Strategic Energy analysis for the Future:

Physics, Thermodynamics, Grid Engineering, Demographics and Economics

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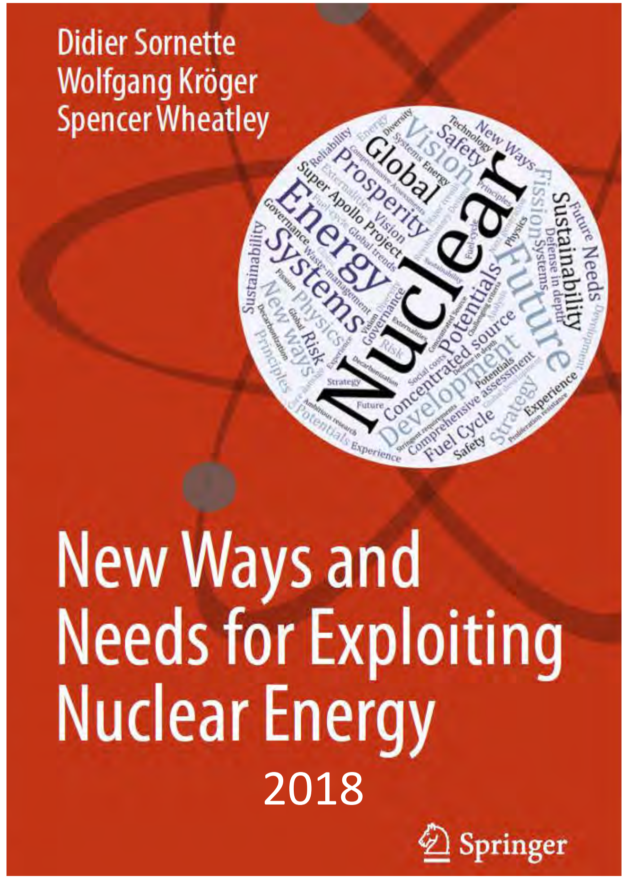
Euan Mearns and Didier Sornette, Comparing electricity generation technologies based on multiple criteria scores from an expert group, ETH Zurich working paper (http://arxiv.org/abs/2101.10220)

Big picture: energy, humanity, and mega-trends

1 man-day = 35 Watt for 8 hrs = 1 Mega Joule
OECD citizens use 0.2 Giga Joule per capita per year = 4.7 tons of oil equivalent
→ 178 "energy slave" man-days per OECD citizen per day

IR1 (1750–1850): coal, steel, steam and railroads;
IR2 (1870–1930): electricity, internal combustion engine, cars, running water, indoor toilets, telephone, wireless telegraphy and radio, movies, petro-chemicals:
IR3 (1960–2000): electronics, computers, the web, the Internet, mobile phones;
IR4 (on-going, from 2000 to the uncharted future)[28]: the progressive fusion of the physical, digital and biological worlds with cloud computing, information storage, the Internet of things, the blockchain, artificial intelligence, robots, self-driving cars, genomics and gene editing, neuro-technological developments.

- Ascent to unprecedented levels of comfort, productivity, and consumption – enabled by the increased mastery of the basic stocks and flows of energy.
- Enabled 3rd and 4th industrial revolutions.
- About 15% of the global pop. at the forefront of this development, the remaining 85% wish to attain the same.
- Global innovation-urbanization trend, future mega-cities.



Manpower + wind power

Oil fired steam

Wind power

Nuclear power

Coal fired steam

Past energy transition always driven by competition where better efficiency, larger quantity and lower price were the main drivers. When Winston Churchill famously converted the Royal Navy from coal to oil fired steam, he did so because oil offered competive advantages of greater range and greater speed. Furthermore free loading liquid oil meant a reduction in manpower (stokers) on board. Sailing ships and rowing boats co-exist today with nuclear powered battleships.

Energy & Development

Energy taken as top problem for next 50 years – Richard E Smalley, «Our Energy Challenge»

- Increasing use of existing energy sources, and adding new sources to the "stack".
- Economics views energy consumption as a consequence of growth, rather than the other way around. Too reductive! Analyses of USA, Japan, and Germany between 1960 and 1996 show that energy drives about 50% of growth!
- More than 80% of current energy met by fossil fuels. Hungry for energy enormous.
- WHO: electrification crucial to avoid staggering health effects of domestic fossil fuel burning.
- Climate problem. Worldwide decarbonization initiative.

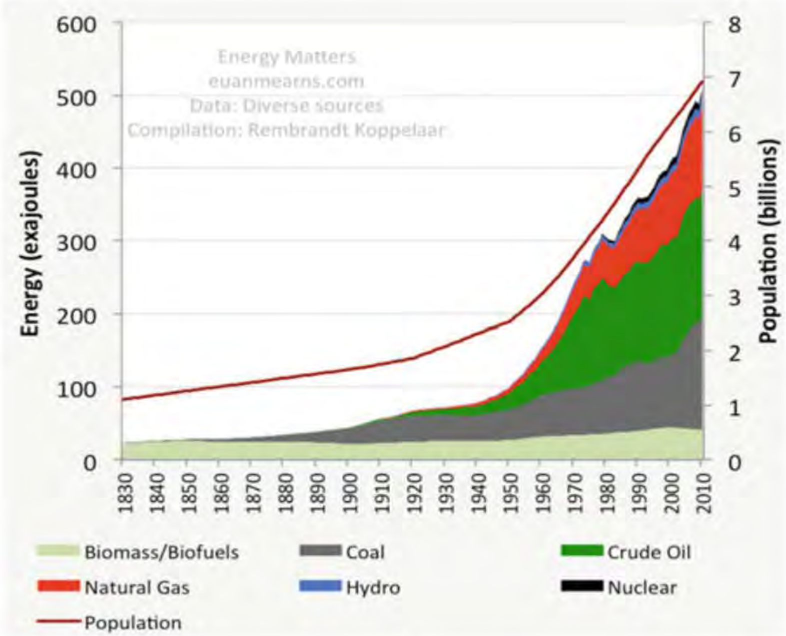


Fig. 1.2 Global energy and population: history of energy transitions for almost 200 years. The brown line shows in comparison the human population (right scale). Courtesy of Euan Mearns, Energy Matters (http://euanmearns.com/energy-and-mankind-part-3/)

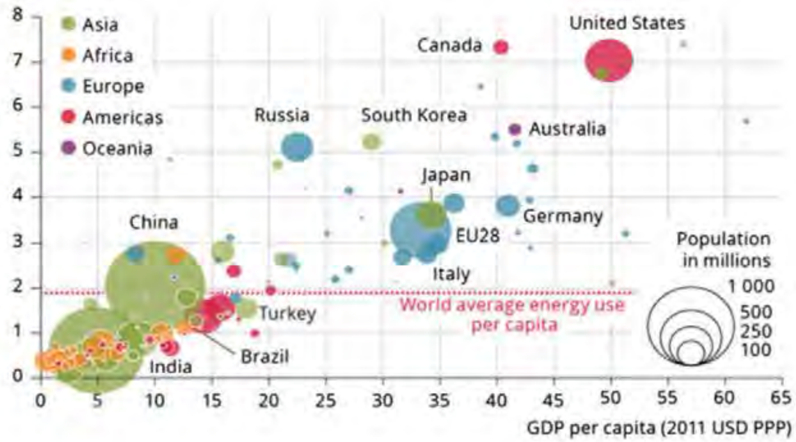


Fig. 1.4 Energy consumption per capita (vertical axis unit is tonnes of oil equivalent) as a function of GDP per capita, PPP (PPP stands for purchasing power parity, and is used to compare countries with different costs of living and to adjust for exchange rates) (horizontal axis unit is thousands of current international U.S. dollars). The size of the bubbles denotes total population per country. All values refer to the year 2011. Reproduced from European Environment Agency (https://www.eea.europa.eu/data-and-maps/figures/correlation-of-per-capita-energy, accessed 3 Aug 2017)

Robert U. Ayres and Benjamin Warr, The economic growth engine (how energy and work drive material prosperity), Edward Elgar, Cheltenham, UK and Northampton, MA, USA (2009)

Summarizing the outlooks: BP, IEA,

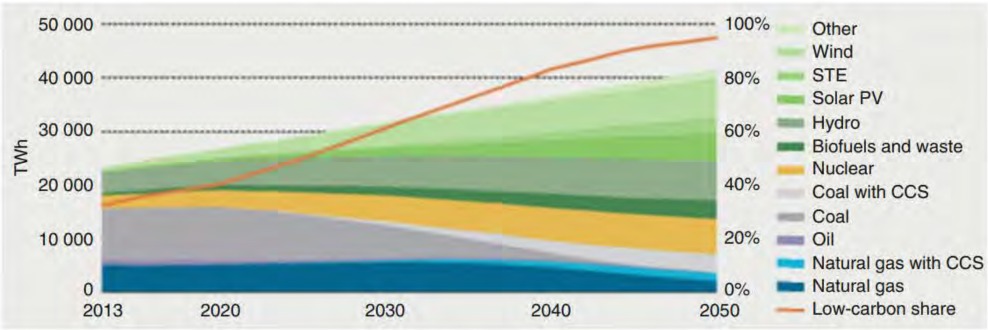


Fig. 1.6 Global electricity generating mix in the 2 °C scenario 2013–2050, produced by the International Energy Agency (IEA),[55] with possible technologies listed on the right. The scenario shows the low-carbon share (orange line) continuously increasing from 2013 to 2050 (right hand scale). CCS means carbon capture and storage. STE stands for solar thermal energy, and solar PV is solar photovoltaic

