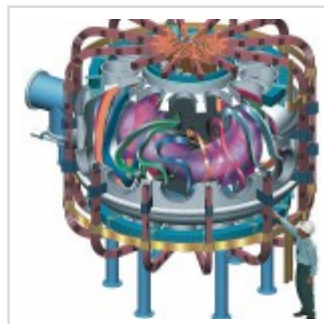
Do the Math

Using physics and estimation to assess energy, growth, options—by Tom Murphy

Link to UCSD Physics Professor Tom Murphy's homepage:
https://tmurphy.physics.ucsd.edu/

Nuclear Fusion

Posted on **2012-01-31**



Ah, fusion. Long promised, both on Do the Math and in real life, fusion is regarded as the ultimate power source—the holy grail—the "arrival" of the human species. Talk of fusion conjures visions of green fields and rainbows and bunny rabbits…and a unicorn too, I hear. But I strike too harsh a tone in my jest. Fusion is indeed a stunningly potent source of energy that falls firmly on the reality side of the science fiction divide—unlike unicorns. Indeed, fusion has been achieved (sub break-even) in the lab, and in the deadliest of bombs. On the flip side, fusion has been actively pursued as the heir-apparent of nuclear fission for over 60 years. We are still decades away from realizing the dream, causing many to wonder exactly what kind of "dream" this is.

Our so-far dashed expectations seem incompatible with our sense of progress. Someone born in 1890 would have seen horses give way to cars, airplanes take to the skies, the invention of radio, television, and computers, development of nuclear fission, and even humans walking on the Moon by the age of 79. Anyone can extrapolate a trajectory, and this trajectory intoned that fusion would arrive any day—along with colonies on Mars. Yet we can no longer buy a ticket to cross the Atlantic at supersonic speeds, and the U.S. does not have a human space launch capability any more. Even so, fusion remains "just around the corner" in many minds.

I am sympathetic to delayed predictions, and the fact that fusion has failed to deliver on the promise that it's "just around the corner" for decades does not mean that it will never arrive. I can compare this to Malthus' insight that exponential population growth was on a collision course with finite agricultural capability, or to various warnings about collapse along the way. Just because the predictions have not yet been satisfied does not mean that they will not be someday. In fact, the two divergent predictions become related. If we can manage to hold it together this century and maintain a high-tech civilization during our forced transition off of fossil fuels, it becomes far more likely that we will get to the point of employing fusion. If, on the other hand, we overshoot and collapse, we may descend too far to viably pursue fusion this century.

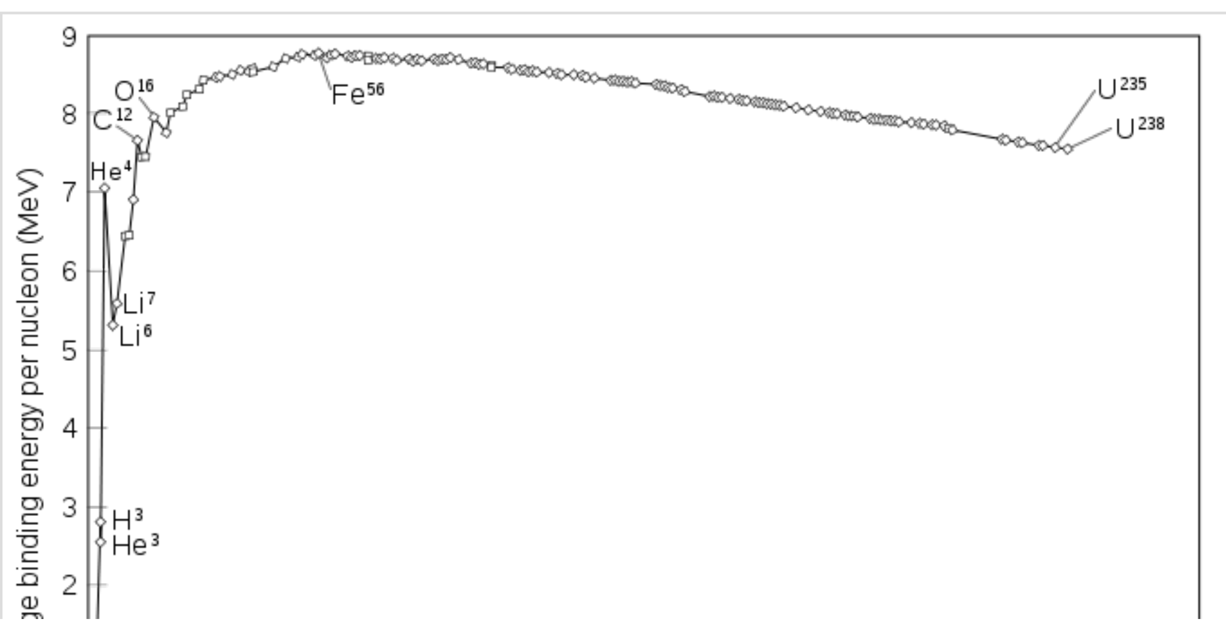
Fusion by the Numbers

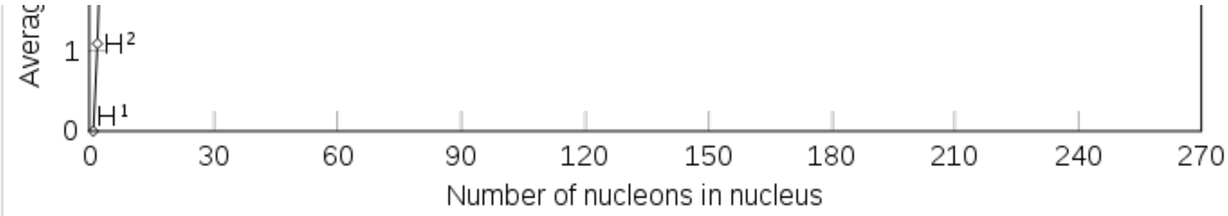
What's fusion all about, anyhow? Let's come at it with numbers. We saw in the post on nuclear fission that allowing a heavy nucleus like uranium to split into two comparable pieces resulted in the sum of the resultant masses being *less* than the initial mass. The missing mass emerges as (kinetic) energy according to $E = \Delta mc^2$, where Δm is the change in mass, and $c \approx 3\times10^8$ m/s is the speed of light. In essence, some of the nuclear *binding energy* invested the heavy nucleus—which actually *reduces* the net mass of the nucleus—has been liberated.

To understand this better, consider the fact that a single neutron has a mass of 1.08665 atomic mass units (amu: 1.66×10^{-27} kg), and a neutral hydrogen atom (one proton plus one electron, minus a trivial amount of electromagnetic binding energy: just 14 parts per billion) has a mass of 1.007825 amu. To make ^{235}U, we take 92 hydrogen atoms, add 143 neutrons, and stir. Without considering nuclear binding energy, the sum would be 236.96 amu. Yet the neutral ^{235}U atom has a mass of 235.044 amu. The "missing" 1.92 amu is the nuclear energy that would be released by building (fusing) this ensemble.

Think of it this way: when a nucleus grabs hold of a passing neutron, the deathly-strong nuclear grip slams the neutron into the nucleus, momentarily giving it kinetic energy. Initially, the nucleus jiggles like jello in an excited state, before releasing this energy (via gamma ray, or fast electron in beta decay, etc.) back to the world. In releasing this energy, its mass must decrement in deference to Einstein's most famous relation. In this way, every nucleon added (proton or neutron) contributes its direct mass to the nucleus, but then subtracts about 0.008 amu of binding energy, on average—in effect weighing in at only 0.992 amu-a-pop.

Of fundamental importance in appreciating the energy gains inherent in fusion and fission processes is the chart of **binding energy per nucleon**. The graph below plots the binding energy per nucleon in units of MeV, where 1 MeV = 1.6×10^{-13} J and is equivalent to 0.00107 amu via $E = mc^2$. Or, roughly speaking, 1 MeV is one-thousandth the mass of a single nucleon. The horizontal axis of the plot is the total number of nucleons—protons plus neutrons—in the nucleus.





Higher binding energy translates to smaller net mass, compared to the dumb sum of constituent masses. So the higher on the curve, the more energy can be given up in building that nucleus. **Iron** sits at the top (with plenty of company in neighbors like nickel). On the left side, adding pieces together constitutes a net energy gain (fusion), while on the right, one must tear nuclei apart (fission) to climb up the hill. Thus it is said that fusion yields net energy for atoms smaller than iron, and that fission yields energy for atoms heavier than iron.

But let's refine that point. If I tried to split ^{86}Kr, for instance, at 8.71 MeV/nuc into two ^{43}Ca atoms at 8.60 MeV/nuc, I have not climbed up the binding energy hill. In practice, one must have mass number above about 100 before fission into two equal pieces will release net energy. But the point is almost meaningless, given that the only three nuclei susceptible to slow-neutron fission have 233, 235, and 239 nuclei—well above the threshold for energy gain.

You may have noticed by now that if climbing the hill is the goal for energy gain, we have a lot more climb available on the left (fusion) side than on the right (fission) side. In particular, notice ^{4}He sitting pretty atop a local spike. ^{4}He is such a tightly-bound nucleus that heavy nuclei undergoing radioactive decay often eject one of these hard nuggets like a boxer spitting out a tooth, called alpha decay. ^{238}U, for instance, will typically spit out 8 "teeth" and 6 electrons (beta) in its journey to become ^{206}Pb. In any case, ^{4}He is unique among nuclei, and bears the special name of **alpha particle**.

