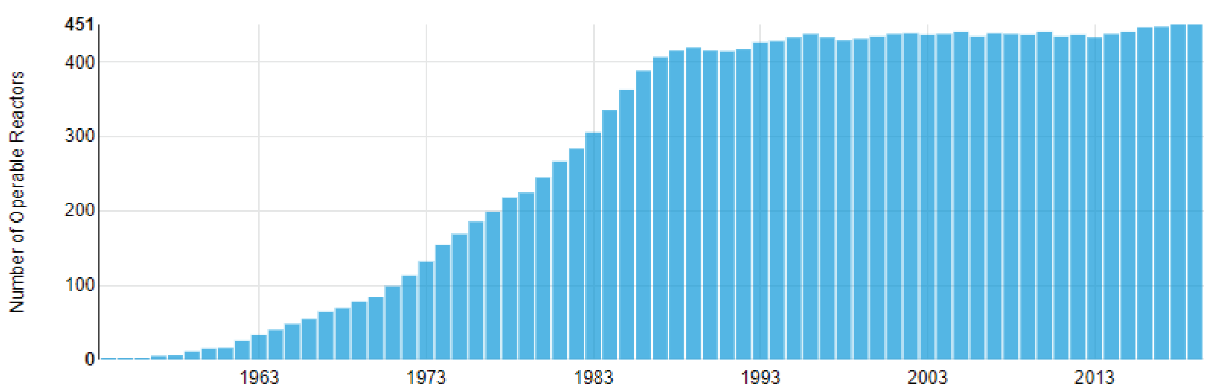
Total Source	GW (year 2018)
Coal	2167.0
Natural Gas	1768.8
Hydro-electric	1139.5
Wind	524.3
Liquid Fossil Fuel	380.7
Nuclear	**373.9**
Solar	352.4
Other Renewable (Biomass)	290.3
Geothermal	18.6
Total	**7015.5**

http://www.eia.gov/forecasts/ieo/ieo_tables.cfm

http://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx

World Production: Nuclear

Number of Operable Reactors Worldwide



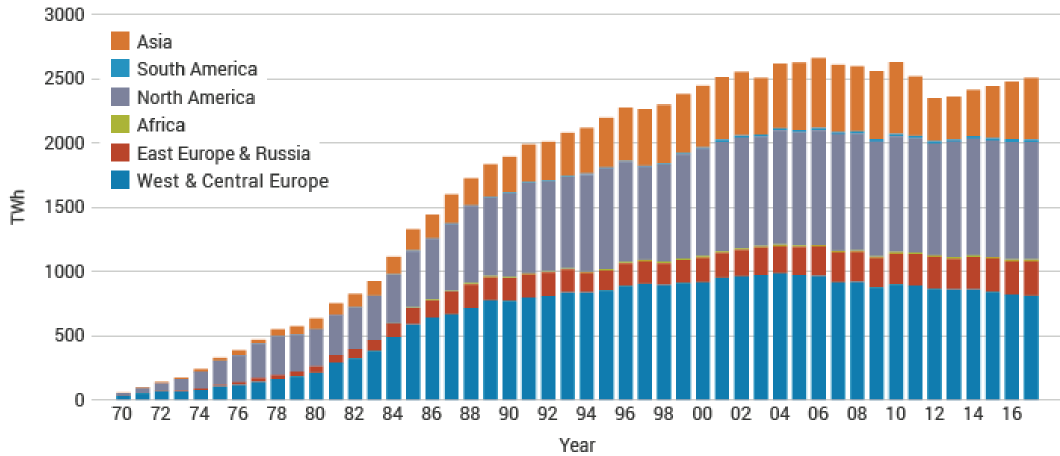
Nuclear Power:

- Generates ~10% of world's electricity
- 450 commercial reactors in 30 countries; 60 presently under construction
- Over 50 countries operate a total of about 225 research reactors and another 180 nuclear reactors power some 140 ships and submarines

http://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx

World Prduction: Nuclear

Global electricity generation production via nuclear peaked 2006 to 2010, declined for a few years, then has slowly risen

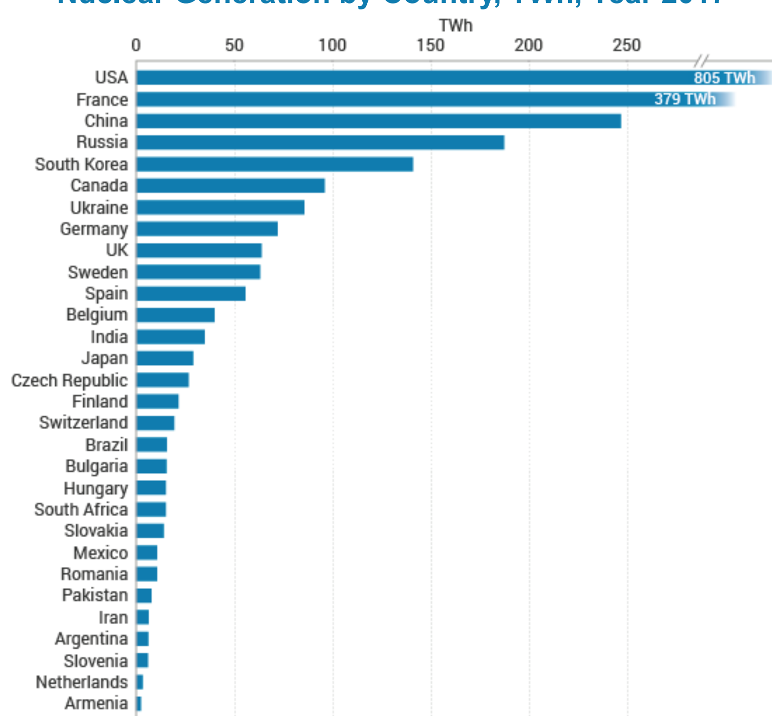


Source: IAEA PRIS

http://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx

World Production: Nuclear

Nuclear Generation by Country, TWh, Year 2017



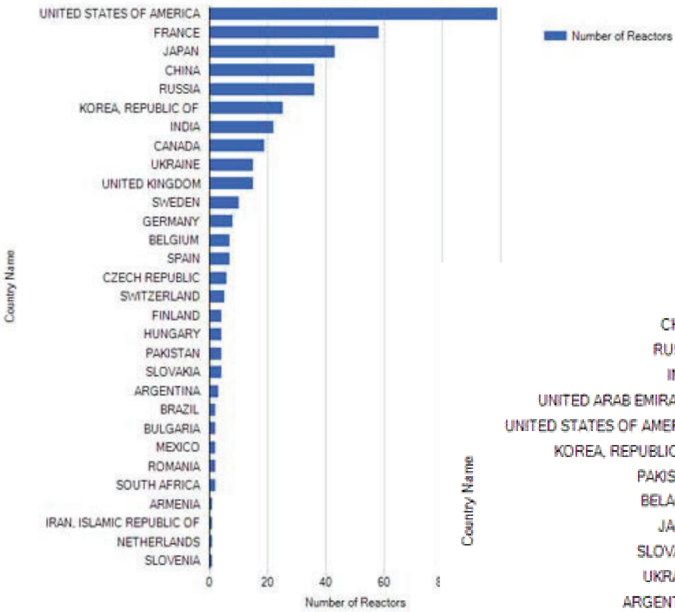
Source: IAEA PRIS Database

http://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx

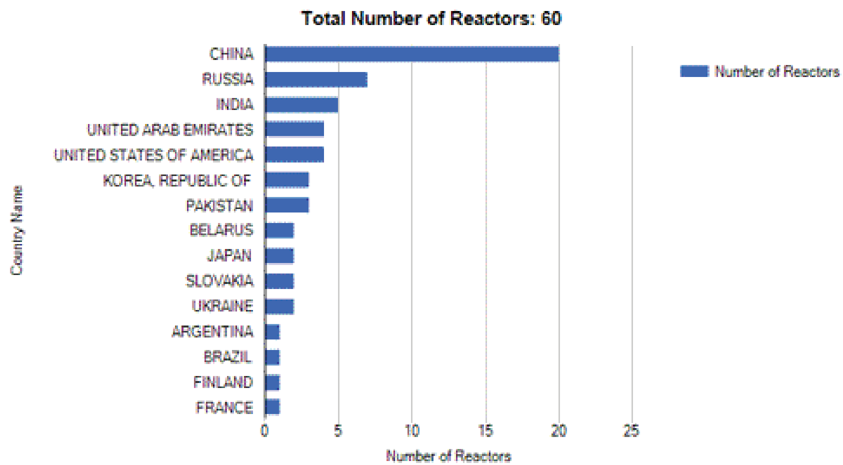
World Production: Nuclear

Total Number of Nuclear Reactors: 450

Nuclear power plants in operation, world-wide, as of 27 November 2016



Number of Nuclear Reactors Under Construction: 60



http://www.euronuclear.org/1-information/map-worldwide.htm

World Production: Nuclear

Chemistry in Context **states roughly 440 nuclear power plants**
European Nuclear Society states 450 as of Nov 2016