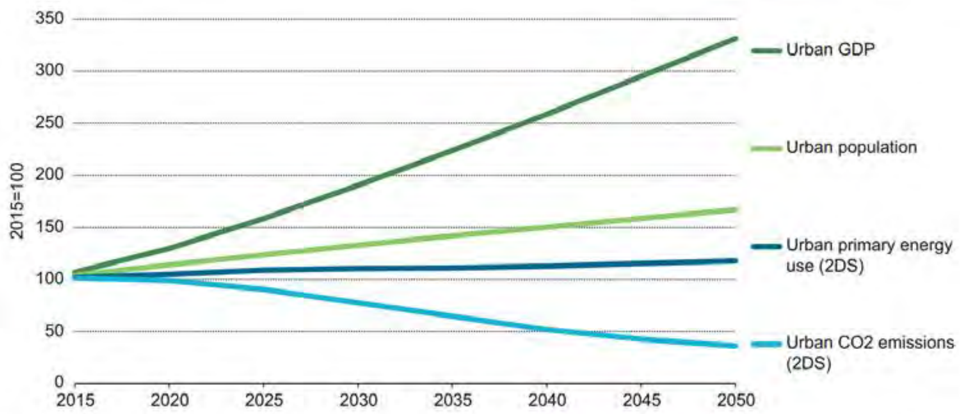


Fig. 1.7 Decoupling of economic growth (GDP) and population growth from CO_2 emissions (OECD/IEA Paris, *Energy Technology Perspectives 2016*, http://www.iea.org/etp/ (accessed June 2016))

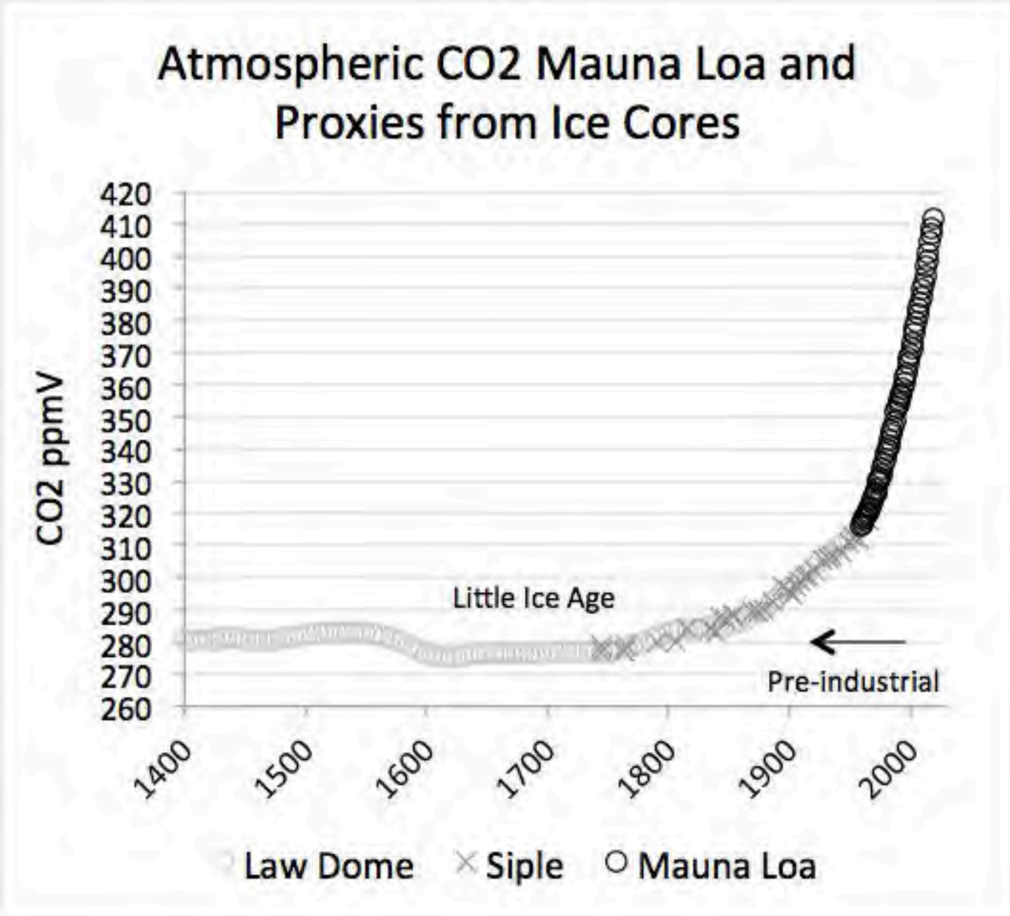
1. Strong global economic growth: more than doubling by 2050.
2. **Expectation that decarbonisation** of the energy supply of the more advanced economies will be progressive and visible in near future.

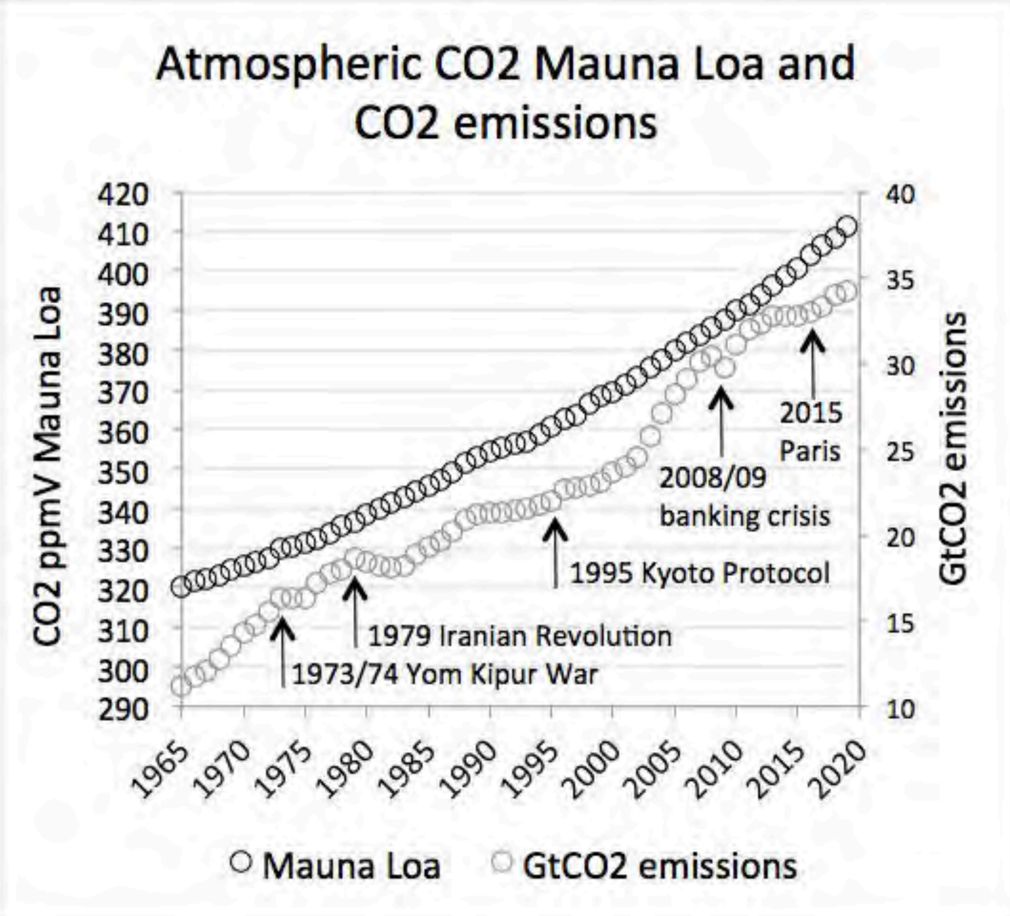
   - Emissions in electricity should reduce by 85% in OECD in next 25 years (Paris COP 21, Katowice COP 24)
3. **Extensive deployment of low carbon electricity generation** options.

   - ESYS [1] study indicate Germany will need to increase wind and PV by 6x and rely extensively on digital control techniques in its new grid.
4. **Growth in energy demand** concerns **mainly electric** power generation.
5. **Declining share of fossil fuels. No consensus on the extent.**
6. **Increasing share of renewables, argued on the basis that renewables are becoming cheaper**
7. **Ambiguous share of nuclear energy.**