For example, building a ^{4}He nucleus out of four protons—as our Sun is so talented at doing—we gain 28.3 MeV (7.07 MeV/nuc times four nucleons). Second-best would be starting with two deuterium (^{2}H, or D) nuclei to build ^{4}He. In this case, we go from two nuclei bound at 1.112 MeV/nuc (times two nucleons each; then times two deuterons for 4.45 MeV total) to 28.3 MeV for a total climb of 23.85 MeV. Still pretty darned good: not much penalty starting with D. Another relevant starting point is combining D with tritium (^{3}H, or T), popping out the unwanted neutron. In this case, we start at 7.88 MeV total, for a net climb of 20.4 MeV.

Compared to fission, where each split releases about 200 MeV of energy, it might appear that this fusion stuff is comparatively wimpy—seeming out of kilter when we look at the steeper slope for fusion on the binding energy plot. The discrepancy is the number of nucleons involved. Mirroring the example in the nuclear fission post, ^{235}U, at 7.6 MeV/nuc splits into ^{97}Rb and ^{137}Cs at about 8.4 MeV/nuc each. Although the slope is meager (a mere 0.8 MeV/nuc step), multiplying by the nucleon number yields a binding energy gain of $97\times8.4 + 137\times8.4 - 235\times7.6 = 180$ MeV.

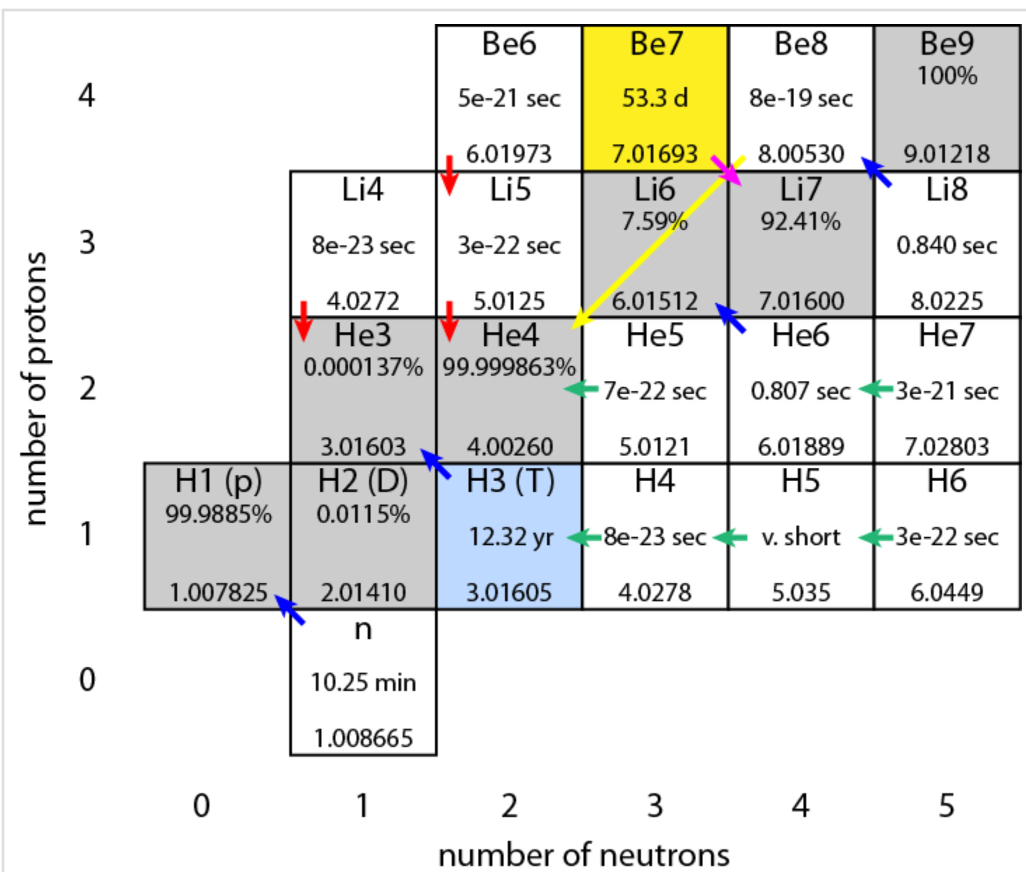
On a *per mass*, or *per nucleon* basis, fusion wins hands-down: one gram of deuterium results in 10^{12} J of energy, or 275 *million* kcal. Fission gives a comparatively small 20 million kcal per gram of ^{235}U. So fusion is over ten times as potent. Keep in mind that chemical energy like that in fossil fuels is capped around 10 kcal/g. Note the conspicuous absence of the word *million*. On the energy scale, then, nuclear in *either* form is outrageously more potent than chemical energy.

Fusion Fuel Options

The two fusion schemes for which we can produce the requisite fuel are D-D and D-T, involving deuterium and/or tritium. Deuterium comprises 0.0115% of natural hydrogen, and is thus abundant in anything containing hydrogen—e.g., water. Tritium, on the other hand, is virtually non-existent in the natural world because it is unstable and decays with a half-life of 12.3 years. But as it happens, the requirements on D-T fusion are less impossible than for D-D, so all current efforts are focused on a technique for which there is **no natural resource available.**

Okay, so the pointy-heads aren't *that* stupid. There is a way to create ^{3}H by smacking lithium (either ^{6}Li or ^{7}Li) with a neutron and knocking out a tooth—er, ^{4}He—leaving either ^{3}H or ^{4}H (in the latter case promptly dripping a neutron to become tritium).

I find it helpful to consult a chart of the nuclides when considering such shenanigans. Here is the bottom-end of the chart, which is basically the physicist's version of a periodic table.



The number of neutrons increases from left to right, and the number of protons increases vertically. Thus all helium nuclei will be on the same row, for instance. Gray shading indicates a stable nucleus (stable well beyond the age of the Universe), light blue is semi-stable, and yellow less so. Each block contains the name of the nucleus/isotope, the fractional abundance (if stable), the half life (if unstable), the mass of the neutral atom in atomic mass units, and the decay path (arrows). Decays can be beta-minus (blue, transition to upper left), beta-plus (magenta to lower right), alpha (long yellow arrow to lower left), neutron drip (green arrow to left), or proton drip (red arrow down) These are the chess-board rules. Incidentally, it is possible to reconstruct binding energies from the mass numbers in each block.

We can use the chart to follow the two reaction types:

$$D + D \rightarrow {}^{4}He$$

The D-D reaction is pretty straightforward. Marrying two nuclei together, each with one proton and one neutron, the result has two protons and two neutrons. No extra neutrons are generated in the bargain.

For D-T, we must first create the tritium from either flavor of lithium:

$${}^{6}Li + n \rightarrow {}^{4}He + T, \text{ or}$$

$${}^{7}Li + n \rightarrow {}^{4}He + {}^{4}H \rightarrow {}^{4}He + T + n$$

In either case, the "decay" chain is not the natural one, but is jarred out of the nucleus in the impact. Nominally, adding a neutron to ${}^{6}Li$ just yields the stable ${}^{7}Li$, and adding a neutron to ${}^{7}Li$ makes ${}^{8}Li$, which beta-decays in about a second to ${}^{8}Be$ and then instantly splits into two alpha particles (${}^{4}He$). But in smackdown mode, one can conjure tritium, possibly yielding an extra neutron, depending on the isotope of lithium used. Then we have:

$$D + T \rightarrow {}^{5}He \rightarrow {}^{4}He + n$$

Note the extra neutron. This is handy, since we *need* neutrons to convert lithium to tritium. But note also that using ${}^{7}Li$ generates two neutrons per D-T reaction, while ${}^{6}Li$ only generates the one. Neutrons will be lost to other parasitic causes, so it's handy to have extras around. On the other hand, neutron capture by the containment vessel makes it radioactive and will also damage its structural integrity, so we want to be careful about how many extra neutrons there are. Unfortunately, natural lithium is 92.4% ${}^{7}Li$, so tuning the ${}^{6}Li/{}^{7}Li$ mix to give the critical number of neutrons implies some sort of lithium enrichment on the front-end.

We aren't exactly swimming in lithium, so did we make a bad trade in picking this horse? Each lithium atom converted to tritium will end up yielding about 20 MeV of thermal energy, so that we need 1.3×10^{32} Li atoms annually to produce our world consumption of 4×10^{20} J. That's about 1500 metric tons of lithium annually, or about 5% of current lithium production. Proven world reserves give us 9000 years, and estimated resources give us 22,000, according to the U.S.G.S. Mineral Commodities Summaries.

For fun, let's look at how much water each person needs to supply each year to provide enough deuterium. The average American demands 10,000 W of continuous power, or 3×10^{11} J of energy per year. At 20 MeV per whack, each person needs 10^{23} reactions per year. In the D-D case (requiring twice the deuterium as D-T), this means we need 2×10^{23} deuterium atoms—coming from 2×10^{27} hydrogen atoms at a fractional abundance of 0.01%. Sounds like a lot, but it's 3,300 moles—amounting to 60 kg of ordinary water. 60 liters is similar to the amount of water used in a typical American shower. It's hard to emphasize enough the extent to which deuterium availability poses **no** problem: there is enough deuterium in the ocean to provide our current energy demand for billions of years.