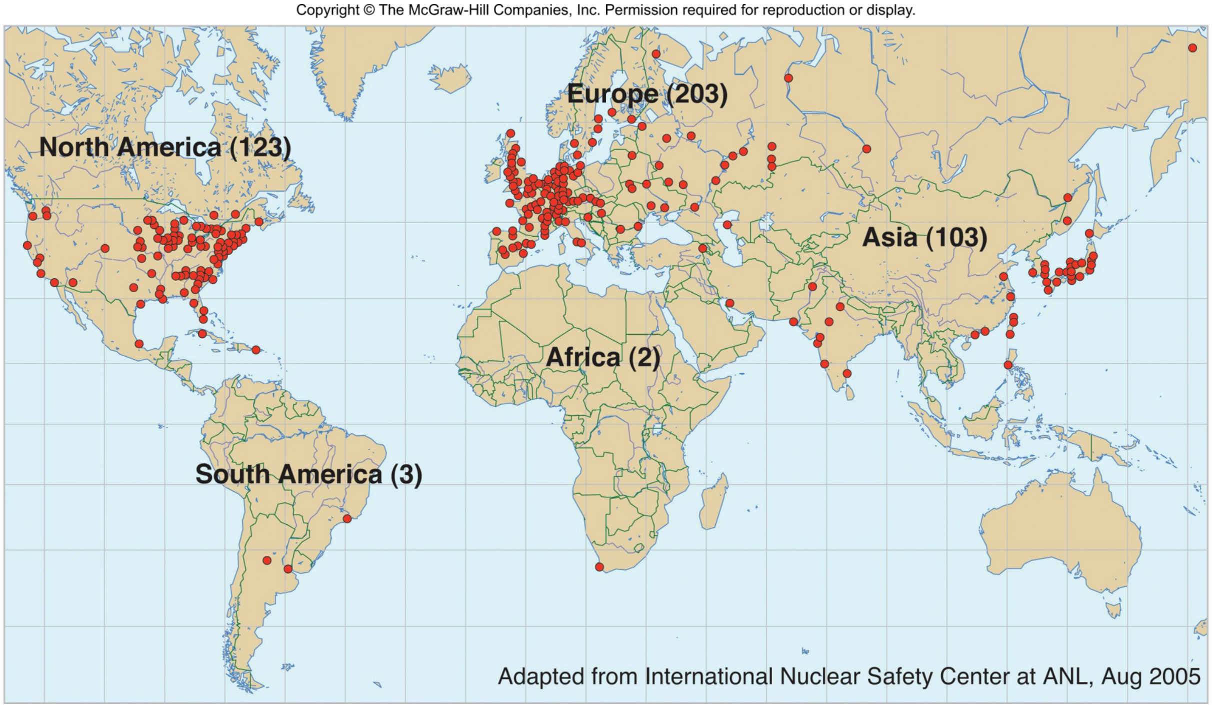
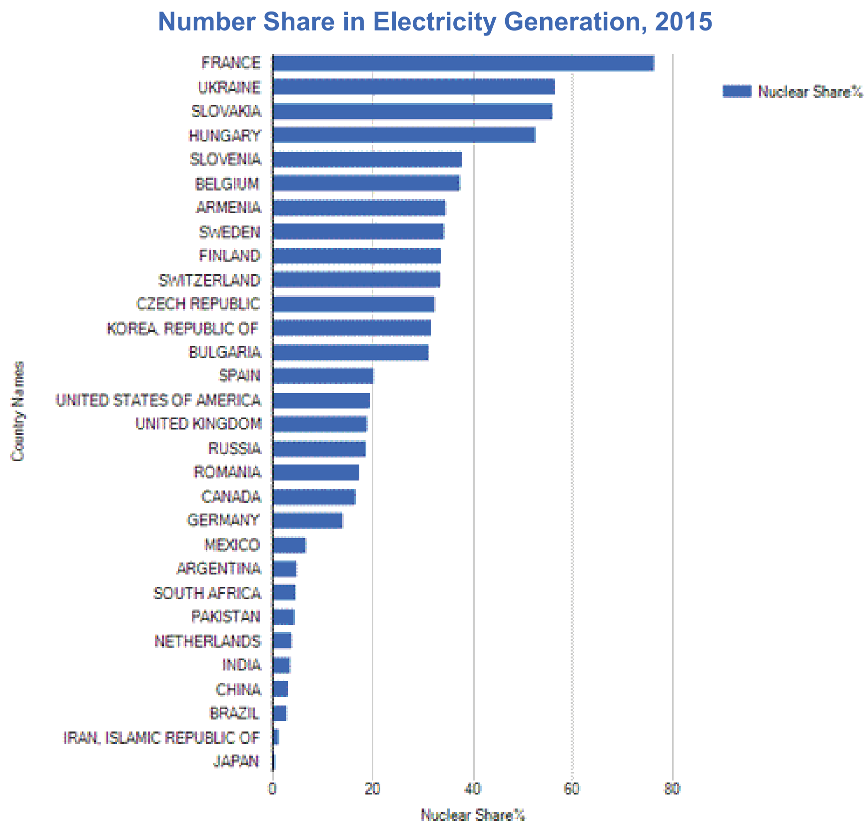


Figure 7.2, Chemistry in Context

World Production: Nuclear



http://www.euronuclear.org/1-information/map-worldwide.htm

U.S. Production: Nuclear

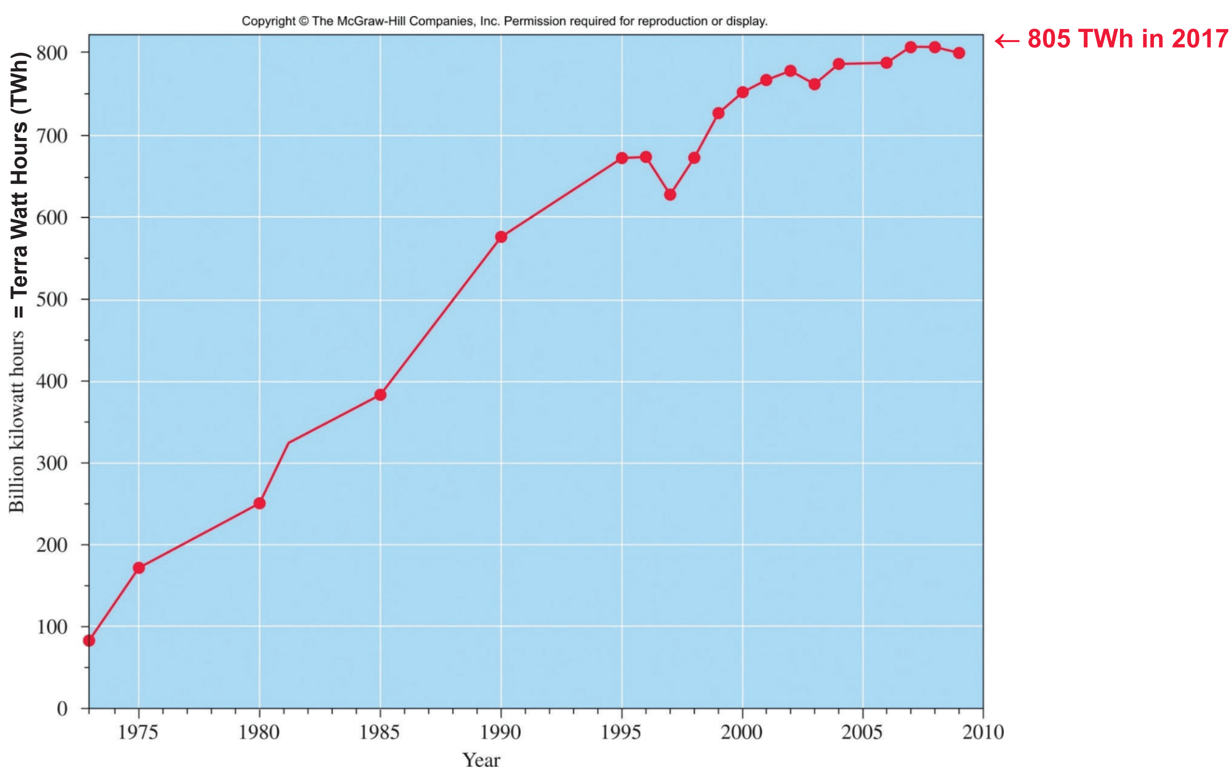
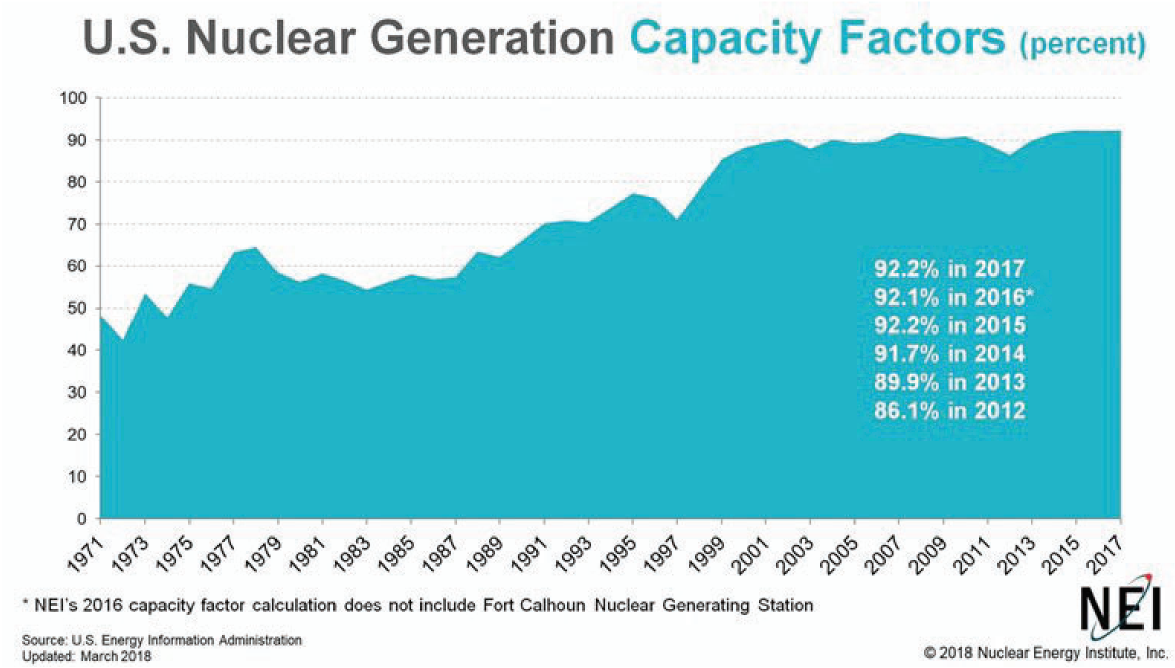