[1] https://energiesysteme-zukunft.de/en/

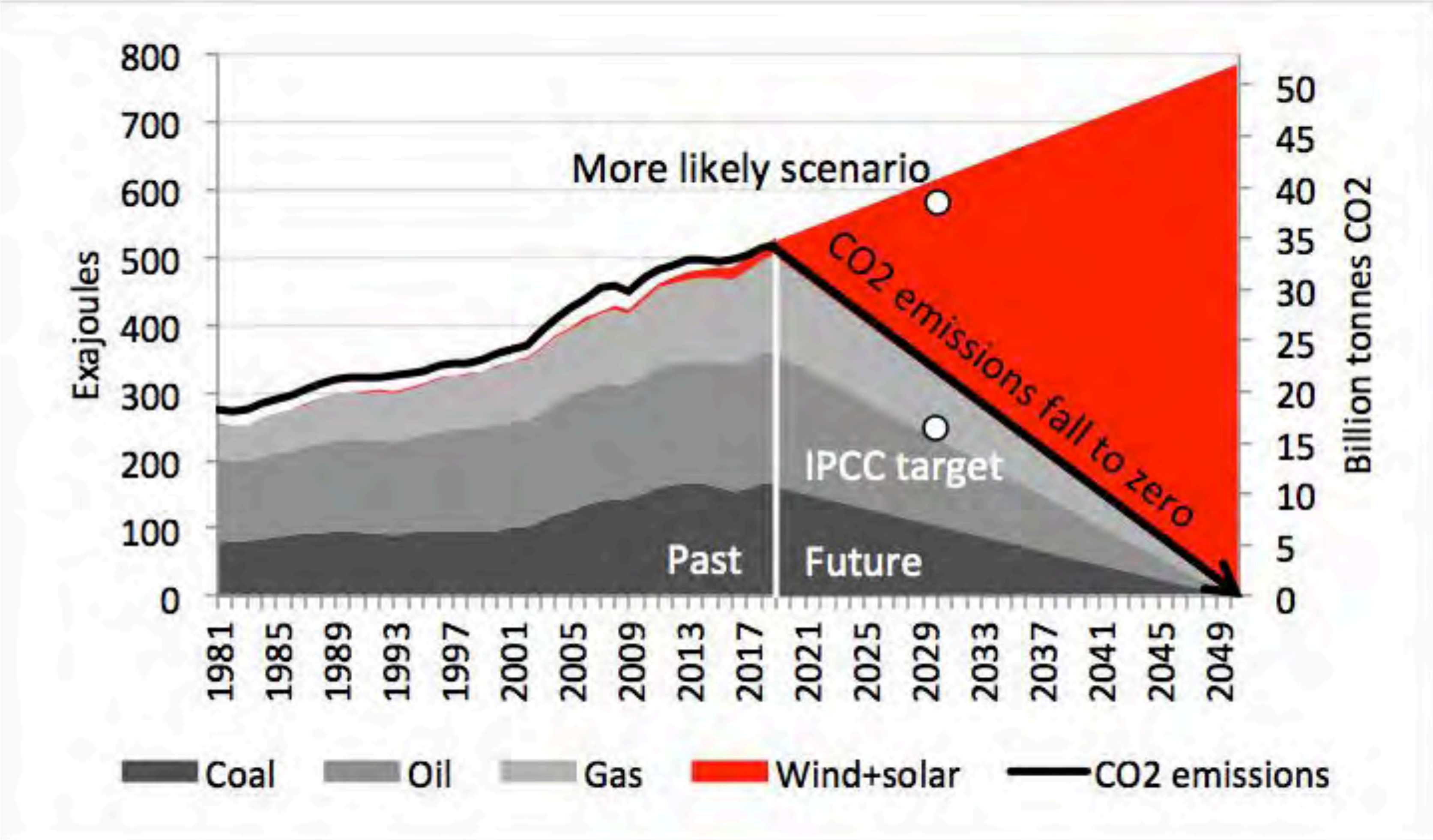
There has so far been abject failure to reduce CO_2 emissions





Since the 1995 Kyoto Protocol, The United Nations has lorded over one dimensional energy policy and has overseen the abject failure to significantly reduce CO_2 emissions and to significantly expand renewable energy. The only events to significantly impact emissions are recessions caused by oil price spikes, the 2008/09 banking crisis and now the Covid-induced lockdowns and stopping of economies.

The United Nations has decreed the world must move to net zero CO_2 emissions by 2050 – that is just 29 years away

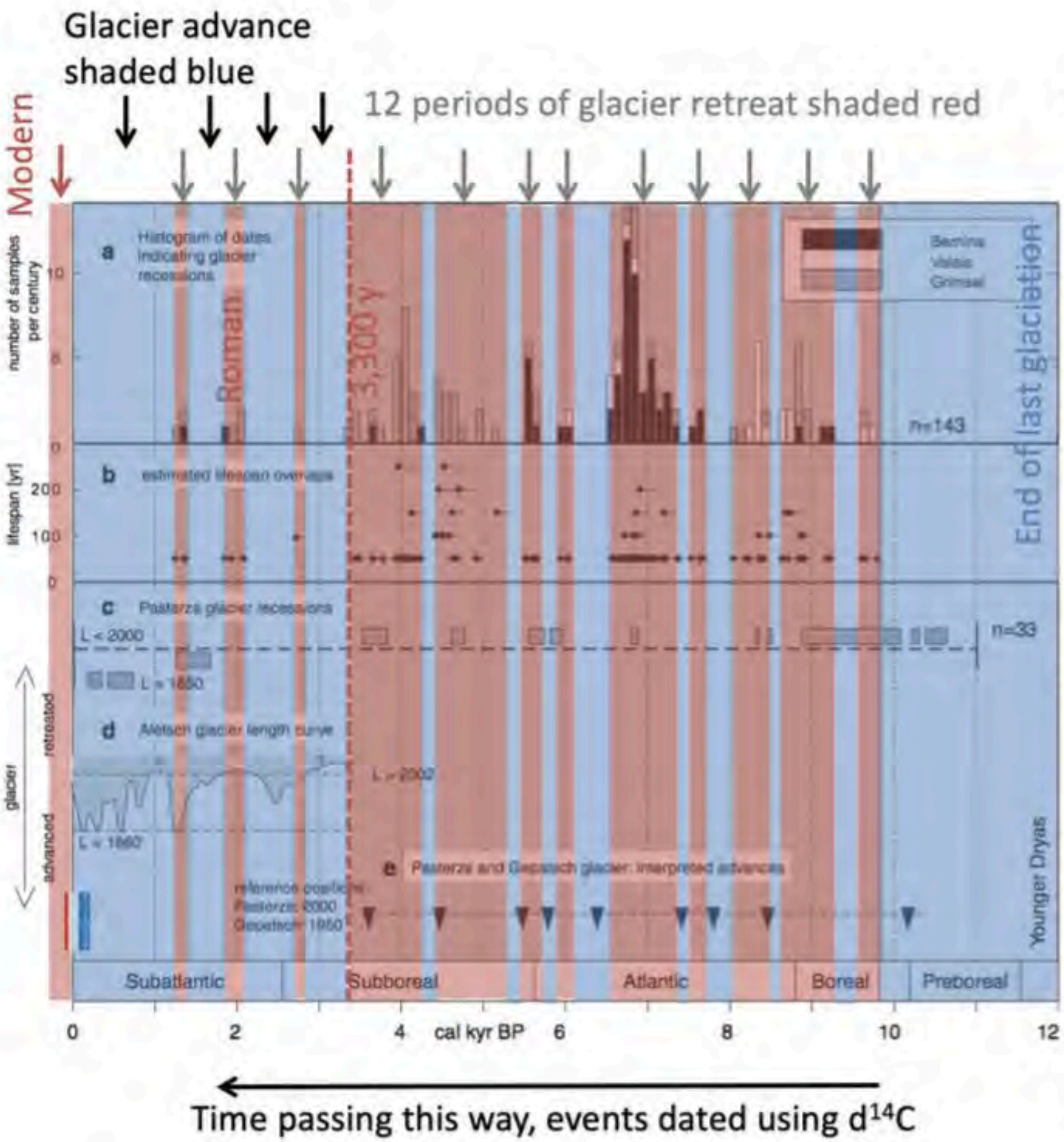


Despite all the rhetoric, wind and solar still represent a tiny fraction of global energy use.

In the last 25 years effectively nothing has been achieved and yet the 193 member states continue to pretend they are protecting the planet, costing prosperity while failing to tackle real problems like poverty, famine, pollution etc.

Does this really matter? What will happen if Alpine glaciers disappear?

Alpine glaciers have completely disappeared 12 times in the last 10,000 years. We should be more concerned if they do not completely melt this time.



- No Alpine glaciers with wooded valleys was the norm until ~3,300 y ago.
- Marked cooling in Greenland ice cores began ~3,300 y ago.
- If Alpine glaciers disappear completely and valleys are collonised by trees this would be completely normal.
- If this does not happen it could signal a slide towards the next glaciation!
- These cycles are probably analogous to Bond Cycles that are controlled by solar activity and not CO_2

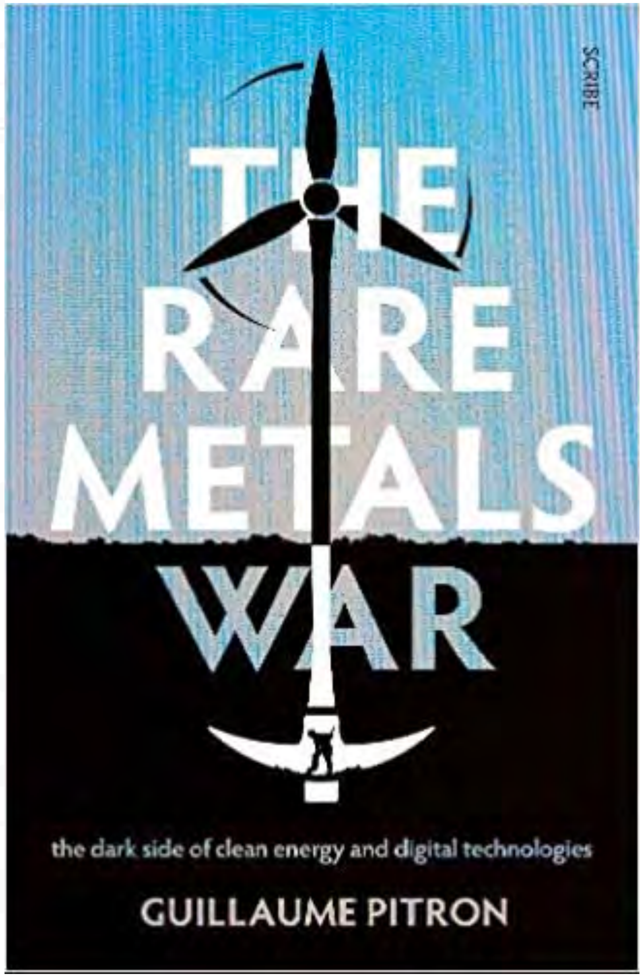
Adapted from Figure 3, Joerin et al, 2006