I think now you're seeing a big part of the reason why fusion makes our eyes sparkle. Even given lithium limitations, I place D-D and D-T fusion in the "abundant" box.

What Makes Fusion Hard

A simple obstacle stands between us and fusion. It's called the **Coulomb barrier**. Protons hate to get near each other, on account of their mutual positive charge and concomitant electrostatic repulsion. And they must get *very* close—about 10^{-15} m—before the strong nuclear force overpowers Coulomb's vote. Even on a perfect collision course, two protons would have to have a closing velocity of 20 million meters per second (7% the speed of light) to get within 10^{-15} m of each other, corresponding to a temperature around 5 billion degrees! Even if the velocity is sufficient, the slightest misalignment will cause the repulsive duo to veer off course, not even flirting with contact. Quantum tunneling can take a bit of the edge off, requiring maybe a factor of two less energy/closeness, but all the same, it's frickin' *hard* to get protons together.

Yet our Sun manages to do it, at a mere 16 million degrees in its core. How does it manage to make a profit? Volume. The protons in the Sun are racing around at a variety of velocities according to the temperature. While the typical velocity is far too small to defeat the Coulomb barrier, *some* speed demons on the tail of the velocity distribution curve *do* have the requisite energy. And there are enough of them in the vast volume of the Sun's core to occasionally hit head on and latch together. One of the protons must promptly beta-plus decay into a neutron and presto-mundo, we have a deuteron! Deuterons can then collide to make helium (other paths to helium are also followed). A quick and crude calculation suggests that we need about 10^{38} "sticky" collisions per second to keep the Sun going, while within the core we get about 10^{64} bumps/interactions per second, implying only one in 10^{26} collisions needs to be a successful fusion event.

Deuterons have an easier time bumping into each other than do lone protons, mainly because their physical size is larger. In fact, a deuteron's relatively weak binding makes them even puffier than the more tightly bound tritium nucleus (go tritons!). At a given temperature, deterons will move more slowly than protons, and tritons more slowly than deuterons. All flavors contain a single proton—and so exert the same repulsive force on each other—but the increased inertia from extra neutrons *exactly* counters the slower speed, so that each has the same likelihood of trucking through the Coulomb barrier. Then we're left with size. Deuterons are bigger than tritons, so D-D bumps will be more common than D-T bumps.

But there's a catch. As soon as D and T touch, they stick together. Conversely, when D touches D, a photon (light) must be emitted in order for them to stick, which doesn't usually happen. It is therefore said that D-T has a greater **cross section** for fusion than D-D. Estimates for the critical temperature required to achieve fusion come in at 400 million Kelvin for D-D fusion, and 45 million K for the D-T variety. But these temperature thresholds depend on the density of the plasma involved, so should not be taken as hard-and-fast. Still, we need our fusion reactors to be hotter than the center of the Sun because we do not have the luxury of volume and density that the solar core enjoys. Does this fact give you pause?

Confinement

Overcoming the Coulomb barrier requires enormous kinetic energies of the particles, translating into enormous temperatures—well beyond any container's ability to hold. No material resists melting above a mere 5000 K. 50 million degrees is not even funny.

At these temperatures/energies, electrons are not able to hold onto their rides, so we get a completely ionized plasma zipping this way and that. At 100 million degrees, for instance, deuterium nuclei have an *average* velocity of about one million meters per second. Left alone, the plasma would explode to the size of a football field in 0.1 milliseconds. Recall that we can't get fusion to happen without these ridiculous velocities, so we're stuck having to herd these hyper-fast particles without the help of Ritalin. It has been found that plasmas at the requisite temperature suffer instabilities from turbulence that we have been unable to tame. It becomes like a game of whack-a-mole, according to my colleague George Fuller: clamp down on one pesky behavior, and another one pops up.

The main scheme being pursued in the world today is magnetic confinement in a plasma containment vessel called a **tokamak**. Charged particles follow curved arcs in a magnetic field, so that strong fields confine the particle paths to tight curls. The radius of the path is proportional to the particle velocity, which spans a large range of values in a thermal plasma. One must produce a magnetic field strong enough to contain the fast tail of the velocity distribution, else the plasma has a leak at the high-velocity end and depletes itself rather quickly. Every particle collision resets velocities, so a leaking fast tail is constantly re-populated. At a field strength of 10 Tesla (near the upper end achievable), the mean-velocity deuteron at 50 million K has a 2 mm path radius. ITER, the International Thermonuclear Experimental Reactor, is a tokamak design being built in France under international support. The current timeline calls for achievement of a 480 second burst of 500 MW power in the year 2026, although there is no plan to capture the generated heat for the production of electricity (note the "Experimental" in the project name).

The other primary scheme gives up on trying to confine the plasma in some steady state, instead following a path similar to the philosophy behind fusion bombs: force an implosion of the fuel to extraordinarily high densities and temperatures, and let the cursed thing *explode*. This scheme goes under the name **inertial confinement**, since one relies on the inertia of the implosion to bring nuclei close together. In the U.S., the National Ignition Facility (NIF) focuses 192 high-power laser beams onto a small pellet to initiate a symmetric crunch. The idea for a power plant would be that pellets are loaded one after the other, detonated, and the effluent heat collected to make steam. As far as I know, there is no current plan to harness any heat generated at the NIF—being experimental, like ITER.

Flies in the Ointment

The ITER experiment, if it adheres to its schedule and projected budget, will cost something like $20 billion to build and produce pops of unharnessed thermal power by 2026. I should note that most large experimental projects have slipping schedules, and it would be a fantastic irony if a *fusion* experiment violated this trend! In any case, we could imagine *another* several decades before commercial fusion tentatively steps onto the scene, putting us at mid-century. The projects will undoubtedly be very expensive, require intimate involvement of the highest level of expertise, and will likely not catch on in a big way until investors see a track record of profitability—if that ever comes to pass. So that's fly number one: we're looking at very long term.

Fly number two is that D-T fusion necessarily involves neutrons, which do not respond to magnetic or electrostatic confinement and therefore hurtle off to the walls of the containment vessel. In doing so, they knock into the atoms comprising the vessel, dislocating them within the lattice and causing structural damage. The integrity of the containment vessel will degrade like plastic in sunlight. The neutron flux from a D-T reactor is substantially higher than for a conventional fission reactor.

Fly number three is also related to neutrons: after doing their damage in the containment walls, the neutrons will marry a nice, plump nucleus and settle down. But the marriage is often radioactive, so that the container becomes radioactively "hot." In fission, we get two radioactive daughters for each 200 MeV produced. For D-T fusion, if we are able to utilize most of the neutrons for conversion of lithium into tritium (and use enriched ^{6}Li), we might be able to lose less than 0.2 neutrons per 20 MeV reaction (pure, uninformed guess on my part), which comes out to the same number of radioactive products per unit of energy. But at least materials choices for the container walls offers *some* control over the menagerie of radioactive products —unlike the randomness of fission. All told, the radioactive toll from a D-T fusion reactor may be comparable to that of a fission reactor, though with shorter half-life.

Then there is the extremely finicky nature of achieving fusion. Getting something to work in the lab is much different from having it operate reliably for years on end. Any significant departure from optimal conditions will see the fusion yield diminish. ITER aims for a thermal output ten times that of the input energy. In an eventual self-running mode, siphoning 10% of the output power in electrical form requires pulling out about 30% of the thermal power to run the heat-engine generator. This makes for a 3:1 net energy gain, which could quickly transition to a net energy *drain* if things are not maintained in tip-top condition through the years.

Another possible fly is that the superconducting magnets used to generate the extreme magnetic fields for confinement could lose cryogenic cooling, "go normal," and explode. An explosion that damaged the tokamak could result in a radioactive release to the environment. Even though the probability is small, we routinely go to great expense to mitigate low-probability catastrophic events, and so a massive, expensive containment building would likely be required.

Each fly translates into cost. In the end, it is unclear whether a fusion plant—even after the physics is tamed—would be economically viable, and attractive enough for investors to take on endeavors of this scale, complexity, and risk.

A Solar Perspective

A few days after watching a television show on fusion, I had an epiphany while walking to the bus. Why are we enamored with fusion? Because the fuel supply is virtually unlimited; the energetics represent the epitome of what physics has to offer; the primary emission is useful helium; the radioactive waste is shorter-lived than for fission (damning with faint praise?); fusion plants could presumably be sited anywhere; surely it's one step closer to warp drive. But then I realized that the Sun (being its own fusion reactor) also provides billions of years of energy, well in excess of our current demand. And my refrigerator and other appliances *already* are run by this source in a modest PV/battery installation at my home. I personally can't ignore the asymmetry between the promise of future technology and technology that sits on my roof! If we removed the storage barrier for solar, would fusion still be viewed as the holy grail?

This prompts two questions. First, what is the relative funding expenditure for fusion research and for battery/storage research? Second, what are the appeals offered by fusion that could leave solar in the shade?

A cursory investigation reveals that the U.S. spends approximately $450M per year on the NIF, and chips in about $32M per year to ITER (though expected to escalate to about $350M/year during the construction phase from 2014–2016). Meanwhile, the U.S. Department of Energy Hub for Batteries and Energy Storage plans to operate at $24M per year, with a similar expenditure in Fuels from Sunlight. It's about as I thought.