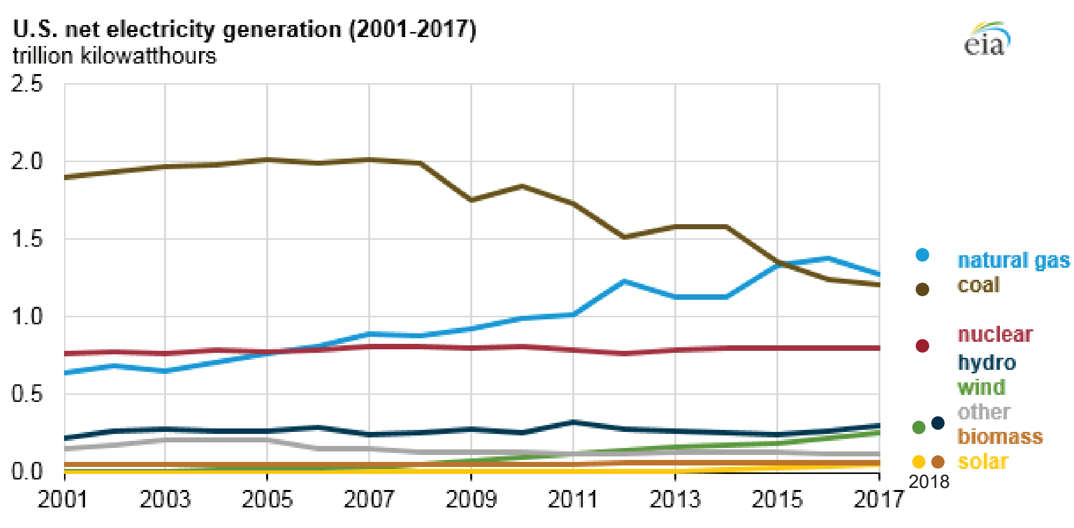
Figure 7.1, Chemistry in Context

U.S. Production: Nuclear



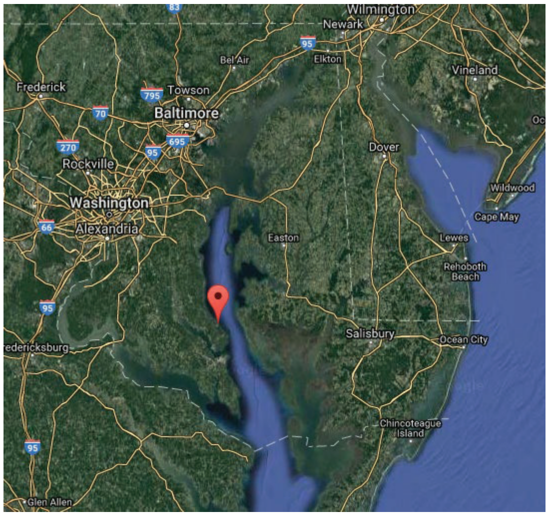
https://www.nei.org/resources/statistics/us-nuclear-industry-capacity-factors

U.S. Electricity Production: All Sources



https://blogs.scientificamerican.com/plugged-in/u-s-electricity-natural-gas-and-coal-fall-as-renewables-continue-to-rise/
2018 data from: https://www.eia.gov/electricity/data/browser/#

Calvert Cliffs



Calvert Cliffs	Start	Size & Type
Unit 1	1975	866 MW, Gen II (PWR)
Unit 2	1977	850 MW, Gen II (PWR)

Capacity Factor = 82.9% (lifetime); 100% in 2017
Cost = \$766 million
Output has been 43 years $\times$ 1706 MW $\times$ 8760 hrs/yr x 0.829 = 5.32 $\times 10^8$ MWh
Cost per KWh is \$766 $\times 10^6$ / 5.32 $\times 10^8$ MWh = \$1.40 / MWh $\times$ (MWh/10^3kWh) $\times$ (100 cents/\$) = 0.14 cents/ kWh

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

U.S.: Only Two Reactors Under Construction

	Project Origin	Size & Type	Start
Georgia	Vogtle 3 & 4	2 × 1250 MW, Gen III Westinghouse AP 1000*	Nov 2021 & 2022
South Carolina	V.C. Summer 2 & 3	2 × 1250 MW, Gen III Westinghouse AP 1000*	Construction Halted

*This Gen III design first achieved commercial operation on 21 Sept 2018 in Sanmen, China

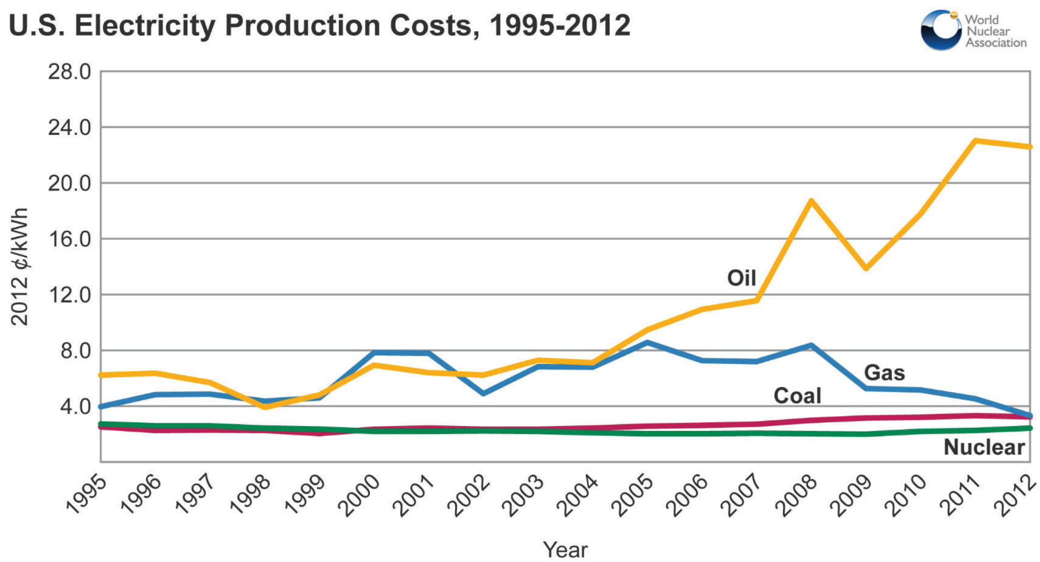
Vogtle 3 & 4 under construction. Source: Southern Company

http://www.lynceans.org/tag/generation-iii-reactors/
http://www.world-nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-power.aspx
https://www.world-nuclear-news.org/Articles/Fourth-Chinese-AP1000-enters-commercial-operation