The forgotten prevalence of Natural climate cycles

20 inches on Valentine's Day
The mother of all snows came on Valentine's Day in 1895. Houston was hit with 20 inches of snow on Feb. 14 and 15. The snow didn't just fall in Houston. It was a massive storm that dropped snow from Tampico, Mexico, to Pensacola, Florida, and set records in New Orleans and Alabama.
https://abc13.com/winter-storm-texas-houston-weather-snow-in-does-it/2753082/

- We are still living in the **Pliestocene Ice Age**, **warm spells** (like now) are infinitely better than the cold spells.
- The Vostok ice core demonstrates that CO_2 has a weak effect in regulating Earth's climate. **Orbital cycles control the glacial – inter-glacial cycles** and are dominated by the 41,000 y obliquity cycle.
- **Dansgaard-Oescheger and Bond cycles**, ~1,200 y duration, modulate N Atlantic climate between warm (**Roman warm period**) and cold spells (**Little Ice Age**). These are controlled by **changes in The Sun** that result in changes to atmospheric and ocean circulation.
- Changes in the geometry and rate of **thermohaline circulation** is an important variable transporting heat and water vapor to high latitudes. Water vapor is by far the most important greenhouse gas.
- The IPCC tends to **downplay all natural forcing leaving only manmade forcing to explain climate variability.**
- Questions on reliability of measurements of surface temperature due to changing conditions (urbanization, homogeneisation…)?
- Uncertainties in climate models.
- The frequency and accumulated energy of Atlantic hurricanes is unchanged for over 100 years. Relative sea level is falling in the Maldives.

The enormous environmental impact of substituting one energy system with another is habitually ignored.



To keep up with projected market growth in turbine demand and construction will require by 2050 some **3,200 million tonnes of steel, 310 million tonnes of aluminium and 40 million tonnes of copper**, Pitron calculates. Chuck in all the raw materials needed to build everything from billions of green car chassis to new solar power plants and “**by 2050, we will have to extract more metals from the subsoil than humanity has extracted since its origin**. Our 7.8 billion contemporaries will absorb more mineral resources than the 108 billion humans who have walked the Earth to date.”

Governments should legislate to ensure that all “Green” devices (turbines, electric cars, power lines etc) are created from renewable energy alone, this to include mining operations.

The world has abandoned competition, market forces, thermodynamics, economics and common sense on energy policy in favour of one-dimensional policy founded on CO_2 emissions and renewable energy.

We asked ourselves some questions:

- If the current, failing policy is one day abandoned, what should replace it?
- How can we decide which of the existing options are best?
- How do we compare natural gas combined cycle with nuclear power with solar PV?

- We were attracted to the methodology used in the 2004-2009 EU majority funded (€7.6 of 11.7 million) NEEDS project where multi criteria decision analysis (MCDA) was used to evaluate and contrast different electricity technologies.
- While attracted to the methodology, we were surprised by the outcome that ranked CaTe thin film solar PV as the top technology with solar thermal in second place.
- How could a group of energy experts conclude that solar technology based on rare toxic elements was the best option for central Europe? And it is already known that solar thermal is barely functional in southern Spain and will likely not work at all in central Europe owing to insufficient and irregular sunshine.

We designed our own hierarchical MCDA and sought the expert judgement of 19 energy experts with diverse backgrounds

EMETS category	EMETS criteria		EMETS technologies
Health	Fatalities	1	Coal
	Chronic illness	2	Gas CCGT
Environment	Environmental costs	3	Biomass
	CO2 intensity	4	Nuclear
	Footprint	5	Wind
Grid	Costs to grid	6	Hydro
	Benefits to grid	7	Solar PV
Economics	Taxes raised	8	Diesel
	Subsidies paid	9	Solar thermal
	Cost of energy	10	Tidal lagoon
Resources	ERoEI	11	Geothermal
	Resource availability	12	Wave
		13	Tidal stream

Participant	Profession / qualifications	Nationality / country of residence	Coal	Gas	Biomass	Diesel	Nuclear	Hydro	Wind	Solar PV	Solar thermal	Wave	Tidal lagoon	Tidal stream	Geothermal
1	Geology / geochemistry PhD	British living in UK													
2	Professor physics / economics / risk, PhD	French living in Switzerland													
3	Chemical Engineer	Irish living in UK													
4	Geophysicist	British living in UK													
5	Engineer (MechEng)	British living in UK													
6	Academic Biology, PhD	Spanish living in Spain													
7	Gas utilisation and distribution engineer	British living in UK													
8	Electronics / software	living in Ecuador													
9	Geologist / geophysicist	British living in Mexico													
10															
11	Systems engineer / CEO nuclear	American living in USA													
12	Professor electrical engineering, PhD	American living in USA													
13	Pharmacist	French Reunion (Indian Ocean)													
14	Nuclear engineer	British living in UK													
15	Physicist	German living in Germany													
16	Investor / mathematics, Cambridge	British living in Malaysia													
17	Asst. Prof. philosophy of science, PhD	German living in The Netherlands													
18	Engineer / management consultant	Brit / German living in Germany													
19	Electrical and petroleum engineer	American living in USA													

-5 Categories of Health, Environment, Grid, Economics and Resources build on the pillars of sustainability.

-12 criteria beneath the categories Applied to 13 common and experimental electricity technologies.

-19 participants cast scores on scale of 1 to 10 using the Energy Matters blog as the platform.

-Diverse background split between academia and industry with diverse mix of disciplines.

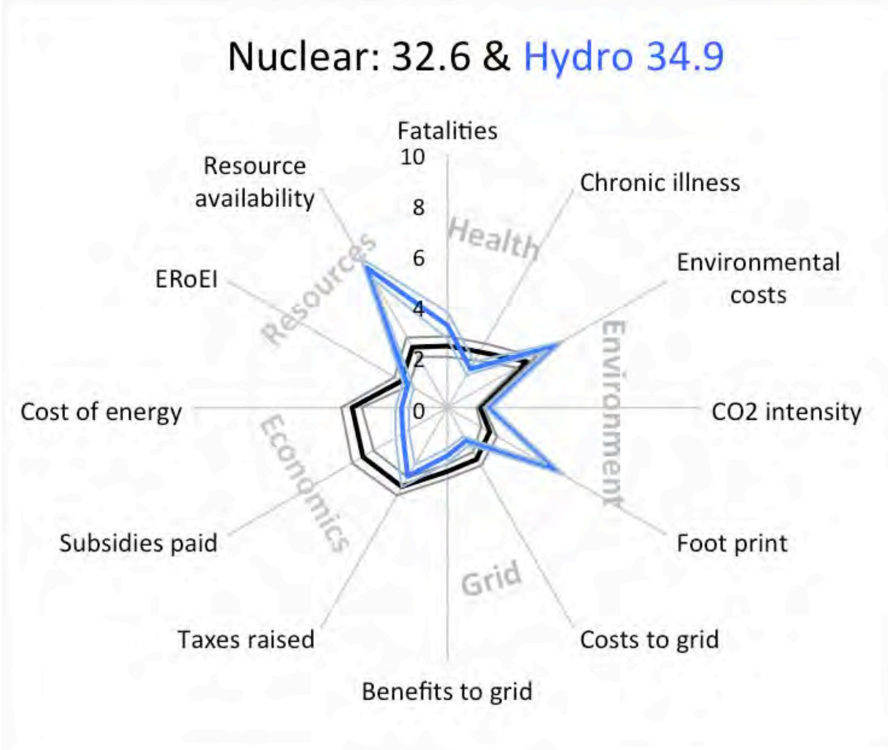
-1=best, 10=worst, total score provides a holistic measure of quality.

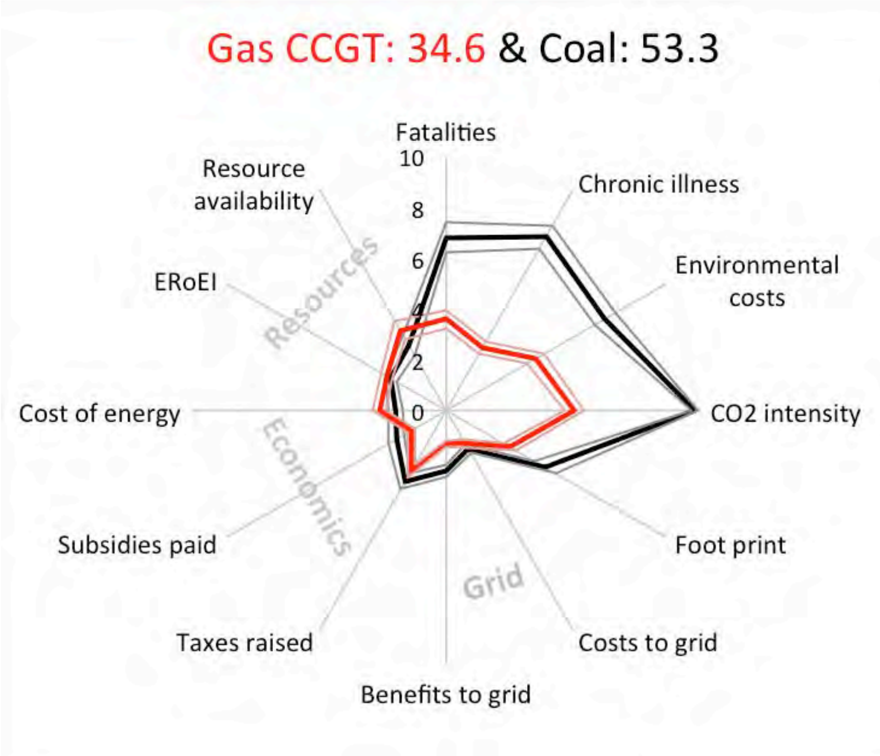
-High total score = bad and low total score = good. Max = 120 and min = 12