I can only muse about the appeals of fusion over solar. I think area is one: fusion plants could be comparatively compact. I think location-dependence is another. Most people don't realize that the worst site in the continental U.S. (Olympic peninsula) delivers fully half as much annual solar energy as the Mojave desert. Given a good storage solution, solar becomes useful almost anywhere. I think in part, we are driven by the sense of progress/conquest. Cracking the fusion problem matches our precious narrative. But I am left wondering if these reasons are compelling enough to keep us reaching for the gold that may continue to disappoint when we have other options whose viability may be closer at hand.

Naturally, it's not an all-or-nothing proposition. I support research whatever the direction. But I want to make sure we aren't falling victim to irrational hangups and expectations. We at least need to evaluate this notion: to know ourselves. One may object that I've simply replaced one holy grail (fusion) for another (storage). Which one is voted more likely to succeed?

Fusion Prospects

No one can truly say whether we will achieve fusion in a way that is commercially practical. If teams of PhDs have spent over 60 years wailing on the problem while spending tens of billions of dollars, I think it's safe to use our fusion quest as the *definition* of **hard**. It's a much larger challenge than sending men to the Moon. We have no historical precedent for an arduous technological problem on this scale that ultimately succeeded to become a ho-hum commercial reality. But for that matter, I don't think we have any precedent for something on this scale that has failed. In short, we're out of our depths and can't be cocky about predictions in either direction.

I am hopeful that fusion can one day become a practical reality. I certainly understand it to be feasible in principle. My misgivings mainly lie in the extreme complexity of the challenge. It may take a year of intense study to become an expert on a coal-fired plant, to the point of being a go-to resource for troubleshooting and maintenance. A nuclear fission plant may take five years to master—it took about that long to get the first break-even performance after discovery of fission. But after a century of development (by the time any commercial fusion reactor sees the light of day), how long must one study plasma physics in order to have a firm handle on operation of a fusion plant? The NIF uses two lasers occupying a floorspace the size of a Wal-mart store (no exaggeration). How many PhDs will it take to keep a state-of-the-art laser of this magnitude operating? I know that the 2 W laser I use in my research causes *this* PhD enough trouble!

I became interested in energy because I sensed that we are approaching a phase change in society as the age of fossil fuels begins to ebb. *So much* of what we have become can be attributed to cheap and abundant surplus energy. Our energy future is highly uncertain. Commercial fusion may come along decades down the road—mid-century at the earliest—but even then it is yet another source of heat that we can use to make electricity. Another step (mobile storage) must accompany fusion development to replace petroleum functions, and even then at significant disadvantage in energy density using current technologies. So yeah—I hope it helps us out one day. But I'm not sure we can wait that long.

I thank Bob Hirsch for his review and comments.

This entry was posted in **Energy**, **Energy Scale** and tagged **fusion**, **nuclear**, **technofix** by **tmurphy**. Bookmark the **permalink [https://dothemath.ucsd.edu/2012/01/nuclear-fusion/]** .

64 THOUGHTS ON "NUCLEAR FUSION"

CyclemotorEngineer
on **2012-01-31 at 07:50** said:

Tom,

Just as there are many fission reactor designs, there are several hybrid proposals which are technically easier than the straight DT fusion you describe.

Fusion induced fission:
http://www.utexas.edu/news/2009/01/27/nuclear_hybrid/

Fission induced (muon catalyzed) fusion:

http://legacyweb.triumf.ca/welcome/h-fusion.html

Thorium cycle fission / DT hybrids:
http://www.thoriumenergyalliance.com/downloads/Fusion_Fission_Hybrid_journal_Ragheb.pdf

Craig
on **2012-01-31 at 08:28** said:

Excellent job, Tom. My one pedantic comment is that ITER is no longer an acronym as you have in your article (yet the name should still be capitalized for some reason).

PersainCAT
on **2012-01-31 at 08:49** said:

Glad u finally got to Fusion, and while i dont disagree with anything you said i would like to point out that this is only a discussion of "hot" nuclear fusion. That is i won't be naive enough to claim cold fusion (LENR as some like to be called) is possible in the sense that the coulomb barrier is broken at low energies, but there are theories and experiment claiming excess heat generation.

In evidence i point to George Miley at UIUC and his research using metallic hydride interactions. (power point on the subject below)
https://netfiles.uiuc.edu/mragheb/www/NPRE%20498ES%20Energy%20Storage%20Systems/Nuclear%20Battery%20using%20Clusters%20in%20Nanomaterials.pptx

And such theories as weak force interactions (Widom-Larsen)
http://newenergytimes.com/v2/sr/WL/WLTheory.shtml
to explain such generations.

I only point these out as such experiments as ITER/NIF have no real likelihood to produce any usable form of energy generation for say 75 years at BEST, it is worth bringing up other sources of fusion in the context that even the best minds WANT there to be something sooner.

tmurphy
on **2012-01-31 at 09:01** said:

Yes, we have to watch out that our sense of urgency, disappointment, and extreme need will drive many irrational fantasies about the magic silver bullet technofix, so far overlooked, shunned, or otherwise conspired against.

Let me warn readers that I will be **rejecting comments** that have to do with cold fusion or other dubious claims. I don't want to run a crackpot gallery. If you feel this is unfair, and I am just playing my role as a mainstream conspirator, then fine—I'm not offended. Surely there are forums to discuss such schemes, but the Math is not there, so I'll steer clear.

Uzza
on **2012-02-02 at 15:01** said:

While I understand the reluctance to look at cold fusion, calling it dubious is wrong.
Cold Fusion has been proven to work in the form of muon-catalyzed fusion, where the heavy muon brings the nuclei together close enough to break the coulomb barrier, causing fusion.

As an energy source it's still very dubious though. Muon-catalyzed fusion for example will never achieve close to break-even as it can only catalyze at most 200 or so fusion events. The current way of creating muons require a lot of energy, meaning that each muon would need to catalyze way more fusion events to get to break-even.

So to reiterate, cold fusion is real. Producing net energy from it is not, at least with current technology.

Falstaff
on **2012-02-04 at 19:14** said:

Todd Rider came out of fusion retirement for a moment to give this talk on the various (hot) fusion alternatives and why they are so difficult (or impossible): "Is There a Better Route to Fusion?". Including the various non-standard approaches – muon catalyzed, spin polarized, etc, it is the best short description I've seen.
http://www.longwood.edu/assets/chemphys/FusionRoute.pdf

tmurphy
on **2012-02-04 at 21:45** said:

I took a quick look at it and thought it was very well done. It would require some serious time investment for me to understand all of the issues/factors. But I am impressed with the breadth of options considered: far outside of the standard big-money approaches, yet still no knights to the rescue.

Dennis
on **2012-01-31 at 08:55** said:

Although I'm not pinning my hopes on fusion, I'll mention a few other projects that could be interesting.

General Fusion (in Canada, with investment by Jeff Bezos), is a variant of magnetized target fusion. It uses molten lead, spins it so a channel opens in the middle, shoots a plasma torus from each end into the middle and then compresses the plasma with an acoustic shock wave, driven by 200 steam pistons around the outside of the device.

Helion Energy has another device involving collision of two plasma toroids. I think this is also a MTF variant, not sure. They're at a middle ground between inertial fusion (very high density) and tokamak (low density) and claim that this makes things easier. Last I checked, they'd built a 1/3 scale device but needed more funding to scale up.

Tri-Alpha is very secretive, but seems to have a device similar to Helion's. Last I checked they had $50 million from venture capitalists, including a Microsoft billionaire.

The NIF has the LIFE project, which is a fusion-fission hybrid that they hope will be practical for power plants.

Bussard's Polywell device uses inertial electrostatic confinement, similar to a fusor but with a different design that Bussard claimed could generate net power. The Navy is funding development, currently for a small device at $8 million. The little information they've released suggests they're doing well so far.

Finally, my favorite, focus fusion. It uses a small plasma focus device, taking advantage of plasma instability to pinch it to high density. They got a paper published last year saying they'd reached the billion-degree temperature required for boron fusion, which doesn't produce neutrons. Instead, you just get a jet of alpha particles, which you can pass through a coil to generate power. The fun thing about these guys is they're very transparent about their research, releasing a report about once a month. If things go well they could prove scientific feasibility (or the opposite) later this year, but they're a small team with a tiny budget and they're prone to delays while they get the hardware working properly.

Several of the other projects think they could either achieve net power, or prove they can't, within the next five years or so.

Joseph Davidson
on **2012-01-31 at 12:36** said:

There is another approach to fusion, also called focus fusion above, stable plasma structures also known as plasma vortices. Ball lightning is an example.
The Trisops project generated two field reversed structures, which guided by a magnetic field collided and were then compressed to a high density. See http://en.wikipedia.org/wiki/Trisops for a description and references . The project was defunded for a variety of reasons including clashing personalities and not-invented-here syndrome. [Full disclosure, I wrote the Wikipedia article, and am a co-author on the paper.]

Paul Koloc is generating ball lightning is his garage lab. I have seen it. He hopes to compress it with air shock waves. See http://www.neoteric-research.org/ .

General Fusion (http://www.generalfusion.com/) is doing something similar.

Compared to the billions poured into Tokamaks, these projects have minuscule funding.

As a side note: I got my PhD in Space Physics in 1972, then taught a non-technical course, "The Physics of Energy" which gave me the same interests as Tom Murphy has. I work in vain to remove the gauze from the dreamy eyes of my green friends who think that we can solve all of our problems with renewables.

Joseph Davidson
on **2012-02-02 at 12:07** said:

Two quick additions to my comment above.