Electricity Costs: Nuclear

- Producing electricity at U.S. nuclear power plants, including fuel, operation and maintenance, declined from 3 ¢ kWh^{-1} in 1990 to 2.3 ¢ kWh^{-1} in 2013
- US nuclear plant capacity factor: 58% in 1980, 70% in 1990, 92% in 2014

increased plant capacity equivalent to 20 new nuclear reactors



Production costs = operation & maintenance + fuel. (excludes indirect costs and capital)
Source: Ventyx Velocity Suite / NEI, May 2013

http://world-nuclear.org/gallery/charts/us-electricity-production-costs.aspx

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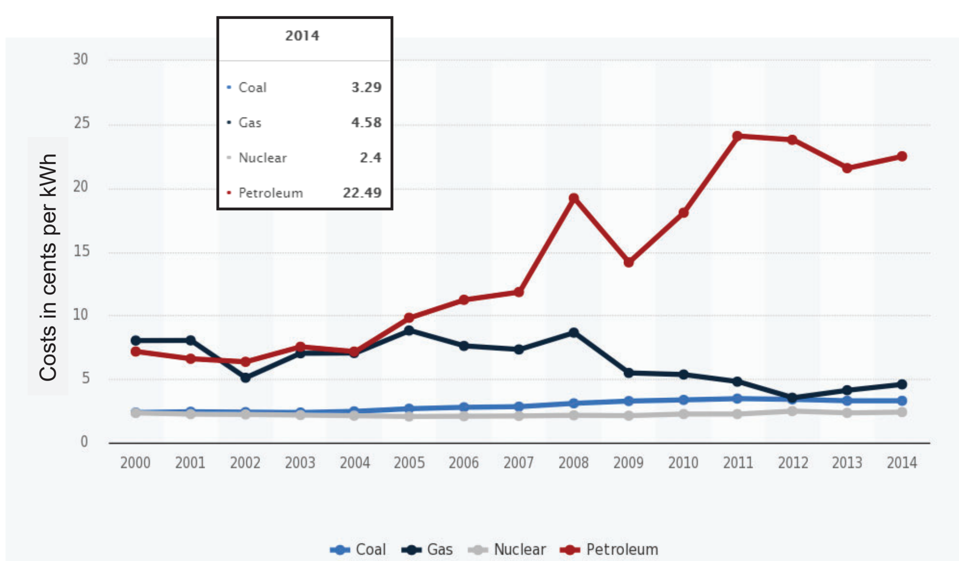
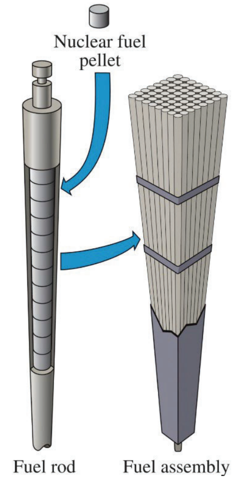


https://www.statista.com/statistics/184712/us-electricity-production-costs-by-source-from-2000

Figure 7.8, Chemistry in Context



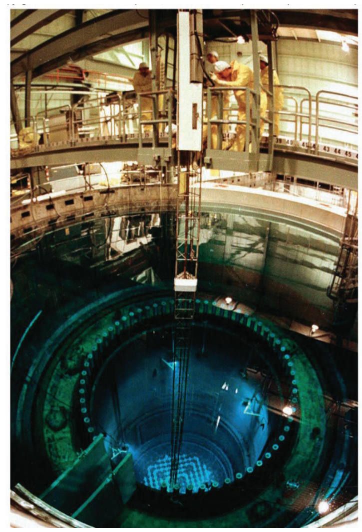
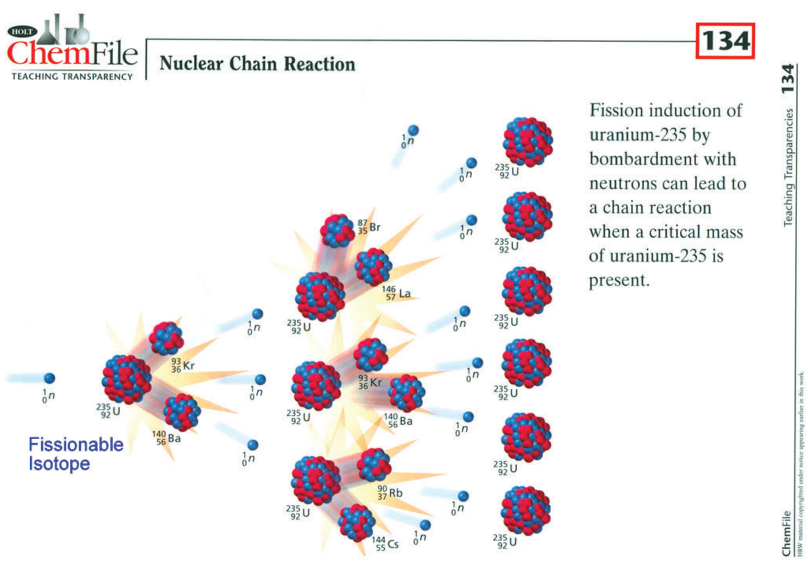


Figure 7.9, Chemistry in Context

Nuclear Power:

- ^{235}U (about 0.7% of natural uranium) is fissile; ^{238}U (dominant form) not fissile
- For reactor, uranium enriched to 3 to 5% using either gas diffusion (1 plant in U.S.) or gas centrifuge (two new plants being developed)
- Bomb grade uranium enriched to 90% ^{235}U
  - critical mass for uncontrolled explosion not present in conventional nuclear reactor
- Enriched UF_6 (gas at 56°C) converted to solid UO_2 pellets "size of a dime"
- Pellets stacked to form "fuel rods"



Nuclear Fission:

http://www.doccasagrande.net

- ^{235}U hit by "slow neutron" $\rightarrow$ splits into two smaller atoms, generating heat, more neutrons
  - slow neutrons: cause ^{235}U to split
  - fast neutrons: can be absorbed by ^{238}U, transmuting this element to ^{239}Pu
  - ^{239}Pu: int'l security concern ; half life of 24,110 yr
- Released neutrons lead to chain reaction (positive feedback) that releases lots of energy
- Most of today's reactors (Generation II)
  - Moderators, either deuterium, helium, or carbon (graphite), quench fast neutrons and maintain "delicate balance" of sustained chain reaction (which ceases with too few neutrons) and regulation of temperature (which gets too high with too many electrons)

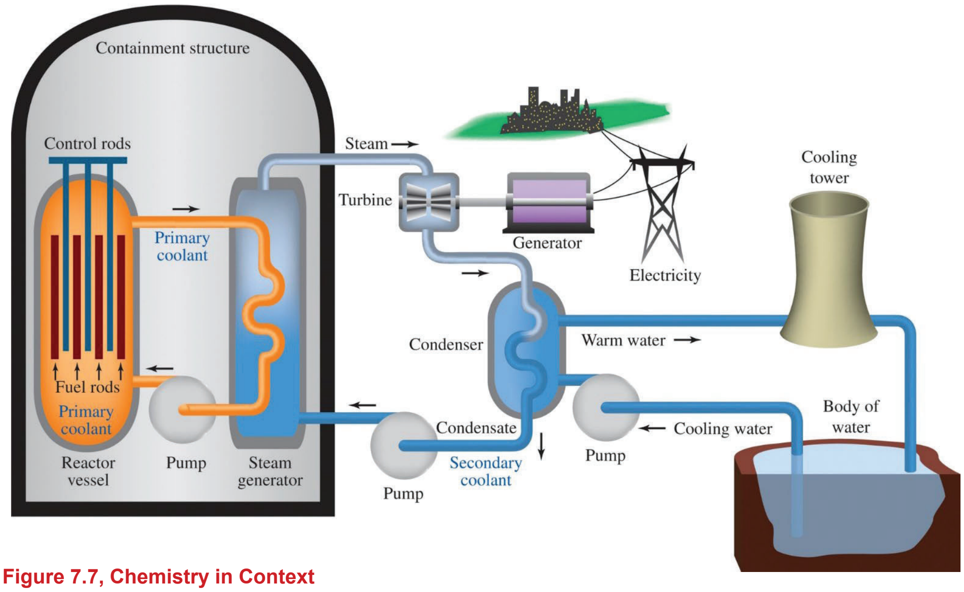


Figure 7.7, Chemistry in Context

Today's reactors (Generation II):

- Regular H_2O used as coolant, transfers heat to another system of H_2O
  – generates steam which turns turbines
- Operates at ~300°C (not too hot) but at very high pressure (~150 times atmospheric)
- Water used for turbines drawn from nearby water source (river, lake, ocean, etc), returned to environment once cooled:
  - intake system not pleasant for local fish
  - concern over output raising temperature of nearby body of water