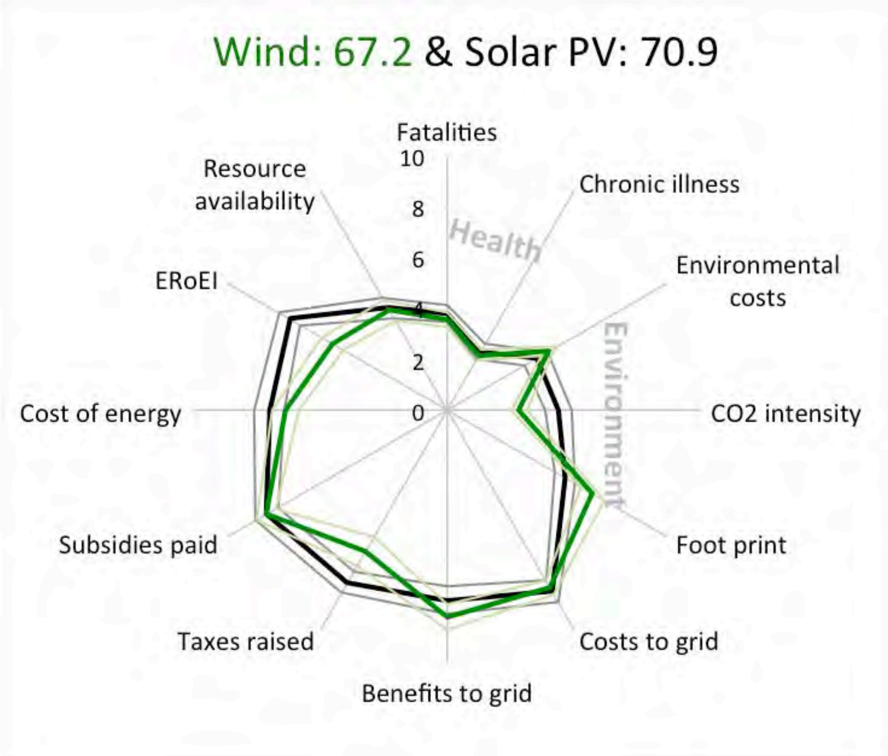
Spider diagrams illustrating mean scores for 6 of the analysed technologies. A tight pattern, like nuclear, means good performance on each criteria while a sprawling pattern, like wind and solar, means poor performance on a number of criteria.

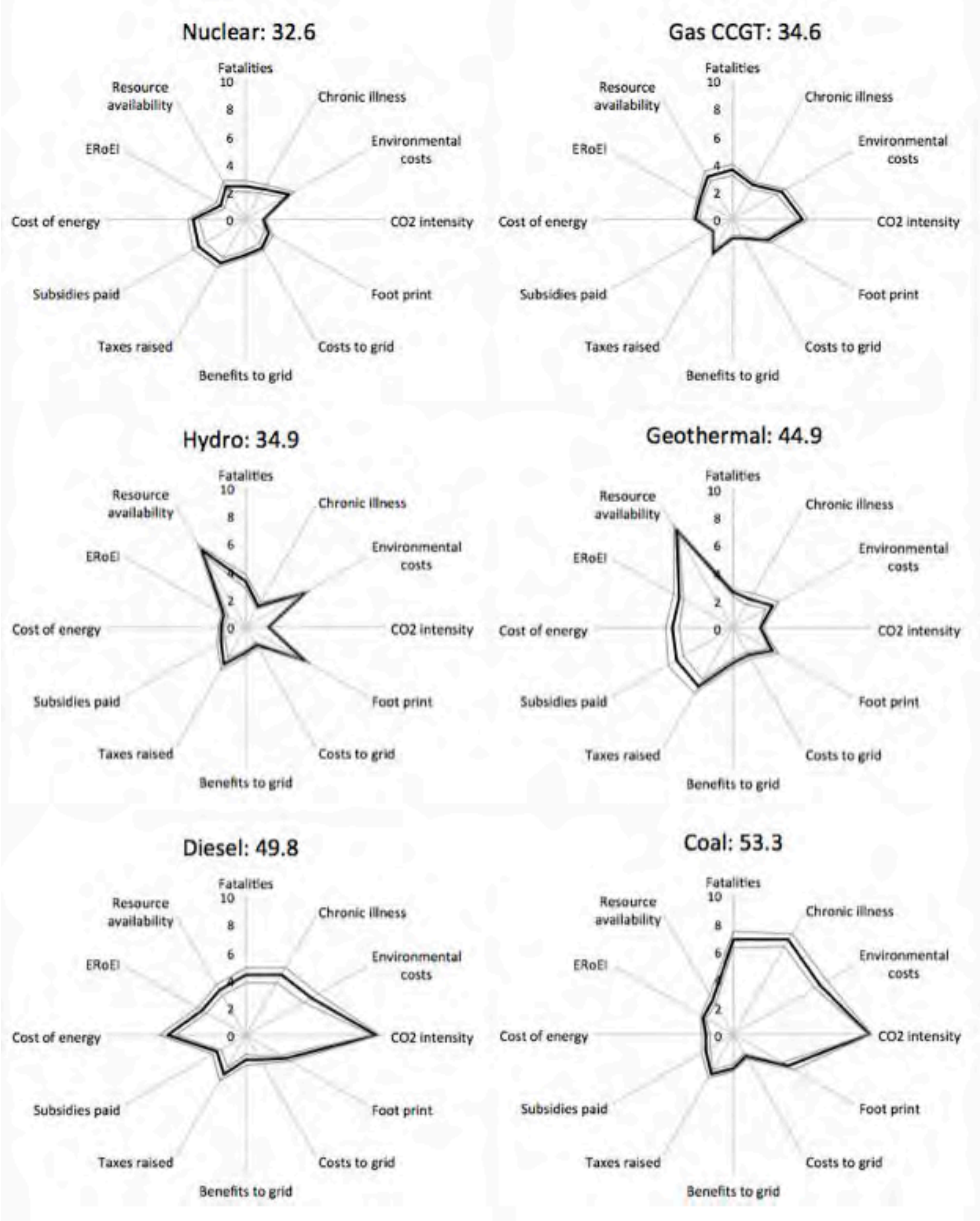
The graphical arrangement illustrates how coal performs badly on health and environmental criteria while performing well on grid, economics and resources. Wind and solar, on the other hand, perform well on health and environment, but poorly on all other criteria.

This epitomises the trade offs we face in designing new electricity supply systems.