The Physical Review Letters paper describing Trisops is available (behind a paywall) at http://prl.aps.org/abstract/PRL/v41/i3/p166_1.

It is titled “D. R. Wells, J. Davidson, L. G. Phadke, J. G. Hirschberg, P. E. Ziajka, and J. Tunstall, High-temperature, high-density plasma production by vortex-ring compression , Phys. Rev. Lett. 41, 166 (1978).”

Second item. When I was working at the Office of Fusion Energy, Department of Energy (US) in the mid 90s. ITER was nicknamed “Money Eater”.

Ivy Matt
on **2012-02-01 at 10:47** said:

Helion and Tri-Alpha both use FRC (field-reversed configuration) approaches.

NIF’s LIFE project at one point was designed as a fusion-fission hybrid, but the most recent design is of a pure fusion plant. NIF is supposed to achieve net gain this year, and they currently have plans for a demonstration reactor by the mid-2020s and commercial plants by 2035.

Some of the alternative approaches have somewhat longer timelines for net gain, but could probably be commercialized sooner.

I’m not sure why people use ITER’s schedule as the best-case scenario for the development of commercial fusion power when the truth is that at this point we just don’t know.

Matt
on **2012-01-31 at 09:10** said:

The meta-joke in the repeated promises and delays of this post's publication was particularly clever.

Hawkeye
on **2012-01-31 at 09:42** said:

[moderator comment: longer than normally permitted, but thoughtful]

Thanks for this in-depth and balanced assessment of Fusion power.

About six months ago I went to visit the UK's Culham Centre for Fusion Energy research, after hearing some very upbeat assessments of fusion energy as our saviour.

They gave an extensive public tour of the MAST and JET laboratories which was fascinating. On the one hand I was over awed by the complexity and sheer technological advancement of the facilities. I was also impressed by the knowledge, integrity and passion of the scientists working on the project.

But, this enthusiasm was tempered by a multitude of practical and economic challenges, many of which seemed insurmountable:

Firstly, one should not underestimate how much energy is needed to jump start the reactors. I believe the figure for these lab reactors was 1.2 GW for a period of a couple of minutes, to heat up the plasma. This is no small amount of kick-start energy to put in; for each and every reaction session (plus the ongoing energy required to contain the plasma in a magnetic field).

Next, is the technology to contain / control the plasma. The JET reactor has undergone something like 80,000 ignitions since installation. Each ignition requires start-up power, running power and ultimately lasts less than one minute. The instability / unpredictability of the plasma is not to be underestimated. After so many sessions, there has been some learning, but the reality is that controlling these things is like herding cats. Putting man on the moon was really just a major engineering feat (requiring lots of cheap fossil fuels), with a bit of maths and physics to work out trajectories etc. Controlling a plasma is a whole different ball game (remember the Sun doesn't need to worry about this, as it just uses it's own gravity to things in place!).

Finally, I posed a question to one of the scientists about the projected run time to down time ratio anticipated for a commercial reactor. He shrugged his shoulders; "We just don't know, yet". It was clear from the experimental sessions, that run time was short (less than a minute), and down time was long (anything from a few hours to days, weeks or months). A collapsed plasma can seriously damage the inside of the Torus. Repairs require a shut down and robotic arms to conduct repairs. Even the most optimistic estimate would place these reactors as having a 1 in 10 run time ratio, but it could be as poor as 1 in a 1000.

Compared to existing power plants, there is a heck of a lot of work to do. I don't believe they should give up, and I think that we as a society should be investing more in the research and development.

But I don't expect it to deliver a magic bullet in our lifetimes either.

Sometimes overwhelming complexity is mother nature's way of saying you're going down the wrong path.

DC
on **2012-01-31 at 09:43** said:

[moderator comment: another longer-than ideal posting; no time to shorten—but please keep them short, folks]

I hear Fusion advocates talk about fusion, in exactly the same manner they used to\still do about fission.

Fusion will be ‘safe’. Based on what exactly? The extensive number of fusion plants humans have built and operated?
Fusion will be ‘clean’ Wrong. It will just be less dirty, and even that is just an assertion, as again, we zero operational experience to back this claim up. Even if fusion is clean, a waste management problem thats only a ‘few’ thousand years, is still beyond our ability to manage.
Fusion will be ‘cheap’. Actually in fairness, you dont really hear this one, in fact, proponents dont seem to want to mention it at all. Why is that? Fission despite six decades is becomeing more expensive and complex, not less! I read a comment recently from an NIF researcher when asked, he estimated that a working fusion plant could be up to 10 times more expensive than fission. Think about that a moment…

Some other questions I have. Fusion plants will be compact? Sited anywhere? Really? Again I ask, based on what experience. Fission plants are hugely complex themselves. A working fusion station would have to be vastly larger and more complex than a fission one. So what would the physical footprint of a fusion station really be? No one knows. And what about water requirements. All our current power schemes require vast anounts of water.Is fusion exempt from this somehow? What would a fusion plant require, and will such water even be available?

What would the rated power output of a ‘typical’ fusion plant be expected to be? 500MW, 1GW? 50GW? I have never seen this question addressed either.

I have read a nuclear fission plant requires (about) 3 years of continuous operaton just to get back the energy that went into building it. If a fusion station is say, to be generous 3 times as complex as a fission plant, does that imply nearly a decade of operation before it starts producing net energy? Even if my numbers are wrong, just what would be the emdodied energy in such a station?

Do we have enough of the exotic rare-earth metals that fusion stations will surely require? We get alll panicky we wont have enough to go around for all the I-junks, hybrid wastes of time, wind turbines and other useful and no so useful tech toys we want to build.

Lastly, I often wonder just what energy crisis fusion is supposed to fix. We dont really have an electricity problem, but a liquid fossil-fuel problem. And since nuclear fission never caused coal or gas power to be phased out, I am very skeptical of the claim fusion will supplant fission, much less coal or gas. How could it at 10 times the cost? Even worse when you consider how heavily subsidized fission is and we cant even really afford that!

Geoffrey Irving
on **2012-01-31 at 09:46** said:

I really like your comparison to solar. It can even be strengthened: even without batteries, solar energy already works for a large chunk of the energy supply, so we also have to compare fusion research money with non-research solar money such as subsidies (Caveat: I work for a company that does solar energy research among other things, so I like research funds too).

Also, I felt compelled to provide a pro-solar comment as an antidote to all the other "fusion is right around the corner due to this other project" comments.

Joel
on **2012-01-31 at 10:59** said:

I think the allure of Fusion is the same that causes some people to wait for the perfect job, perfect house, or the perfect mate. Sure there are other jobs, houses, and mates, but some people are paralyzed by wanting the very best while ignoring the perfectly lovely girl next door (solar)

For the record I married the down to earth girl with the low upkeep, so its no surprise I think solar will win long before Fusion.

> **Mark_BC**

on **2012-01-31 at 12:43** said:

Well put. Solar does, and has for several billion years, powered (almost) all life on Earth, including all our fossil fuel sources, so in embracing solar power would we just be returning to what we should have emulated all along — do as nature does? Why should our "economies" operate any differently than "ecosystems"? Can economies be separated from ecosystems? I guess people prefer dazzling complex techno-solutions over tried and true ways of getting things done that require a bit of hard work, restraint and patience.

Our reluctance to fully embrace solar as the best energy path forward (it seems to be at the bottom of the list of priorities for the current PTB) provides as much insight into human psychology as it does to physics.

Steve Pawlak
on **2012-01-31 at 15:42** said:

One reason I can think of is that Government and politicians like big science projects. That is why NIF gets like 9x times the funding than all the solar (according to the article). Why we had Apollo, Shuttle, Space Station. Why we are looking at an even bigger rocket to carry a massive load all at once, instead of building a ship out of smaller parts, assembling in space, and "fly" it out of LEO.

Pragmatism has lost its way in society.

Andy
on **2012-02-07 at 13:05** said:

The other reason NIF gets a lot of funding is that part of its mission is to advance the US weapons program.

Charles Pye
on **2012-01-31 at 12:03** said:

“Naturally, it’s not an all-or-nothing proposition. I support research whatever the direction. But I want to make sure we aren’t falling victim to irrational hangups and expectations. We at least need to evaluate this notion: to know ourselves. One may object that I’ve simply replaced one holy grail (fusion) for another (storage). Which one is voted more likely to succeed?”
Does it matter? Let’s just keep researching both, as well as anything else that seems potentially useful. But in the mean time, climate change and peak oil are both pressing problems that need to be dealt with immediately, so we need to do as much as possible with the technology that’s available right now. Which means finding ways to cut down on our energy usage.

Greg vP
on **2012-01-31 at 12:06** said:

A great post!

The real cost of fusion is not so much the money, but the waste of very smart and creative people, who could be solving problems with quicker and better pay-back both in terms of the science and in material welfare. The global physics community should park fusion, and come back to it in the 22nd century.

Andrew
on **2012-01-31 at 12:30** said:

Thank you for a great article with some math that is not easy to find. 7% speed of light for a head on collision. Gets one thinking.

But I really don’t understand the solar suggestions. It is kind of like saying we should invest in bicycles just when talk of the combustion engine might replace horses. Sure, bikes are easier and get the job done, sans industrial revolution.

I think Dennis above posted a great list of initiatives you did not highlight.

> Damien RS
> on **2012-02-02 at 20:14** said:
>
> Except that these “combustion engines” have been talked about for 60 years and still aren’t here and clearly aren’t coming any time soon either. It’s more like investing in bicycles or cars or mopeds or just about anything, instead of waiting for flying cars.