Figure 7.10, Chemistry in Context

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Nuclear Power: Waste

- HLW: High Level Waste (i.e., spent fuel)
  - 20 tons per plant per year → 2000 tons per year in the U.S.
  - contains ^{235}Uranium, ^{238}Uranium, ^{239}Plutonium, ^{131}Iodine, ^{137}Cesium, ^{90}Strontium
  - About 70,000 tons of spent fuel generated in U.S. (as of 2010)

Table 7.4 Half-life of Selected Radioisotopes

Radioisotope	Half-life ($t_{1/2}$)	Found in the spent fuel rods of nuclear reactors?
uranium-238	4.5×10^9 years	Yes. Present originally in fuel pellet.
potassium-40	1.3×10^9 years	No.
uranium-235	7.0×10^8 years	Yes. Present originally in fuel pellet.
plutonium-239	24,110 years	Yes. See equation 7.13.
carbon-14	5715 years	No.
cesium-137	30.2 years	Yes. Fission product.
strontium-90	29.1 years	Yes. Fission product.
thorium-234	24.1 days	Yes. Small amount generated in natural decay series of U-238.
iodine-131	8.04 days	Yes. Fission product.
radon-222	3.82 days	Yes. Small amount generated in natural decay series of U-238.
plutonium-231	8.5 minutes	No. Half-life is too short.
polonium-214	0.00016 seconds	No. Half-life is too short.

- Spent fuel from plants encased in ceramic or glass (vitrification)
  - radioactivity remains, but glass isolates waste from water supply
  - In U.S., presently stored "on site" at reactors with design capacity for ~25 yrs of waste

Nuclear Power: Waste

U.S.

- 1997: Federal Government Designated Yucca Mountain, Nevada (not far from Las Vegas) as sole site for long-term, high level nuclear waste storage
- Nevada opposed
- 2002: Senate gave final approval for Yucca Mountain Site based on EPA 10,000 year radiation compliance assessment
- 2004: U.S. Appellate Court ruled compliance must address N.A.S. study that peak radiation could be experienced 300,000 yrs after site had been filled and sealed
- 2009: EPA published in Federal Register a final rule, increasing compliance period to **1,000,000** years
- 2011: Obama administration stopped financial support for Yucca, after $54 billion has been invested for capacity of 70,000 tons of spent fuel plus 8000 tons of military waste
- 2019: Trump Admin has $116 million budget request to process DOE license to open Yucca site. Bills moving through House & Senate that would open Yucca as a permanent waste repository

https://www.cbsnews.com/news/in-nevada-trump-administration-revives-a-radioactive-campaign-issue
https://www.reviewjournal.com/news/politics-and-government/nevada/nevada-braces-for-renewed-fight-over-yucca-storing-nuclear-waste-1656701

Members of a congressional tour make their way through the north portal of Yucca Mountain near Mercury on Saturday, July 14, 2018.

Chase Stevens Las Vegas Review-Journal

Nuclear Power: Waste

Rest of the world:

- many countries recycle waste, considerably reducing mass of waste

  Once reactor fuel (uranium or thorium) is used in a reactor, it can be treated and put into another reactor as fuel. More than half of France's electricity comes from nuclear power and recycles used fuel. Other countries that use used fuels include the United Kingdom, Russia and Japan. The United States currently does not allow the recycling of nuclear waste because of the risk of nuclear proliferation. Countries that recycle or reprocess nuclear waste include Belgium, China and Switzerland.
- Japan considering storing waste at Fukushima reactor site

  http://www.bloomberg.com/news/2011-05-26/fukushima-may-become-graveyard-for-radioactive-waste-from-crippled-plant.html
- Many conuntires considering burial of waste in ~2 to 5 km boreholes:

Option	Suitable waste	Examples
Near-surface disposal at ground level or in caverns at depths of tens of meters	LLW & short-lived ILW	Implemented for LLW in many countries, including Czech Rep., Finland, France, Japan, Netherlands, Spain, Sweden, U.K. & U.S Implemented in Finland and Sweden for LLW & short-lived ILW.
Deep geological disposal at depths between 250m and 1000 m for mined repositories, or 2000 m to 5000 m for boreholes	Long-lived ILW & HLW	Many countries have investigated deep geological disposal and it is official policy in several countries. Implemented in the USA for defense-related transuranic waste at WIPP. Preferred sites selected in France, Sweden, Finland, & U.S. Geological repository site selection process underway in U.K. and Canada.

LLW: Low-level waste **HLW: High level waste**
ILW: Intermediate level waste **WIPP: Waste Isolation Pilot Plant**

http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/storage-and-disposal-of-radioactive-wastes.aspx

Nuclear Power: Waste

Deep boreholes

As well as mined repositories, which have been the focus of most international efforts so far, deep borehole disposal has been considered as an option for geological isolation for many years, including original evaluations by the US National Academy of Sciences in 1957 and more recent conceptual evaluations. In contrast to recent thinking on mined repositories, the contents would not be retrievable.

The concept consists of drilling a borehole into basement rock to a depth of up to about 5000 metres, emplacing waste canisters containing used nuclear fuel or vitrified radioactive waste from reprocessing in the lower 2000 metres of the borehole, and sealing the upper 3000 metres of the borehole with materials such as bentonite, asphalt or concrete. The disposal zone of a single borehole could thus contain 400 steel canisters each 5 metres long and one-third to half a metre in diameter. The waste containers would be separated from each other by a layer of bentonite or cement.

Boreholes can be readily drilled offshore (as described in the section below on sub seabed disposal) as well as onshore in both crystalline and sedimentary host rocks. This capability significantly expands the range of locations that can be considered for the disposal of radioactive waste.

Deep borehole concepts have been developed (but not implemented) in several countries, including Denmark, Sweden, Switzerland, and the USA. Compared with deep geological disposal in a mined underground repository, placement in deep boreholes is considered to be more expensive for large volumes of waste. This option was abandoned in countries such as Sweden, Finland, and the USA, largely on economic grounds. The borehole concept remains an attractive proposition for the disposal of smaller waste forms including sealed radioactive sources from medical and industrial applications[f].

An October 2014 US Department of Energy (DOE) report said: “Preliminary evaluations of deep borehole disposal indicate a high potential for robust isolation of the waste, and the concept could offer a pathway for earlier disposal of some wastes than might be possible in a mined repository.” In January 2016 the DOE commissioned a team led by Battelle to drill a 4880-metre test borehole into crystalline basement rock in North Dakota.

http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/storage-and-disposal-of-radioactive-wastes.aspx

Public pressure stops French nuclear waste export to Russia

Feature story - 29 May, 2010

On this page

- Nuclear waste shipments exposed by Greenpeace
- AREVA's lies
- Greenpeace welcomes decision to stop the scandalous and immoral transporting
- To end the nuclear age

AREVA, the French nuclear energy company, admitted Friday that their contract to ship nuclear waste to Russia has been halted four years early, ending this July. Transports we have tirelessly highlighted, taken action against and lobbied to have ended. But , where to now with all their dangerous waste? AREVA says it plans to let the, ahem, "stocks" build up in their facilities at home.

Greenpeace activists along side the transport ship carrying AREVA's nuclear waste, bound for Russia

For Greenpeace campaigners, activists, and supporters, it's a well-earned occasion to celebrate and reflect on over 25 years of efforts to expose and oppose these scandalous nuclear waste shipments to Russia.

The contract between AREVA and the Russian nuclear agency Rosatom was due to expire in 2014. However, the Russians have decided to end the collaboration, which began in 1972, effective 11 July 2010.

Last month our ship the Esperanza pursued the Russian transport ship Kapitan Kuropte, on its way to Russia carrying nuclear waste from France. Activists in rubber boats got along side the ship displaying banners reading "Russia is not a nuclear dump", before being sprayed with water canons.

http://www.greenpeace.org/international/en/news/features/Public-pressure-stops-French-nuclear-waste-export-to-Russia/

PUBLISHED 17:23 APRIL 23, 2019 UPDATED 17:23 APRIL 23, 2019

France debates what to do with its nuclear waste

By NEOnline | IR

France launched a national debate on how to treat its 1.6 million cubic meters of nuclear waste as part of the country's National Plan for the Management of Radioactive Waste takes place under the auspices of Andra, the national agency responsible for its management.

Currently, Cigéo, the €35 billion Industrial Centre for Geological Storage, is being built in Bure, in eastern France, a region with no seismic activity and thick layers of slate that keep water out.

The idea is to create chambers 500 meters below the surface and seal the waste inside galleries. However, the emission of hydrogen from the waste could lead to explosions, so the waste needs to be ventilated, which suggests maintenance work for a few million years.