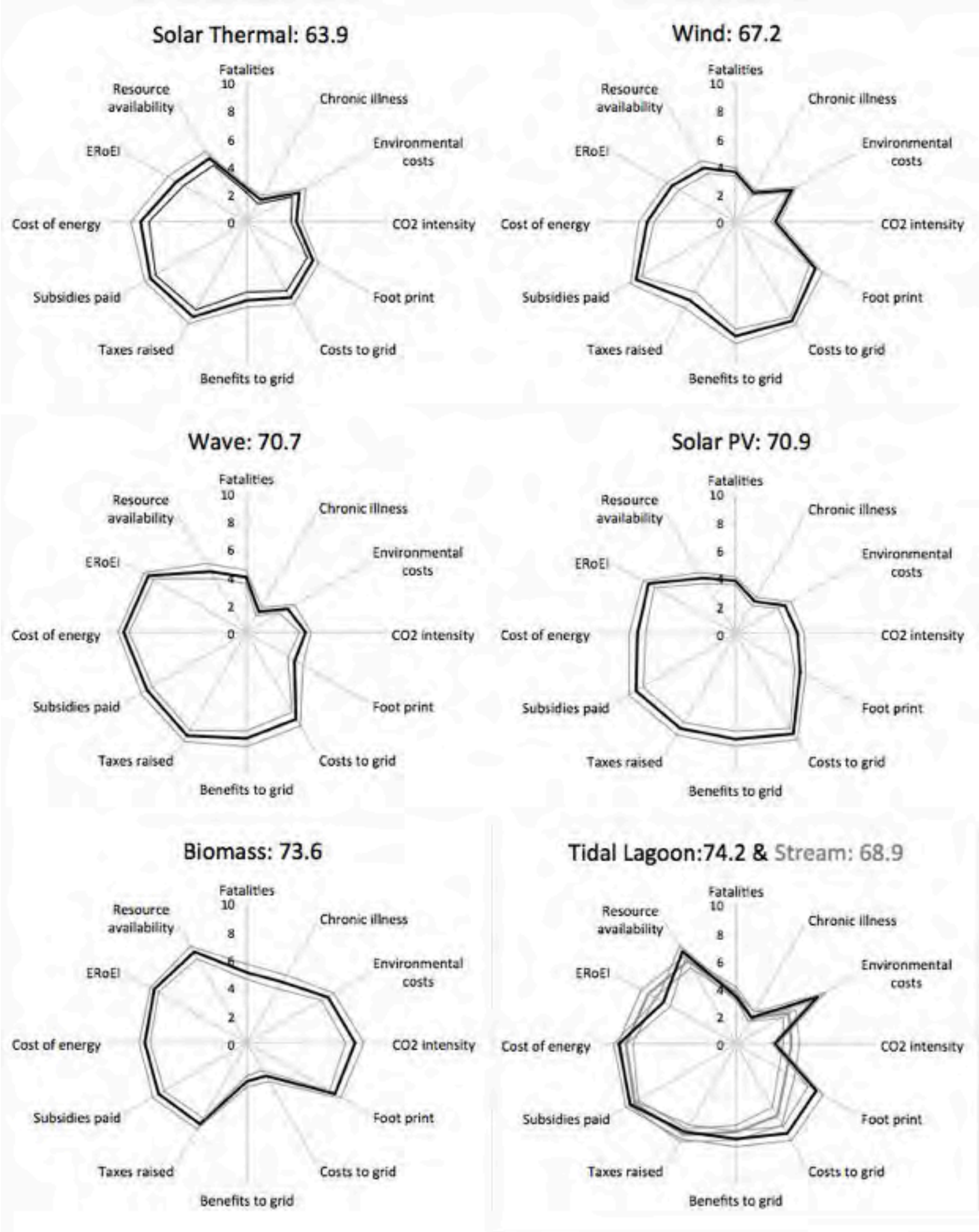






Top 6 technologies

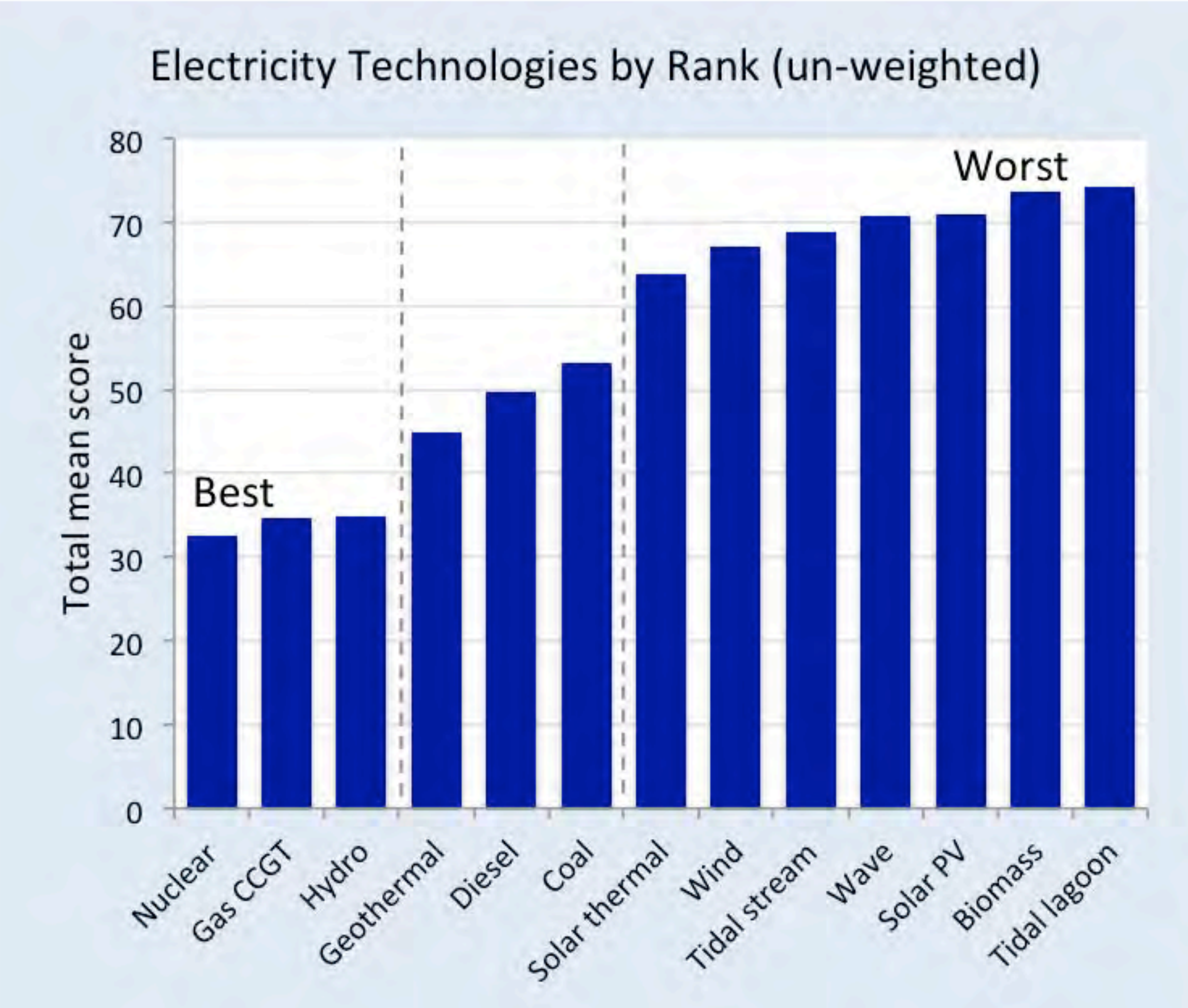
- There are too many observations to list, so we stick to some of the key points.
- Top three technologies are Nuclear power, Gas CCGT, Hydroelectric power.
- Hydro and geothermal both fail on resource availability => few large hydro sites left to be developed. Geothermal restricted to high heat flow areas.
- Diesel and coal both fall down on health and environmental grounds.
- Gas and coal have similar shapes but environment and health concerns are amplified with coal.



Bottom 6 technologies

- There is a strong commonality to the shapes and areas of the 6 renewable technologies.
- They all fare well on health and environment categories but fail on Grid, Economics and to an extent on Resource categories.
- One exception is biomass that is dispatchable and therefore fares well on grid. However, in the UK, biomass is run in base load mode to maximise income from subsidies.
- On Resources, most fare OK on resource availability but fall down on ERoEI where a large amount of energy (normally fossil fuels) is required to harvest the energy.

Rank order

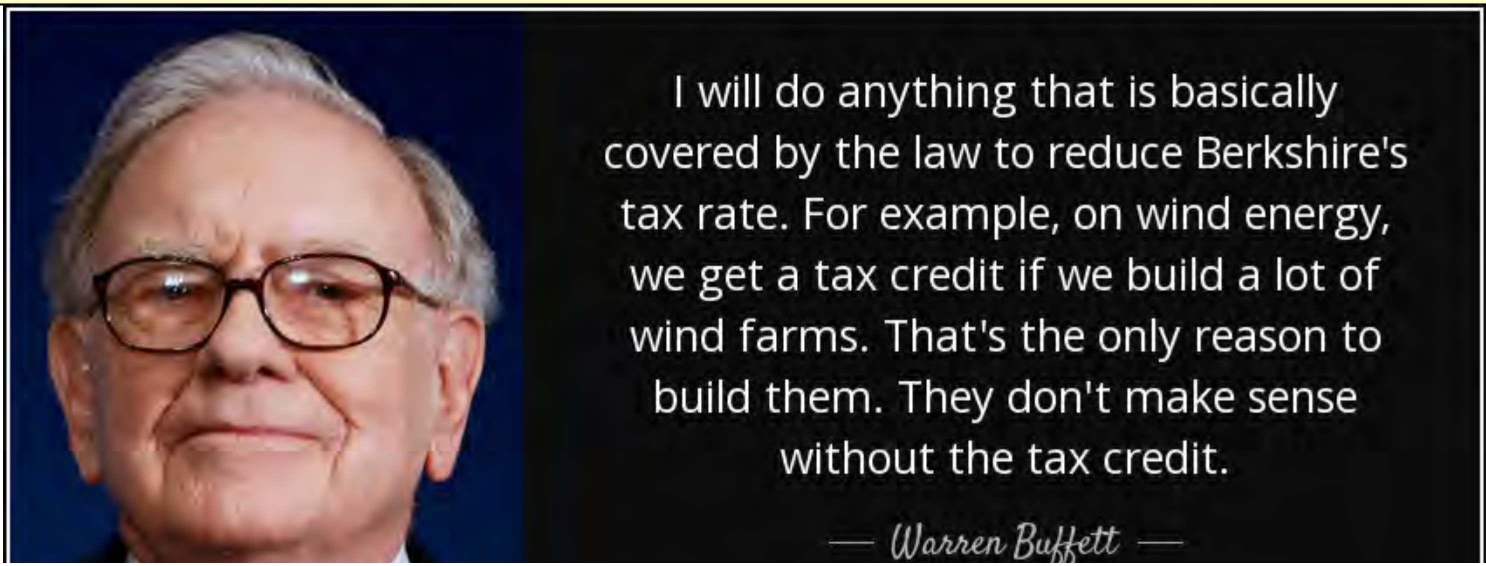


- Ranking on total scores we see that no technology comes close to zero, => no electricity technology is close to perfect. Likewise none come close to 120 => none are totally useless.
- The rank order arranges the technologies into three groups where there are three clear winners: nuclear, gas CCGT and hydroelectric power and 6 clear losers: solar thermal, wind, tidal stream, wave, solar PV, biomass and tidal lagoon.
- Of the new renewables, solar thermal performed best and it is clear that this technology may work in hot desert areas – nat available to many.
- Notably tidal lagoon has failed to get government support in the UK and it is now recognised that subsidising biomass has been a huge mistake.
- It then remains an odity that solar PV has widespread government support in parts of Europe.

Why subsidise solar PV and wind?

Sir David Mackay was one of the worlds leading energy analysts and worked as chief scientific advisor to the government on energy 2009 – 2014. He sadly died in 2016. The quote is from his final interview, days before he died.