Tom Schülke
on **2012-01-31 at 13:32** said:

Many thanks to this one. As an ordinary Architekt, its rather hard to follow your Blog, but its worth it. (long time ago i wanted to study physik). and also your path to make one think on its own is much better than studying suspiciious studies.

Well two questions for me are left..

first, how long would the radioactive output be problematic. You mentiioned, it would be less long as fission, but for arguing with non experts this is a very important thing, as well, as the question where to storige these radioactive materials, if we would reach to use it globaly for energyrequirements.

the secound question is, how long with usual exponential growth the suply of tritium would last, if growth woud follow the usual path of about 2.5% more energyconsumtion per year.

For deutherium i tried on my own as a non physicist the calcultion and came to the conclusion , whithout growth, deutherium would fire our energy for abour 128 billion yeras, but with continous growth of about 2.8% roughly about 1200 years, which isnt that much aboundant, as one would think.

also i remember your post about heating the globe untill paper burns and so on, and think we would reach this point maybe earlier.

So an end of exponential growth in consumption still would be nessesair..

no warp so far…. 🙁 .

What i wished was a german translation, for it would be easier for me in Hamburg. But never the less. many many thaks for this very good blog.

> **tmurphy**
> on **2012-01-31 at 13:48** said:
>
> I would need to dig into the details of the waste products to a much greater degree before I could speak with any confidence on the details. The Wikipedia page on Fusion Power has some good info under the subheading Waste Management. Also, see http://www.sciencedirect.com/science/article/pii/0920379691900855 for a study (behind a pay-wall, though).
>
> As for tritium (lithium) resources in a growth scenario, here's a simple approach. Current world estimated resources put us at 22,000 years. Let's say it's 50,000 if we found all the viable lithium. At 2.3% per year, we increase our activity a factor of ten every 100 years. So in 100 year, we'd be looking at 5000 years of supply. But 100 year later, it's 500 years left. In another 100 years, it looks like 50. We would therefore not make it much beyond 350 years in a 2.3% growth scenario. By then, the Earth's surface would be about hot enough to boil water.

Petridishling
on **2012-01-31 at 13:53** said:

A very Well reasoned article and conclusion, thanks. I had thought that the time and money spent on tokomat fusion would be better spent on thorium fission but as you note, solar & storage (& conservation) could be more effective use of effort.

Did you know that the late Dr Robert Busssard, who used to help run the US tokomat program, claimed that the program was actually a hoax concocted by himself, Dr Alvin Trivelpiece and Dr Robert Hirsch (of "Peaking of world oil production: impacts, mitigation, & risk management" fame) ?
He said they decided that tokomat fusion was a technological dead end, but continued with it in order to get funding to explore other fusion ideas.

See middle of page 2:
http://www.askmar.com/Robert%20Bussard/2007-10%20Robert%20Bussard%20Interview.pdf

> **tmurphy**
> on **2012-01-31 at 15:51** said:
>
> I think this as far too strongly worded, calling it a hoax. I know that Hirsch et al. were initially enthusiastic about the promise of tokamaks, but that Hirsch later concluded them to be technically too difficult. Some fans of tokamaks were born, and I think you can credit the continued flow of funding to the fans, rather than to people who had lost faith (and moved on to other things, in the case of Hirsch).

Bill
on **2012-01-31 at 13:59** said:

The hubris of man: attempting to create a tiny artificial sun in order to boil an egg.

Damien RS
on **2012-01-31 at 15:11** said:

Wow, 10x as much research funding to fusion as to solar/batteries? Not surprising, but depressing given the track records. Though solar/batteries are at least close enough to practical to get private funding too; everyone would love better batteries.

Error in your first graph, I think: H-3 is placed above He-3, but H-3 decays to He-3.

One amusing thing: via fusors and such, fusion reactions to be rather easy to achieve, actually; tabletop electronics can do it. It's fusion that comes even close to generating energy that's very very hard. But if you want to just make fusion — and neutrons — happen, then no problem!

I still suspect that blowing up fusion bombs underground and tapping the heat would be more practical than conventional fusion approaches.

The Wikipedia pages on Nuclear fusion and Fusion power seem good in their way, and are also fairly depressing, especially if you want to be a fan of some of the more exotic reactions. Even higher temperatures and lower power densities and Bremsstrahlung probably sabotaging it all…

> **tmurphy**
> on **2012-01-31 at 16:03** said:
>
> The graph is correct. Helium-3 has a binding energy per nucleon of 2.573 MeV, while tritium has 2.827 MeV/nuc. Intuitively, one would expect helium-3 to decay into tritium, releasing energy. The reason why not is that the neutron is 1.29 MeV heavier than the proton, so that the effective

mass of helium-3 is ever-so-slightly lower than tritium (3.01603 vs. 3.01605). Other factors contribute to the math, but the net effect is that helium-3 is favored, even though the binding energy per nucleon is slightly less.

Mark
on **2012-01-31 at 17:54** said:

I think aneutronic fusion reactor (helium-3, p-B11) is the most revolutionary path to harness the fusion energy. Because most of the energy produced by aneutronic fusion is in the form of charged particles instead of neutrons, which can be converted directly into electricity by various methods: inductive, based on changes in magnetic fields; or electrostatic, based on making charged particles work against an electric field. Additionally, by using a more efficient thermoelectric converter it is possible to recover most of the heat energy into electricity assuring definitively a net gain. http://www.crossfirefusion.com/nuclear-fusion-reactor/overview.html

Brian
on **2012-01-31 at 19:03** said:

Just a comment on the D+D reaction. It has three branches. One of the branches produces a neutron. Two particles must be created in a fusion reaction to conserve momentum. If D+D goes to He-4, a gamma is produced but this branch is very unlikely. The product T+p and He-3+n dominate the reaction products.

tmurphy
on **2012-01-31 at 21:24** said:

Makes perfect sense: thanks for this contribution.

Falstaff
on **2012-01-31 at 19:03** said:

Uh oh. A physics professor questions the best use of NIF and ITER funding streams in print? Lidsky was right when he published "The Trouble With Fusion" in 1983, but it appears there are consequences to being right about fusion. The after story is he ended up resigning his post as an assistant director of the MIT Plasma Fusion Center a short time after publication, and Congress reduced fusion funding the next year.
http://tech.mit.edu/V122/N10/10lidsky.10n.html

An interesting tangent is that Lidsky's shot at fusion did not end with him. One of Lidsky's students, Todd Rider, wrote a dissertation that used solid thermodynamics arguments to finally kill off the seductively compact and cheap idea of inertial electrostatic confinement fusion, of which Bob Hirsch was a pioneer with Farnsworth back in '68. Rider since left physics for molecular biology. I read that Hirsch still has a small IEC reactor on his desk that will put out some neutrons if coaxed.
http://en.wikipedia.org/wiki/Inertial_electrostatic_confinement

G
on **2012-01-31 at 23:26** said:

I believe we will have fusion gain from the NIF soon since they are ramping up the experiments to get it now; no construction needed, the current apparatus should suffice to achieve gain. But I don't think I will see a fusion power plant in my lifetime.

Ignoring the engineering challenges, the industry to make all the special purpose optics for ICF simply doesn’t exist. They exist at that annoying size between medical optics and astronomical optics and require incredible manufacturing precision. Why would a government create an entire industry when they could just build some fission plants that would be cheaper to run and more efficient?

Robert Bernal
on **2012-02-01 at 00:40** said:

Hi,
I’m new to “Do the math” and thus posted out of context last week… And thanks for explaining these very important topics.
Anyways, being rather fond of the reactor in space, I’d say…
Go for the storage!
For mobility, perhaps the LiFePO4 which is already good enough (the name of the researcher who led the team in Texas is John Goodenough), though less energy dense, offers better longevity and much less thermal problems than the other lithium batteries.
However, once D-T fusion (was ever to) becomes mainstream, I’m sure it would be worth tapping into the “recycling program”.

Travis Dunlap
on **2012-02-01 at 00:42** said:

Tom, thanks for the article especially a detail of the science. I knew about the containment problems but not nearly as much about the other challenges.

I was wondering in one of your articles if you could talk about batteries more in depth. I know you would desire funding to focus on battery technology, but are there some physics-like limitations we could look at?

I know very little about battery reactions myself, is it even possible to realize storage potential energies in the neighborhood of fossil fuels….even at a theoretical level?

tmurphy
on **2012-02-01 at 07:45** said:

Theoretical limitations to battery storage would make an interesting post. It would force me to brush up on chemistry, too, which is something I have been wanting to do. I have seen several times some estimate of theoretical maximum energy density of batteries, and it is woefully shy of liquid fuels. The closest I came in a quick search was 6% of oil's energy density. Batteries are used more efficiently than burning oil in a car (factor of 4), but this only half-way closes the factor-of-16 gap, and is a theoretical maximum —never to be realized.

Addendum: I am regretting opening up the battery can of worms, as I'm getting loads of comments veering off in that direction. If you want to compare the desirability of batteries to fusion, go for it—but let's not get bogged down in battery details here. Sorry to those who have already submitted comments along this line.