The question is whether this solution will be able to maintain the waste "safely" for a few million years. Neptunium 237 requires 2,1 million years to be half as dangerous as it is today; iodine 129 will take 16 million years and chlorine 36 merely 300,000 years.

French physicist **Bernard Laponche** argues for an end to all talk about burying, which is irreversible and, therefore, "the worst of all options," as the leak of a single container would suffice to spell disaster.

An alternative approach would require authorities to wait for science to create a more efficient solution, with experiments focusing on neutron bombardment to reduce the radioactivity of plutonium. Laponche argues that capital should be diverted from storage to research, to develop a more efficient solution.

https://www.neweurope.eu/article/france-debates-what-to-do-with-its-nuclear-waste/

Nuclear Power: Safety

- U.S.
  - 1979 : Three Mile Island near Harrisburg, Pennsylvania
  - Loss of coolant and partial meltdown
  - Release of radioactive gases: no fatalities, normal cancer rates in area

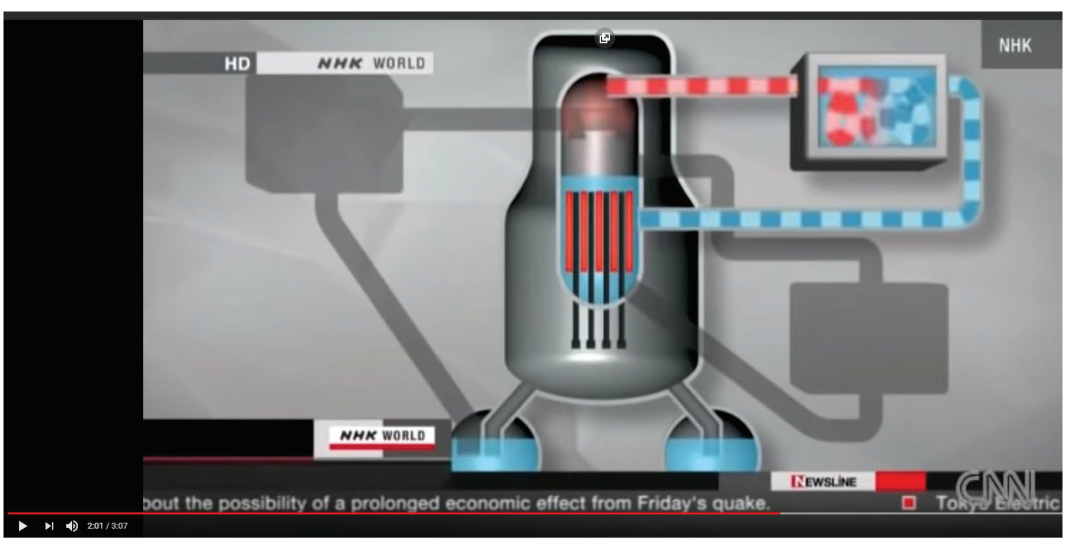
    The accident began about 4:00 a.m. on March 28, 1979, when the plant experienced a failure in the secondary, non-nuclear section of the plant. The main feedwater pumps stopped running, caused by either a mechanical or electrical failure, which prevented the steam generators from removing heat. First the turbine, then the reactor automatically shut down. Immediately, the pressure in the primary system (the nuclear portion of the plant) began to increase. In order to prevent that pressure from becoming excessive, the pilot-operated relief valve (a valve located at the top of the pressurizer) opened. The valve should have closed when the pressure decreased by a certain amount, but it did not. Signals available to the operator failed to show that the valve was still open. As a result, cooling water poured out of the stuck-open valve and caused the core of the reactor to overheat.

    For more info, see http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html
- Russia
  - 1986 : Chernobyl
  - During a test, operators interrupted flow of cooling water to core
  - Insufficient control rods were in reactor
  - Heat surge resulted, leading to ***chemical*** explosion
  - Water was sprayed; water reacted with graphite producing H_2 ($2H_2O + C \rightarrow 2H_2 + CO_2$), which caused additional ***chemical*** explosion
  - 31 firefighters and several people in plant died from acute radiation sickness; an estimated 250 million people were exposed to elevated radiation that may shorten their lives
  - Nuclear engineers state that no U.S. commercial reactors have Chernobyl design defects

Chemistry in Context, pages 299 to 302

Nuclear Power: Fukushima

Fukushima
- 11 March 2011, Earthquake off the coast. Reactors undamaged – go into containment isolation
- Diesel generators power emergency cooling systems
- Reactors designed to withstand 6.5 meter tsunami – reactor complex hit by 14 meter tsunami
- Cooling system powered by electricity
- Loss of electricity power led to pressure build up, coolant turned to steam, fuel rods exposed to air; and began to burn



Fukushima Nuclear Reactor Problem Explained (CNN) Up next

https://www.youtube.com/watch?v=BdbitRlbLDc

Nuclear Power: Fukushima

Fukushima

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https://www.reuters.com/video/2019/03/11/fukushima-cleanup-threatened-by-water-wo?videoId=523384208

See also https://www.washingtonpost.com/world/asia_pacific/as-japans-leader-junichiro-koizumi-backed-nuclear-power-now-hes-a-major-foe/2019/03/09/d1106ee8-4037-11e9-85ad-779ef05fd9d8_story.html

Fukushima: Could this have been avoided?

- Diesel generators were located in basement
- Fuel located in above ground, external fuel tanks
- Tsunami flooded generators, wiped out fuel tanks

If generators had been on upper level of the building and fuel buried or kept at a higher elevation, we wouldn't be having this discussion!!!

The red box shows location of the destroyed back-up fuel tanks.

http://www.forbes.com/sites/bruceupbin/2011/03/16/idiotic-placement-of-back-up-power-doomed-fukushima

See also https://www.washingtonpost.com/world/new-report-blasts-japans-preparation-for-response-to-fukushima-disaster/2012/07/05/gJQAN1OEPW_story.html

Could another Fukushima happen?

National Geographic, 23 March 2011

For a world on the brink of a major expansion in nuclear power, a key question raised by the Fukushima disaster is would new reactors have fared better in the power outage that triggered dangerous overheating?

The answer seems to be: Not necessarily.

The nuclear industry has developed reactors that rely on so-called "passive safety" systems that could address the events that occurred in Japan: loss of power to pump water crucial to cooling radioactive fuel and spent fuel

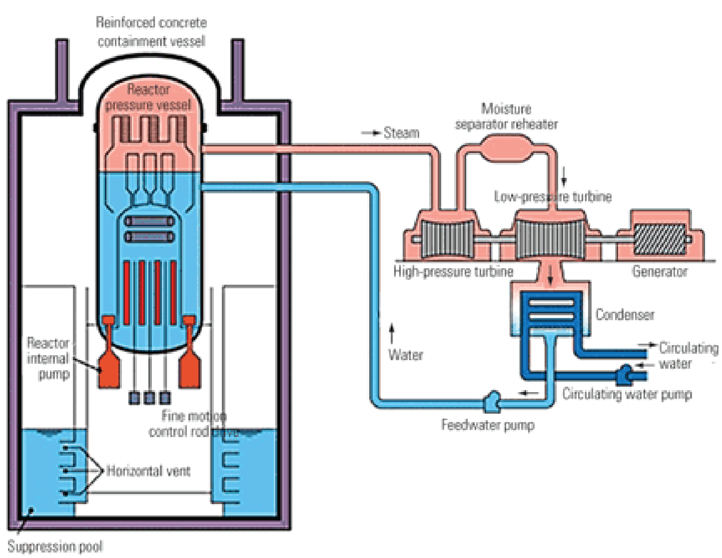
But these so-called Generation III designs are being deployed in only four of the 65 plants under construction worldwide. (Four reactors that are in the site-preparation phase and still awaiting regulatory approval in Georgia and South Carolina in the United States would make that eight of 69 plants.)

The vast majority of plants under construction around the world, 47 in all, are considered **Generation II** reactor designs—the same 1970s vintage as Fukushima Daiichi, and **without integrated passive safety systems**.

At the San Onofre Nuclear Station on the Southern California coast, modifications have been made that allow the operators to use a gravity-driven system to circulate the water to cool the plant for a period of time upon loss of power … But there are limits to such retrofits. "This is a huge volume of water," says Adrian Heymer, executive director of strategic programs for the NEI. "What happens to that tank in an earthquake?"