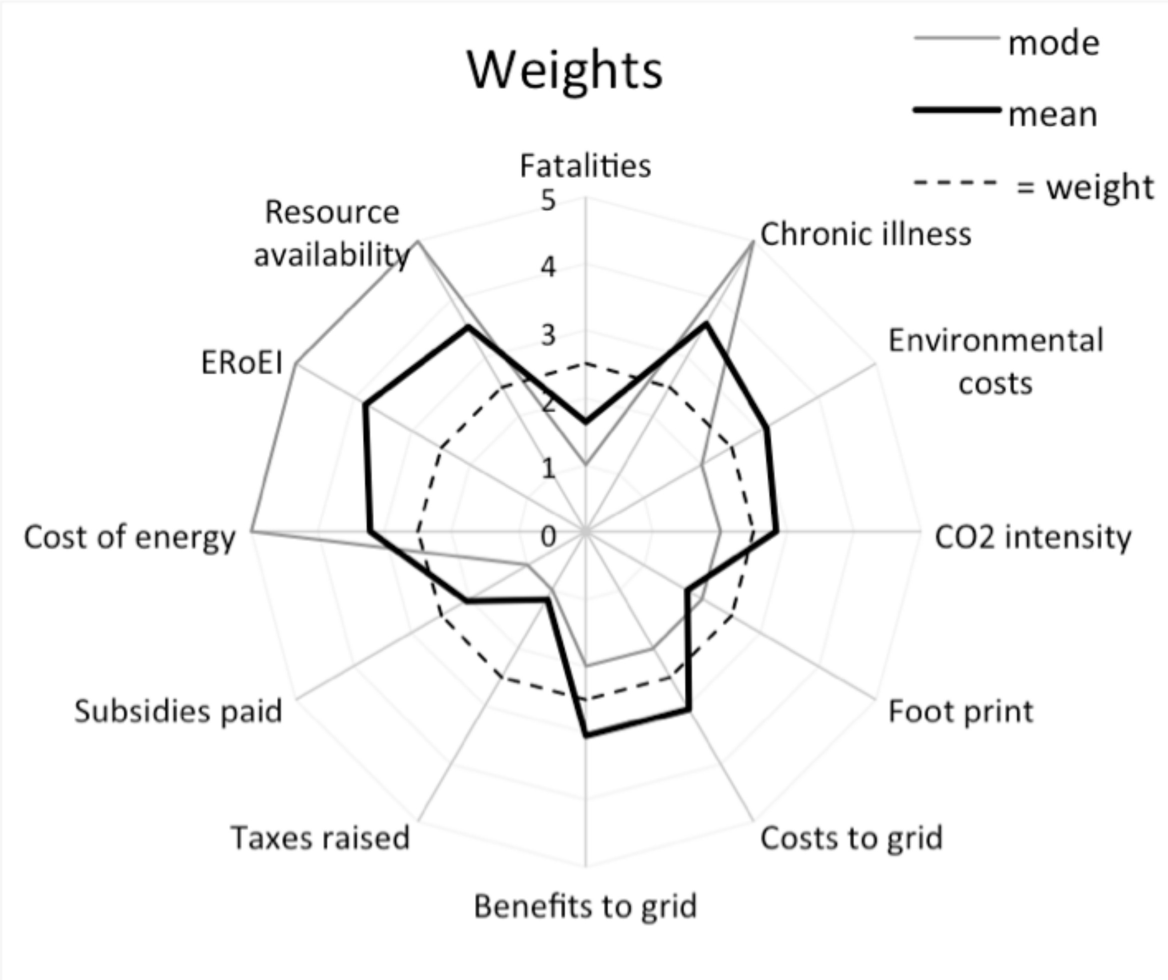
"The only reason solar got on the table was democracy. The MPs wanted to have a solar feed-in-tariff. So in spite of the civil servants advising ministers, 'no, we shouldn't subsidise solar', we ended up having this policy. There was very successful lobbying by the solar lobbyists as well. So now there's this widespread belief that solar is a wonderful thing, even though … **Britain is one of the darkest countries in the world**."



Weighting of criteria

- It is common practice in MCDA studies for participants to vary the weight given to the various criteria to reflect their preferences, i.e. variable importance.
- In our study we tried to ensure that each of our 12 criteria had roughly equal weight. For example, maintaining health, not killing people and low cost are all of approximately equal importance.
- We are naturally suspicious of allowing participants to engage in the subective process of deciding what is important and what is not important.
- We recognised the risk of all weight being cast onto two or three criteria in which case the “multi” component of the exercise fails.
- Nevertheless we conducted an experiment to evaluate the impact of weighting using a scheme of 1-2-5 where individual criteria could be weighted double or 5 times as important.

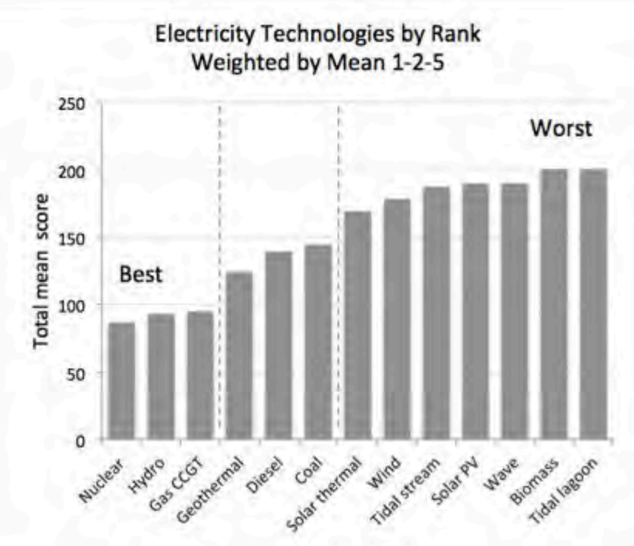
Weights as cast by our 19 participants

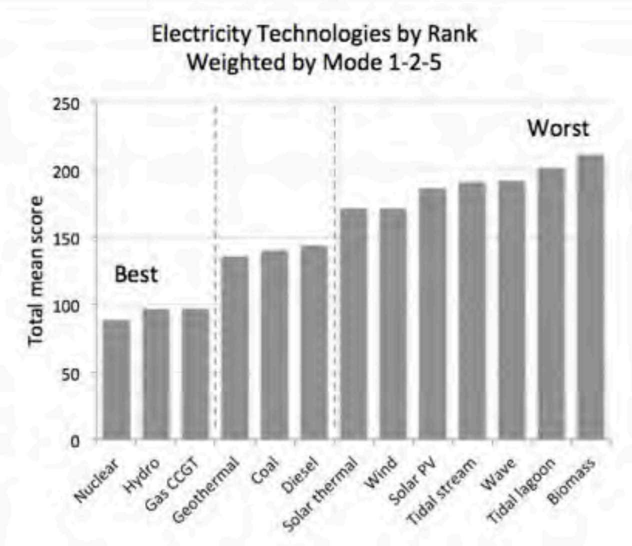


The results of this exercise were a little surprising. We have a preference for using the mean scores.
Four criteria emerged with <equal weight, i.e. reduced importance, namely fatalities, foot print, taxes raised and subsidies paid.
The most surprising is perhaps fatalities that we rationalise with the fact that deaths from electricity production are rare. So it is not that they are unimportant.
We can simply express our surprise at the low importance given to subsidies and taxes. It certainly deflects any hint of bias among our participants.

It is common practice in MCDA studies for participants to vary the weight given to the various criteria to reflect their preferences, i.e. variable importance. In our study we tried to ensure that each of our 12 criteria had roughly equal weight. For example, maintaining health, not killing people and low cost are all of approximately equal importance.
We are naturally suspicious of allowing participants to engage in the subjective process of deciding what is important and what is not important. We recognised the risk of all weight being cast onto two or three criteria in which case the "multi" component of the exercise fails. Nevertheless we conducted an experiment to evaluate the impact of weighting using a scheme of 1-2-5 where individual criteria could be weighted double or 5 times as important.

Weighting results





			Rank order difference		
Un-weighted	Mean 125	Mode 125	Un v mean	Un v mode	mean v mode
Nuclear	Nuclear	Nuclear	0	0	0
Gas CCGT	Hydro	Hydro	1	1	0
Hydro	Gas CCGT	Gas CCGT	1	1	0
Geothermal	Geothermal	Geothermal	0	0	0
Diesel	Diesel	Coal	0	1	1
Coal	Coal	Diesel	0	1	1
Solar thermal	Solar thermal	Solar thermal	0	0	0
Wind	Wind	Wind	0	0	0
Tidal stream	Tidal stream	Solar PV	0	1	1
Wave	Solar PV	Tidal stream	1	1	1
Solar PV	Wave	Wave	1	2	0
Biomass	Biomass	Tidal lagoon	0	1	1
Tidal lagoon	Tidal lagoon	Biomass	0	1	1
Sum of rank order difference			4	10	6

- The outcome of our weighting exercise surprised us a little, since it has made **no significant difference to the rank order or the arrangement into three groups.**
- The table shows the difference created in the rank order.
- Comparing unweighted with mean weighted scores the total rank order difference is only 4, i.e. two pairs of technologies have swapped position in the rank order.

Validation

We naturally asked ourselves the question if the scores cast by an expert group had any meaning at all? This question can be raised at two levels:

1. Is there consistency within and between the scores?
2. Does our 12 criteria scheme successfully capture and describe the holistic quality of electricity systems, including externalities?