Damien RS
on **2012-02-01 at 09:23** said:

But from the same page:

".”To get really ambitious, we imagine storing energy as elemental aluminum or elemental lithium. Those two highly electro-positive elements yield a theoretical energy density–when oxidized in air–of 32 and 43 mega-joules per kilogram. At least now the theoretical limit is between 60 percent and 80 percent to that of hydrocarbons; we just have to figure out how to extract a large fraction of the energy from that oxidation.”

Plus hydrogen or hydrocarbon fuel cells.

I don't know how to calculate the battery limits, but the simple upper bounds are based on the energy of reaction, mass of reactants, and whether the oxidizer has to be contained (which divides density by like 5) or can be taken from the air. Real upper bounds may be lower due to other considerations…

Pete
on **2012-02-01 at 02:25** said:

You forgot to mention PACER:

http://en.wikipedia.org/wiki/PACER_%28fusion%29

The future is already here! We can forget about responsibly managing our energy supply if we just devoted our entire industrial base to manufacturing a huge, poorly-secured pile of hydrogen bombs.

Surely that is worth it to avoid the hassle of having to turn the light off when you leave a room?

Damien RS
on **2012-02-01 at 09:31** said:

Neat link, also http://en.wikipedia.org/wiki/Project_Gnome

"if we just devoted our entire industrial base"

This seems hyperbole.

As for number of bombs, there would seem to be the possibility of using few large bombs, trapping heat in rock for artificial geothermal, rather than many small bombs in a prepared chamber. The PACER bombs are 10,000x smaller yield than the largest bomb ever detonated.

"Surely that is worth it to avoid the hassle of having to turn the light off when you leave a room?"

Might be worth it to be able to turn the light on at all.

b.
on **2012-02-01 at 09:41** said:

"I think it's safe to use our fusion quest as the definition of hard. It's a much larger challenge than sending men to the Moon."

In space cadet terms, fusion is also a much larger challenge than constructing, deploying and maintaining any global scale scheme requiring space based solar power. For a price tag much lower than possible fusion, we could already be tapping into the great reactor in the sky!

Of course, in turn, ground-based solar power and even Desertec-scale projects are yet again much less of a challenge than space based solar power. There was a time when engineering projects of that scale and ambition captured the imagination even if they were designated to take place in the hinterlands. These days, it has to be the sun in a bottle, or at the least orbit, to be worthy of dreams.

b.
on **2012-02-01 at 10:02** said:

On a – space – related note, I am amazed nobody has brought up 3He yet.

"Safe, Clean Abundant Energy from the Moon."
http://fti.neep.wisc.edu/gallery

http://fti.neep.wisc.edu/ncoe/dhe3

tmurphy
on 2012-02-01 at 10:08 said:

Please **don't** bring it up! Will make my head explode to make the hardest thing we've ever done hard-squared. Sometimes I think there are only seven practically-minded people left on the planet.

mdelage
on 2012-02-02 at 23:55 said:

I can never understand the proponents of He3 moon mining… it's only useful for fusion fuel once D-T net gain has been achieved (since it's easier). D-T fusion allows for tritium breeding from lithium. Breed extra and wait for the tritium to decay to He3. (12 year half life)

Even just breeding tritium from neutron sources and having it decay to He3 would seem orders of magnitude easier than moon mining.

Russ
on 2012-02-01 at 12:32 said:

Hi Tom,

Any thoughts on the feasibility of the focused fusion approach? If I understand it correctly, they are trying to create density (and/or temperature?) extremes by collapsing a magnetic field in on itself. Maybe it eventually runs into the same problems as the tokamak approach?
http://lawrencevilleplasmaphysics.com/

The lead investigator, Eric Lerner, gave a google talk several years ago, but I don't know enough to tell if it is totally bogus or plausible.
http://www.youtube.com/watch?v=O4w_dzSvVaM

From what I can tell, these guys are doing bench top fusion, but are not yet collecting all the energy back out.

The other approach that sounds somewhat plausible to me, is Magnetized Target Fusion, which I think is closer to inertial containment than electromagnetic containment. If I understand this one correctly, they are using sonic energy to try to create a focused point of high pressure. Any thoughts or back of the envelope calculations on the feasibility of this approach?
http://www.greentechmedia.com/articles/read/jeff-bezos-invests-in-nuclear-fusion-but-whens-the-demo/

However, even if either of these do work out (faster than more traditional approaches), I agree that it would still be a long road to commercialisation.

Thanks,
Russ

Dennis
on **2012-02-01 at 14:48** said:

I'm interested in Tom's take too, but my amateur impression of focus fusion is that it seems to have enough respect from other researchers to not be bogus. Not everybody thinks it will work, of course, but it seems to be respectable research, and they got a paper published a year ago.

One possible problem is plasma cooling by emitted x-rays. Lerner says that a strong magnetic field will sufficiently reduce this, and that this effect is well-known to astronomers. Another possibility is that at higher energies the plasma just won't act the way he expects. So far he's getting the scaling his theory predicts, but he's nowhere near breakeven yet.

If it works, it seems to me that for focus fusion the road to commercialization would be pretty short. The reactor is small, and doesn't require a steam turbine. Capital cost for a 20MW plant would be under half a million bucks, and it would fit in a shipping container. Fuel cost is negligible. Lerner and friends estimate it could produce power at a tenth the price of coal. I ran some numbers recently and figured out that with these numbers, if you replaced a coal plant with the same amount of focus fusion, you'd make your money back in less than a year of fuel savings.

So the economic incentive is enormous, the capital cost isn't a barrier, and the only thing you have to do once you prove it'll work is engineer a production plant. That's not trivial, but Lerner estimates it'll take about five years with $50 million or so invested. Other alternative fusion projects have gotten that level of private investment already, without even achieving net power yet.

Pete
on **2012-02-01 at 13:46** said:

I have a question about this analysis, and also the one you have done for space-based solar.

Both tap a mind-bogglingly huge raw resource, but both require an immense amount of time and money to develop (and neither has been done before so we don't know exactly how long and how much.) Elsewhere you point out, correctly I think, that during a time of energy depletion it will be increasingly harder to get people behind making the big investments needed to transition to any kind of post-fossil fuel technological society.

Don't these two arguments add up to an argument in favour of going for the big outlay solutions like fusion and space based solar NOW whilst we have reasonably plentiful energy and industrial capacity, and turning to cheaper, quicker (but in the long run more limited) Earth-bound solar plants once our backs are really to the wall?

Both are very difficult, and both are very uncertain, but both could pay off immensely. Why not take that risk, and aggressively pursue them at a time when we still have the capacity to soak up their possible failure?

Walter Bushell
on **2012-02-01 at 15:02** said:

You realize that at 2.8% increase for 1200 years the amount of energy used would be about 2.5*10^14. Not likely. Talk about global warming.

ivan
on **2012-02-02 at 06:36** said:

As you imply, however cheap and abundant the fuel of fusion power, it is a waste of time if its capital costs end up being an order of magnitude more expensive than solar and storage per W. Does doing experiments on torus-type generators tell us anything about anything other than how to build torus-type generators? I think not. Do we believe that torus-type generators could possibly be built except at an order of magnitude more costly per W than PV and storage? Estimates I have found required quite considerable optimism to get anything like a useful cost per W. And when we still have such difficulty building fission plants, controllably, my realistic assessment of this is “no”, at least until the day arrives when the technology of the day is so advanced to today’s it would look like magic to us (as someone once described the effect of the last 250 years progress on those from that past time). I’d reallocate money to a diversity of the more small scale methods, which are at least on a scale capable of delivering an economic power source if, by some miracle, they work.

Alexander McMurray
on **2012-02-02 at 09:11** said:

Personally, I am more optimistic about fusion. But you seem to have overlooked what is surely the biggest difference between fusion and solar power – the energy density.

As the energy density (I mean amount of power generated per area, or per generation unit) is far far lower for solar than for fusion, this means that solar power necessitates a vast number of solar panels.

As solar panels are currently constructed using quite rare and valuable materials it seems difficult to assume that it would be economically viable to mass produce solar panels (and the associated hypothetical energy storage mechanisms). And then there are considerations of having sufficient land to place the panels – in desert areas this is simple, but if one were to use the desert as a kind of massive power plant then efficient energy distribution would also be needed to minimise losses.

The processes of extracting the materials for solar panels are rarely environmentally sustainable and if they were scaled up massively to meet full energy demand then the damage could be catastrophic. Likewise the cost of the panels is already very high and is often only viable through subsidy which would be impossible were we to shift to large scale solar development.

There is simply no clear case that solar energy, deployed on a large scale, will be either economically or ecologically viable.

Meanwhile the fusion triple product continues to increase at a rate faster than Moore's Law (see Figure 4 http://www2.efda.org/eu_fusion_programme/r-plasma_physics.htm) and we are quickly approaching ignition and breakeven. The high energy density and short-lived waste products mean that fusion could solve the energy crisis and with it many of the other resource shortages (e.g. potable water can be created by desalinisation given sufficiently abundant energy, same with synthetic oil). Fusion is by no means an easy problem, but problems worth solving rarely are.

tmurphy
on **2012-02-02 at 09:56** said:

Good points, and I'll not say solar is *easy*—just possible today, at small scale. It is not clear to me that solar panels require rare substances (high-purity silicon accounts for the bulk of the active material in most PV panels today). But if your point is that meeting our energy challenge this century is going to be *very* difficult, you'll find no argument from me. It's why I'm worried.