That's why there's been an effort to integrate a fully passive system from the get-go of the design process, he said. There is no ready reference list of which plants around the world have been modified with gravity-driven or other safety features. And as for new nuclear plants with integrated passive safety systems, deployment is slow.

http://news.nationalgeographic.com/news/energy/2011/03/110323-fukushima-japan-new-nuclear-plant-design/



Newer reactors (Generation III):

- Standard design – cheaper and quicker to build and license
- Simpler, rugged design easier to operate and less prone to accidents
- Redundant safety features
- Longer operational lifetime
- Includes many **passive safety features** that decrease likelihood of meltdown

http://editors.eol.org/eoearth/wiki/Nuclear_power_(About_the_EoE)

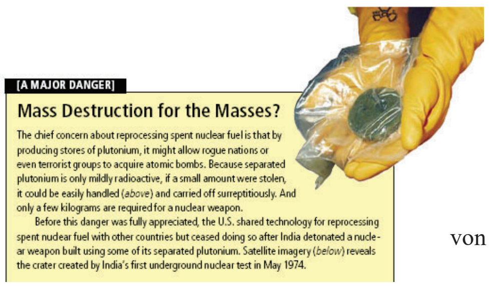
https://www.youtube.com/watch?v=rvxVCl2rZnU

Generation IV

- Initiated by DOE in 1999
- Focusing on “fast spectrum” reactors that cool using sodium
- Fast spectrum refers to use of “fast neutrons”, which convert ^{238}U to ^{239}Pu
- Operate at atmospheric pressure but ~1000°C
- Lower pressure reduces risk of explosion
- ***<u>But</u>***: sodium + water would generate lots of energy (fire!!!) →
  safety concerns focused on prevention of this chemical reaction!
- Can recover more than 99% of energy from spent nuclear fuel
- Supported by members of both political parties, leading scientists
- Plutonium would be separated in process:

  Good News: resulting waste would only have to be managed for ~500 years!
  (for sufficient decay of 90-strontium to occur)

  Bad News: presently, plutonium is mixed with nasty, shorter lived radionuclides.
  If plutonium is isolated, it literally can be handled using gloves


[A MAJOR DANGER]

Mass Destruction for the Masses?

The chief concern about reprocessing spent nuclear fuel is that by producing stores of plutonium, it might allow rogue nations or even terrorist groups to acquire atomic bombs. Because separated plutonium is only mildly radioactive, if a small amount were stolen, it could be easily handled (*above*) and carried off surreptitiously. And only a few kilograms are required for a nuclear weapon.

Before this danger was fully appreciated, the U.S. shared technology for reprocessing spent nudear fuel with other countries but ceased doing so after India detonated a nuclear weapon built using some of its separated plutonium. Satellite imagery (*below*) reveals the crater created by India's first underground nuclear test in May 1974.

von Hippel, *Scientific American*, May 2008.

http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/generation-iv-nuclear-reactors.aspx

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For more info, see:

“Next Generation Nuclear Power”, Lake, Bennett, and Kotek, *Scientific American*, Jan 2002.
“Smarter Use of Nuclear Waste”, Hannum, Marsh, and Stanford, *Scientific American*, Dec 2005.
“Rethinking Nuclear Fuel Recycling”, von Hippel, *Scientific American*, May 2008.
“Power to Save the World, the Truth about Nuclear Energy”, Gwyneth Cravens, 2008.

Operating conditions of Generation IV reactors attractive for “high temperature hydrolysis of steam for hydrogen production”
(Olah et al., Section 9.3.5)

http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/generation-iv-nuclear-reactors.aspx

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The Hydrogen Economy

Hydrogen as a fuel source:

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(l) + 286\ \text{kJ}$$

1 gram of hydrogen can yield 143 kJ

Much higher energy yield than fossil fuels and *no harmful emissions* !!!

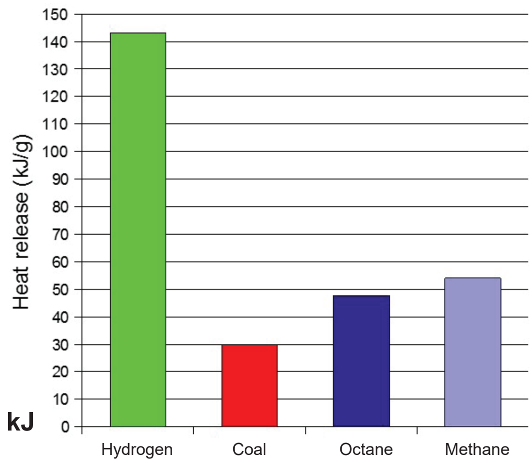
How does this compare to gasoline?

1 gallon of gasoline ≈ 2800 g ⇨ 2800g × 47.8 kJ/g =1.34×10^5 kJ

1 kg of hydrogen = 1000g ⇨ 1.43×10^5 kJ

In terms of energy available, 1 kg of hydrogen ≈ 1 gallon of gasoline

Since fuel cells are more efficient than internal combustion engines. in theory, not as much hydrogen is needed as gasoline, to obtain same propulsion



The Hydrogen Economy

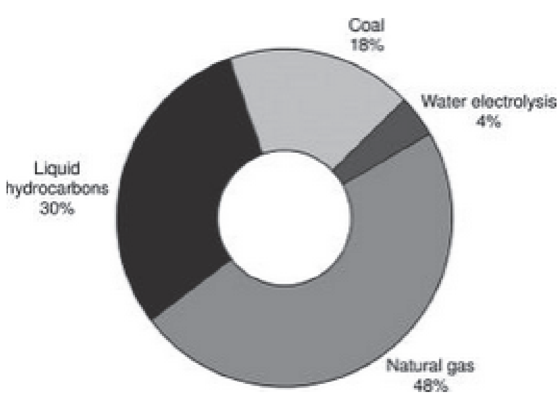


Figure 9.5. Sources for current worldwide hydrogen production

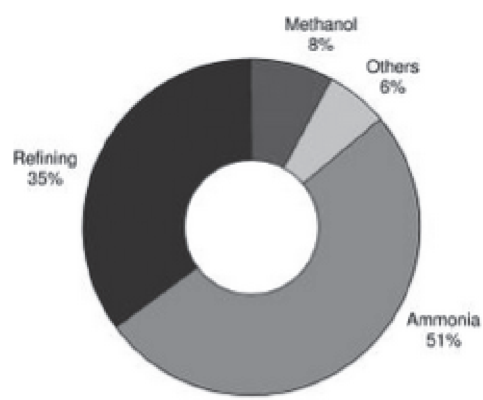


Figure 9.4 Main hydrogen consuming sectors in the world

Majority of world hydrogen produced using fossil fuels

used to create ammonia for fertilizer and to refine petroleum products

The Hydrogen Economy: Sources

Steam Reformation:

CH_4 is reacted with high temperature steam (700-1000º C) to create H_2

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

CO can further react with water (*water-gas shift reaction*)

$$CO + H_2O \rightarrow CO_2 + H_2$$

Net: $CH_4 + 2\,H_2O \rightarrow CO_2 + 4H_2$

accounts for most of hydrogen produced in the US

The Hydrogen Economy: Sources

Water electrolysis:

286 kJ are released when hydrogen reacts with oxygen to create water.
This reaction can be run in reverse to create hydrogen.

$$H_2O + 286\text{ kJ} \rightarrow H_2 + ½\,O_2$$

but 286 kJ are needed!

While this uses a lot of energy, it is potentially the cleanest way to make hydrogen.

No emission of GHGs if the electricity needed for electrolysis comes from either nuclear or renewable energy.

The Hydrogen Economy: Storage

Compressed gas:

Need high pressure cylinders to hold enough hydrogen to power a vehicle

Assuming a normal car (10 gallon tank) is 25% efficient

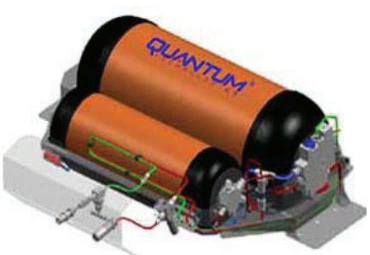
$$10 \text{ gallon} \times 1.34\text{x}10^5 \text{ kJ/gal.} \times 0.25 = 3.35\text{x}10^5 \text{ kJ}$$

Newer hydrogen vehicles are supposedly ~60% efficient,

$$3.35\text{x}10^5 \text{ kJ} / (1.43\text{x}10^5 \text{ kJ/kg} \times 0.6) = \sim 4\text{kg}$$

Hydrogen tanks for vehicle use are rated at 5500 PSI (~375 atm)

From the ideal gas law,

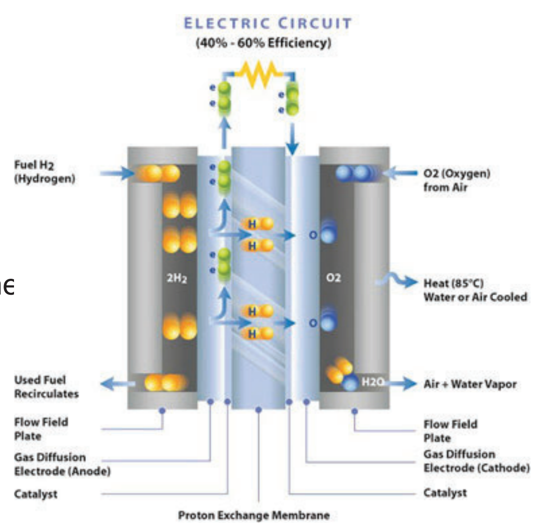


$V = 2000 \text{ mol} \times 0.0821 \text{ L atm mol}^{-1} \text{ K}^{-1} \text{ 295K /375 atm}$
$= 129 \text{ L}$
$=$ 34 gallons **… 3.4 times bigger than a standard liquid tank**