Gunnar Rundgren
on **2012-02-02 at 12:42** said:

The argument against solar that it is subsidized has very little merit, when you compare it with other energy forms. Compared to the enormous subsidies poured into fossil fuel and nuclear, I think support to solar is negligeable in most countries apart from possibly Germany. Even coal is subsidized in the US (see last the Economist) The reality is that societies tend to subsidize emerging technologies in general, both good and bad. We would have had no antibiotics and no internet and no railroads without government "subsidies"; almost no education either.

I share some concerns about scalability of solar, and in particular its ability to fuel our transport needs in any efficient way. But then I think we better drive less cars and fly less (admittedly I score very good on the first account having neither car not license, and very bad on the second count, having many long, very long, flights every year) rather than putting our faith into fusion (be it cold, hot, dry or wet…).

Gunnar Rundgren
on **2012-02-02 at 10:05** said:

Interesting post as usual and some thoughtful comments.
In particular the comment "Sometimes overwhelming complexity is mother nature's way of saying you're going down the wrong path." by hawkeye.

Two secondary, but still serious problems with fusion are that it diverts resources and brilliant brains from more promising and simpler solutions, and that it keeps people dreaming that we will find another bag full of candy, similar like the fossil fuel boon, that allowed us to, seemingly, detach from natural boundaries.

And even if it could work, which I don't think it will, and even if it would be a very efficient and cheap source of energy, which is much less sure, I don't think humanity will benefit much from another candy bag. Cheap energy is the prime driver to exhaust all other resources. We don't need more of that, as little as we need more sugar or fat in our diet – and those two things are related…

> Dennis
> on **2012-02-02 at 11:20** said:
>
> If you're correct that renewables are not "another bag of candy," then it's a pretty sure bet that if we don't go with some form of nuclear, we'll burn all the fossil fuels we can dig up, and guarantee climate catastrophe. We won't voluntarily scale down our energy usage as long as fuels are available.
>
> I'm not convinced that energy itself is bad, if it's not directly damaging. Cheaper energy without pollution would allow more urbanized populations, which have much lower birthrates. It would allow cheaper recycling and desalination. It would let us economically extract CO_2 from the atmosphere.
>
> On the other hand, I'm not convinced that it would partic-

ularly increase deforestation, mining, or any other extractive industry. With more recycling and more concentrated populations, there will be less demand for those things.

Gunnar Rundgren
on **2012-02-03 at 01:12** said:

Dennis, Tom is normally insisting that comments should be to the point, which was about fusion. I digressed by discussing general energy issues. And these are big things. In short my view is that First. There will be no more "bag of candy". Not even fossil itself is that bag of candy no more. The Energy return on energy invested is going down. Renewables are good and should be promoted, but they are not bags of candy in the same way. Neither is nuclear of any sort. The sooner we all realise that there will be no more bags of candy the better as it allows us an organised transition and not a total chaos and war over the candy. I think this first point rests on very solid science, and I believe Tom's posts are very good at showing exactly this.

My second point is more like an opinion or a reflection with some empirical support, but I am aware of that I can't prove it – as little as its opponents can prove the opposite. Which society is wasting most energy, the one where it is cheap or where it is expensive? Clearly the one where it is cheap. Worst example was the Soviet Union where energy was basically for free. So far I think we can agree? Second step: does a society that has cheap and abundant energy waste other resources or preserve them? Well, there is a direct global correlation between world materials use, energy use and GDP. In general, there will be more mines and more degradation with cheap energy, with one very important exception. Forests. As firewood is the "second best" energy source and also "for free", a cheap energy source will relieve pressure on forests. Can't we use all that cheap energy to clean up pollution, to bind CO2 from the atmosphere to reverse climate change? We can, and we do to some extent – introducing CCS will radically diminish the ERROI for coal for instance. But still, high energy consuming societies have an overall BAD performance when it comes to preserving nature resources, especially if you consider their global "footprints" (i.e. that they have externalised a lot of the dirt to other people and countries).

To dream about an abundant clean energy source for everybody is like saying: Why don't we solve the problem of poverty by making everybody RICH? Nice dream.

2 billion people on this planet would need MORE access to energy for a good life, primarily to get electric light and clean cooking. They can get that with an equitable world and with existing technologies. That should be the energy priority. As little as they have been helped by a world awash in cash (and debt!) will they be helped by a world awash in energy.

Johan
on **2012-02-07 at 00:53** said:

Tom, forgive me if I divert too far from the subject at hand here but I feel that the point Gunnar is making is important to comment.

Gunnar, I disagree. If you use the UN medium scenario for future population growth the average energy consumption would have to be lowered to some 50-55 GJ per capita and year in order for the world energy consumption not to increase above todays level of about 74 GJ/capita

/year. This would mean energy savings in the order of 80 % in the US, do you thing is reasonable or even possible? Organisations speak like WWF and Greenpeace speak about 40 % lowering of energy consumption in their most advanced scenarios.

You write:
"Which society is wasting most energy, the one where it is cheap or where it is expensive? Clearly the one where it is cheap. […] Second step: does a society that has cheap and abundant energy waste other resources or preserve them?"

There is no rule saying that energy must be cheap for end-users just because it is cheap to produce and abundant. Keep taxes on energy high and you can keep consumption down if you need to. There are ways to counter Jeevons…

My personal view is that a transition to a sustainable society will be much easier if we have clean and abundant energy sources to lean against. As others have pointed out, many hurdles can be overcome or avoided simply by throwing clean energy at them.

Marty Sereno
on **2012-02-02 at 13:55** said:

It's important not to forget that the helium required for the superconducting confinement magnets is mined — it comes from a very small number of methane wells that have tight enough caps that the helium generated by radioactive decay in the crust is not lost into the atmosphere and then space. The plan is that the helium generated could be saved and used for this purpose once fusion is up and running. At the current burn rate of helium (we are likely past peak helium), however, we may not get that chance. For reference, my day job involves MRI magnets.

Sandre du Plessis
on **2012-02-03 at 00:30** said:

I love your blog, Tom, even if the math goes way over my head most of the time. I agree with your comments about pursuing solar rather than fusion. As for the space issue regarding solar panels, you may find this article of interest:
http://www.economist.com/node/21543123

Adrian Wilkins
on **2012-02-03 at 05:23** said:

@Marty : You may be aware that the main reason we are in a bind in terms of helium supply is that the USA elected to sell off their strategic reserves of helium in 1996 [1][2][3] ; this has depressed the market price to the point where it's now considered economic to use this vital resource to float children's party balloons – cheap enough to give away in every chain restaurant and just allow it to escape into the atmosphere – and from there, into space.

[1] http://en.wikipedia.org/wiki/National_Helium_Reserve
[2] http://www.independent.co.uk/news/science/why-the-world-is-running-out-of-helium-2059357.html
[3] http://europe.theoildrum.com/node/3484

Marty Sereno
on **2012-02-03 at 09:57** said:

Yeah, I wrote a short article for the oildrum on it in 2006. The short term price is one thing. The long term problem is that very few methane wells contain recoverable amounts of helium. It is true that a small amount is wasted for party balloons and advertising blimps, but the great majority goes into high tech welding, sensors, and superconducting magnets. There are no hi temp superconductors with the critical properties of being strong and being able to carry high current densities — both absolutely critical for high field superconductivity. Get your MRI now…

Gerry Todd
on **2012-02-03 at 05:47** said:

Your down-to-earth reminder – "we can no longer buy a ticket to cross the Atlantic at supersonic speeds, and the U.S. does not have a human space launch capability any more" – might indicate an inflection point in the trajectory of history.

The costs of human exceptionalism might have caught up with us.

So, where should we turn next? I would suggest working on: (1) awarding Nobels and other incentives for figuring out how to accept limits and live quality lives within those limits; (2) taking responsibility for managing our personal and collective footprint-growing novelty-seeking; and (3) working toward a political-economic system that pursues inter- and intra-generational justice rather than "more now!"

Some may see these as insufficiently aspirational for our self-anointed position of supreme species, but I hope most of us can see them as supremely aspirational.

Thanks, Tom, for your Nobel-caliber contribution to the most Nobel-worthy project of our time.

Arclite
on **2012-02-04 at 02:48** said:

Nice article. I didn't appreciate exactly how difficult fusion was until now. I've been dreaming of it for 30 years, seems like I'll be dreaming another 30.

Given that we will be replacing fossil fuels with electricity (whether solar or fusion), what kind of infrastructure will we move toward to make that transition? I foresee the USA and the world using more electric trains for both distance and urban travel, and street cars with transoms for smaller towns, with electric buses for rural areas that have transoms to recharge their batteries once they come back on the grid. There will always be cars, but I see them becoming more niche due to their cost.

It seems to me our best current option is to build lots of concentrated solar power (oil in pipes heated by parabolic troughs) in the south west desert, with a larger reserve of oil or molten salt to provide electricity over night or on cloudy days. Transporting electricity using high voltage direct current results in only 5% loss over 1000 miles, so that region could power the entire USA. I've read an estimate that 10,000 square miles of CSP would provide the energy needs of the USA. That is an undertaking, and would be expensive, but expensive electricity is better than no electricity.

On the other hand, new fluorine battery tech supposedly has ten times the energy density of lithium, so maybe we'll have our electric cars after all…

M.Ivers
on **2012-02-06 at 10:56** said:

Isn´t Lithiumtritid used in existing neutron bombs?
This might be a better source for tritium than breeding from lithium, for at least a few years.
What i´m sure about is deuterium is used in H-Bombs, so we

needn´t concentrate it from water.

Comments are closed.