- Gas tanks are heavy
- Hard to monitor how much fuel remaining

Hydrogen Fuel Cells

- Hydrogen comes in contact with platinum anode, converts $H_2 \rightarrow 2H^+$
- $2e^-$ pass through circuit to power car
- Protons pass through proton exchange membrane (PEM) and come in contact with oxygen and e^- to form H_2O
- Process generates < 1 volt, so need stack of fuel cells to power vehicle



http://hydrogenfuelisthebest.weebly.com/hydrogen-fuel.html

Two hurdles to widespread use of hydrogen fuel cell cars:
– source of H_2 that does not involve release of GHGs
– "chicken & egg" dilemma of re-fueling infrastructure
This hurdle seems to have been solved:
✓ past prototype cars have been prohibitively expensive

Hydrogen Fuel Cell Cars

Is that really water that comes out of the exhaust?

Believe it or not, yes. Out of the exhaust comes water so pure you could drink it (but shouldn't).

The fuel you pump into these cars is hydrogen gas. The energy is created in the fuel cell by reacting the hydrogen in the tanks with oxygen from the air over what is called a "proton exchange membrane" and the end result is electricity and water. Water is made up of two hydrogen atoms and one oxygen atom (hence H2O) and is the only remnant from this fuel-air interaction.

For the record I would have taken a drink of this water, but Toyota's people didn't allow me to for legal reasons. The exhaust pipes can pick up dirt and pollutants while driving around, so it was hard to trust what else besides water could be in that glass.

http://america.aljazeera.com/watch/shows/techknow/articles/2014/10/8/6-questions-abouthydrogenfuelcellcarsyouweretooembarrassedtoask.html

The Hydrogen Economy: Problems

Hydrogen Leaks:

- **Not a problem if occurring outside**
- **If inside (parking garage, house garage, etc.) hydrogen will quickly fill spac**
  - **— easily ignited**
  - **— explosive in air at concentrations between 18 and 59%**
  - **— burns with a colorless flame**
- **Pressurized tank explosion**
- **Containment during car accident**

These problems assume that the hydrogen is pressurized or liquefied
If metal hydrides are used, these problems aren't as much of an issue.

Infrastructure:

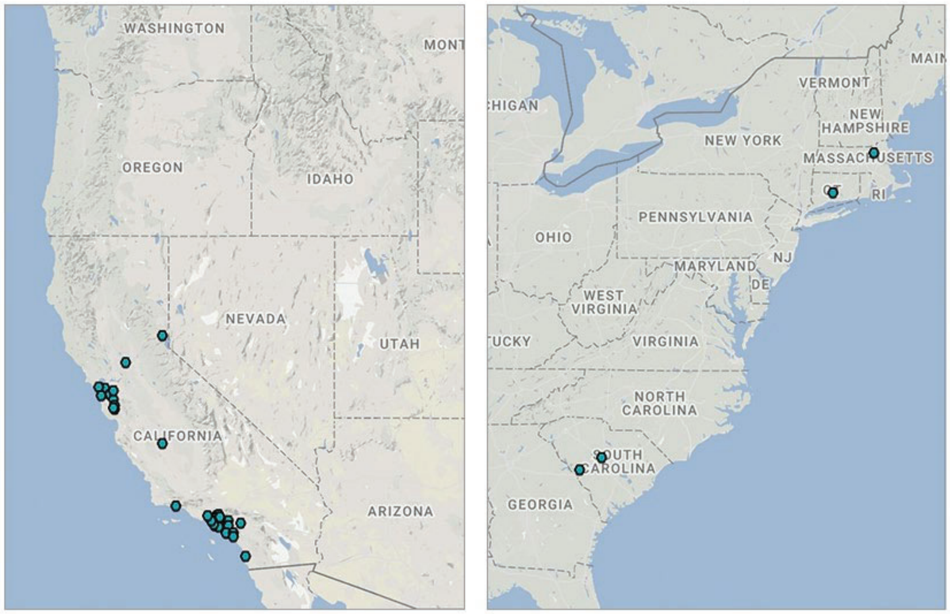
US has: 168,000 gas stations
20,000 public electric charging stations
39 public hydrogen refueling stations

Energy and Climate

Need to produce, store, and distribute H in a manner that is energy efficient and approaches carbon neutrality

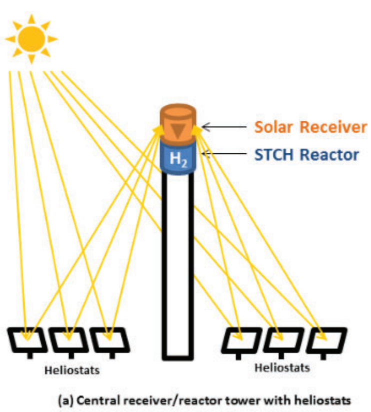
The Hydrogen Economy: Problems

PUBLICLY AVAILABLE HYDROGEN STATIONS IN THE UNITED STATES AS OF JANUARY 25, 2018

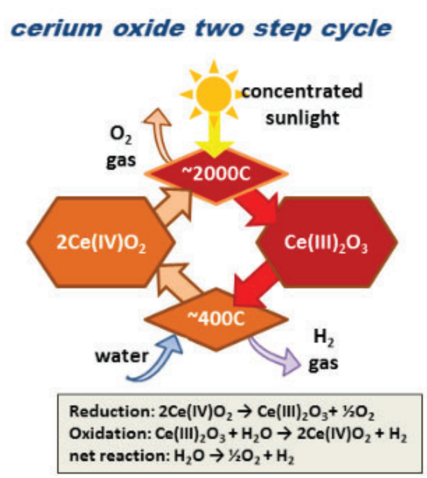


https://www.energy.gov/eere/fuelcells/fact-month-18-01-january-29-there-are-39-publicly-available-hydrogen-fueling-stations

The Hydrogen Economy: Solar thermochemical



(a) Central receiver/reactor tower with heliostats



Can read more about splitting of water at high temperature at:
http://energy.gov/eere/fuelcells/hydrogen-production-thermochemical-water-splitting

Effects of Hydrogen Economy on Atmospheric Composition

If the world moved to a hydrogen economy, what would happen to atmospheric levels of H_2?

Presently, H_2 is about 0.5 ppm and is ***long lived in the troposphere***

H_2 is not a greenhouse gas.

If future levels of atmospheric H_2 happen to rise, this may have an important effect on atmospheric composition.

What effect could occur?

Hints: what happens to H_2 in an oxidizing atmosphere?

where will this transition occur?

Effects of Hydrogen Economy on Atmospheric Composition

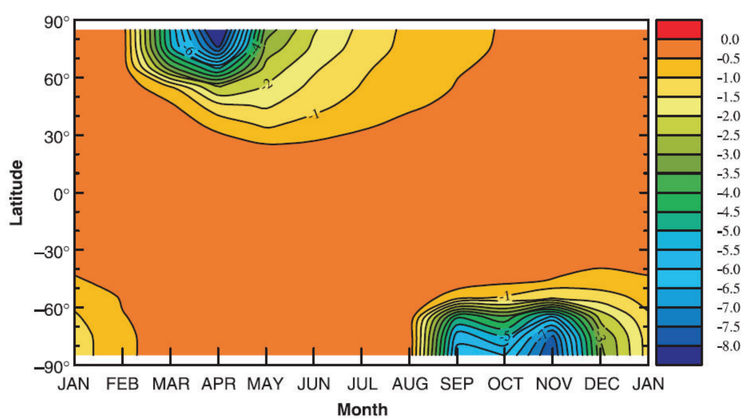


Fig. 3. Latitudinal and seasonal distribution of column ozone depletion (in %) due to an assumed fourfold increase of H_2, simulated by the Caltech/JPL 2-D model.

Increases in stratospheric H_2O will lead to chemical loss of O_3, cooling the lower stratosphere. Decreasing temp. will promote the formation of PSC's, further decreasing O_3 (Tromp *et al.*, *Science*, 2003)

Some believe this study is flawed:

- unrealistic H_2 leakage rates
- recovery of ozone layer not considered in model (mentioned by authors, though)
- questioned validity of citations used in study

http://www.sciencemag.org/cgi/reprint/300/5626/1740.pdf