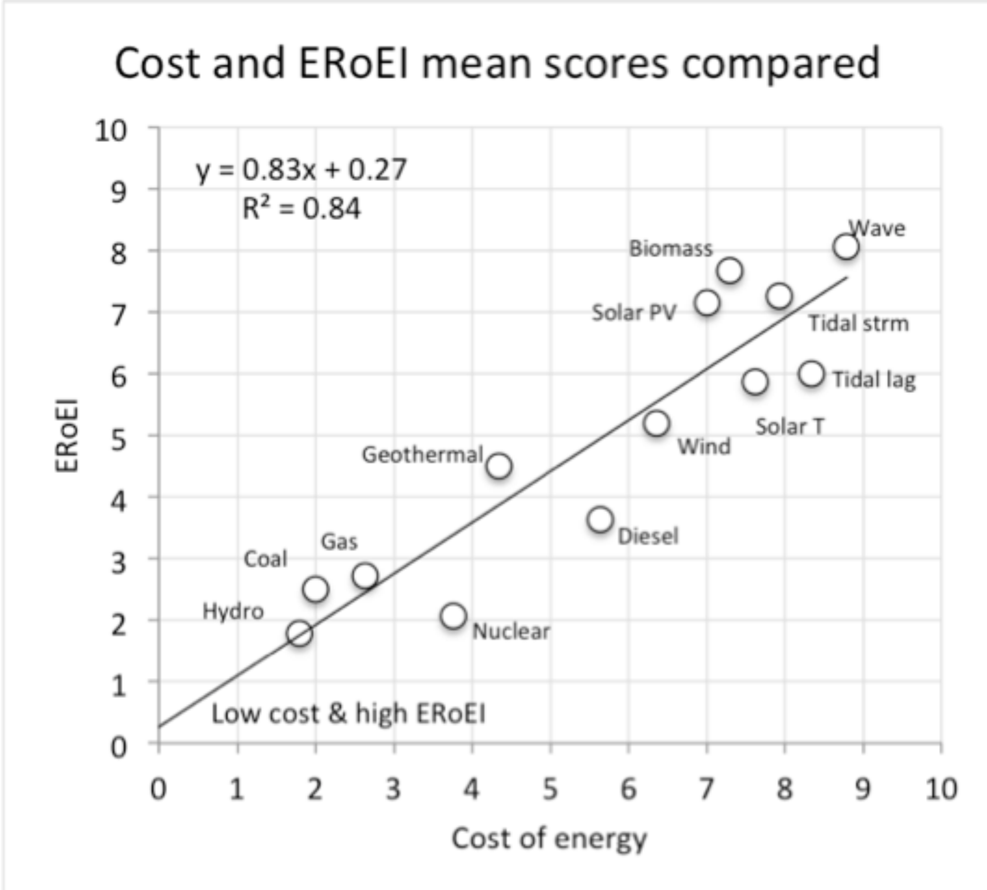
Validation was aimed at level 1 where we conducted 3 different kinds of tests namely:

1. Pairwise correlations between scores where a correlation was to be expected, for example between cost and ERoEI.
2. Comparison between our MCDA scores and real data, for example cost and reported LCOE values. (levelised cost of energy)
3. Comparison between our MCDA scores and total costs as determined by the NEEDS baseline cost approach.

Pairwise comparison

Cost of energy v ERoEI	0.84
Cost to grid v benefits to grid	0.97
Fatalities v Chronic illness	0.77
Cost of energy v Subsidies	0.83
CO_2 intensity v ERoEI	0.90 (non-combustion technologies)
Fatalities v Resource availability	0.05 (non-correlating)

The correlation coefficients are generally high, >>0.75 suggesting a high degree of consistency in the way our expert group allocated scores.

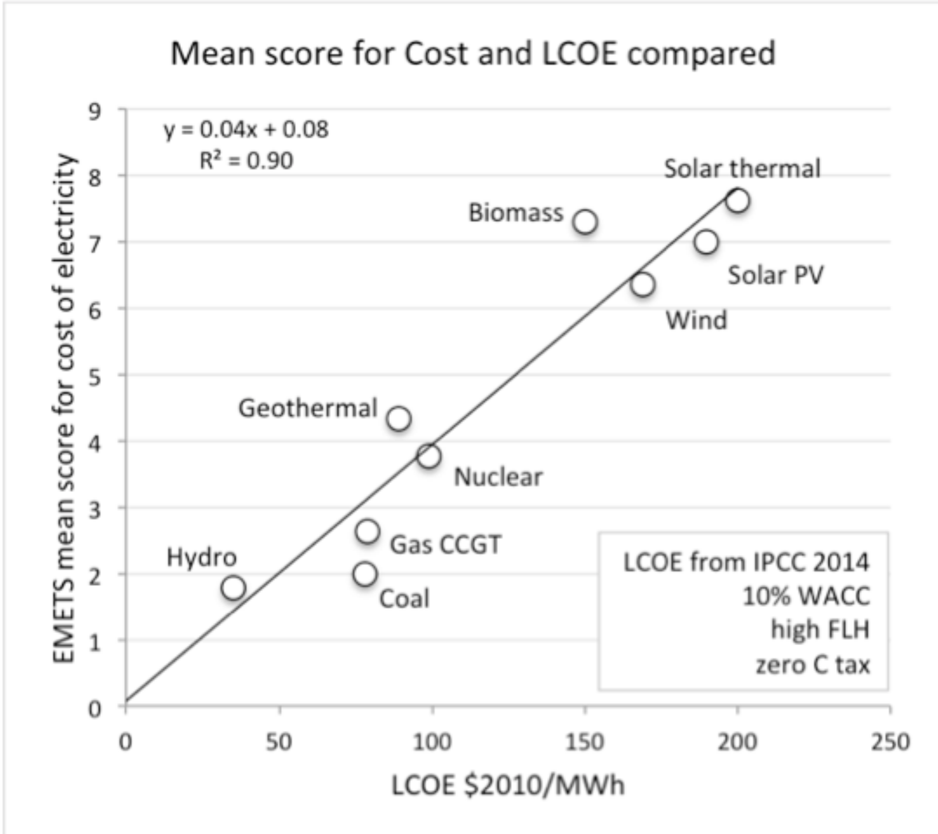


Comparison between MCDA scores and real data

	R^2
Cost of electricity versus Levelised Cost of Electricity [ref 47]	0.90
Fatalities versus Deaths per TWh [ref 48]	0.64
Fatalities versus Deaths per TWh [ref 49]	0.74
Chronic illness versus serious illness [ref 48]	0.80
ERoEI versus buffered ERoEI [ref 50]	0.92

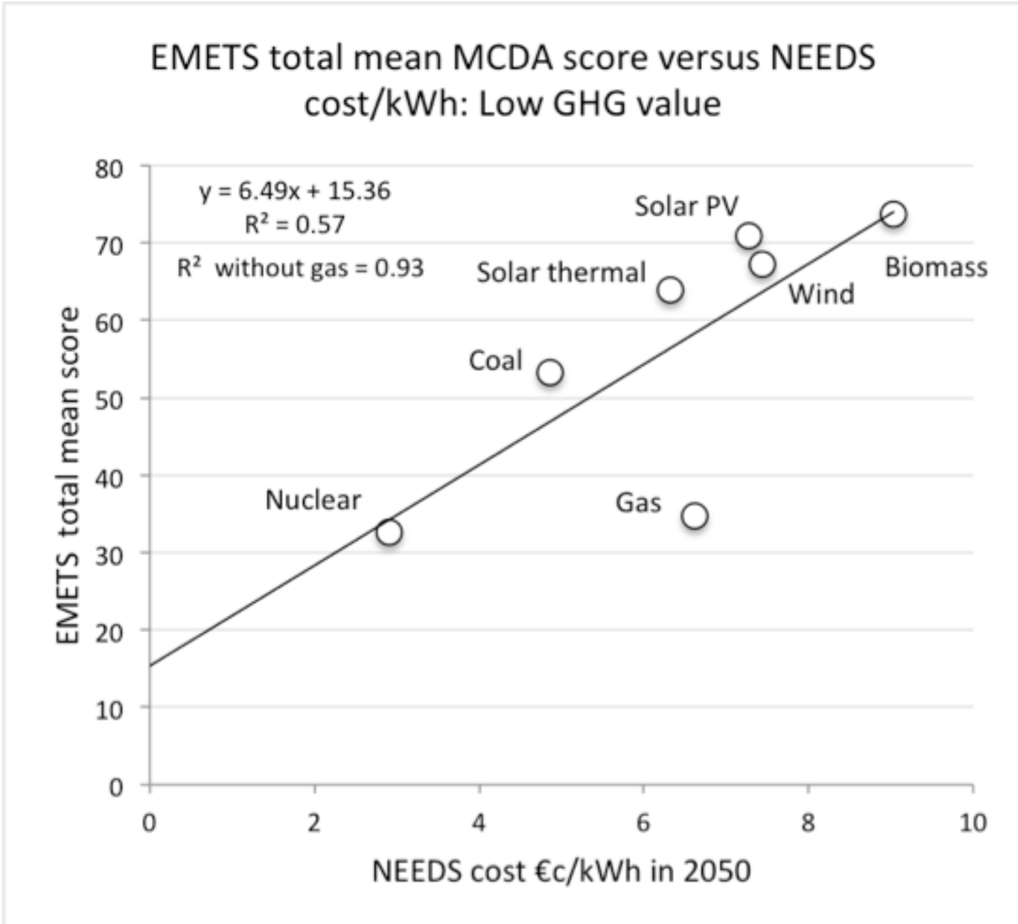
Where real world data could be found there is generally good agreement between our MCDA scores and the real world => we could reach the same conclusions without depending upon the expert judgement component of our study.

Expert judgement has the advantage of allowing a value to be attached to more obscure criteria such as external environmental costs and benefits to grid. And it is also very simple to acquire data.



Comparison between MCDA scores and NEEDS baseline costs

The NEEDS project assessed 26 electricity technologies, many of them highly specialised. We found approximate overlap with 7 of the 12 technologies we assessed. Comparing our total mean score with NEEDS baseline cost we find R^2=0.57. Gas is an outlier, and removing gas from the regression R^2, improves to 0.93. We observe that NEEDS estimated gas electricity to have similar cost to solar thermal and PV, but these estimates are for the year 2050. Its possible that NEEDS anticipated a rise in gas prices and / or the price of carbon. Alternatively, they perhaps did not properly price in the value of dispatch. Regardless, excluding gas we observe a high degree of consistency between the NEEDS baseline cost approach and our total MCDA scores.

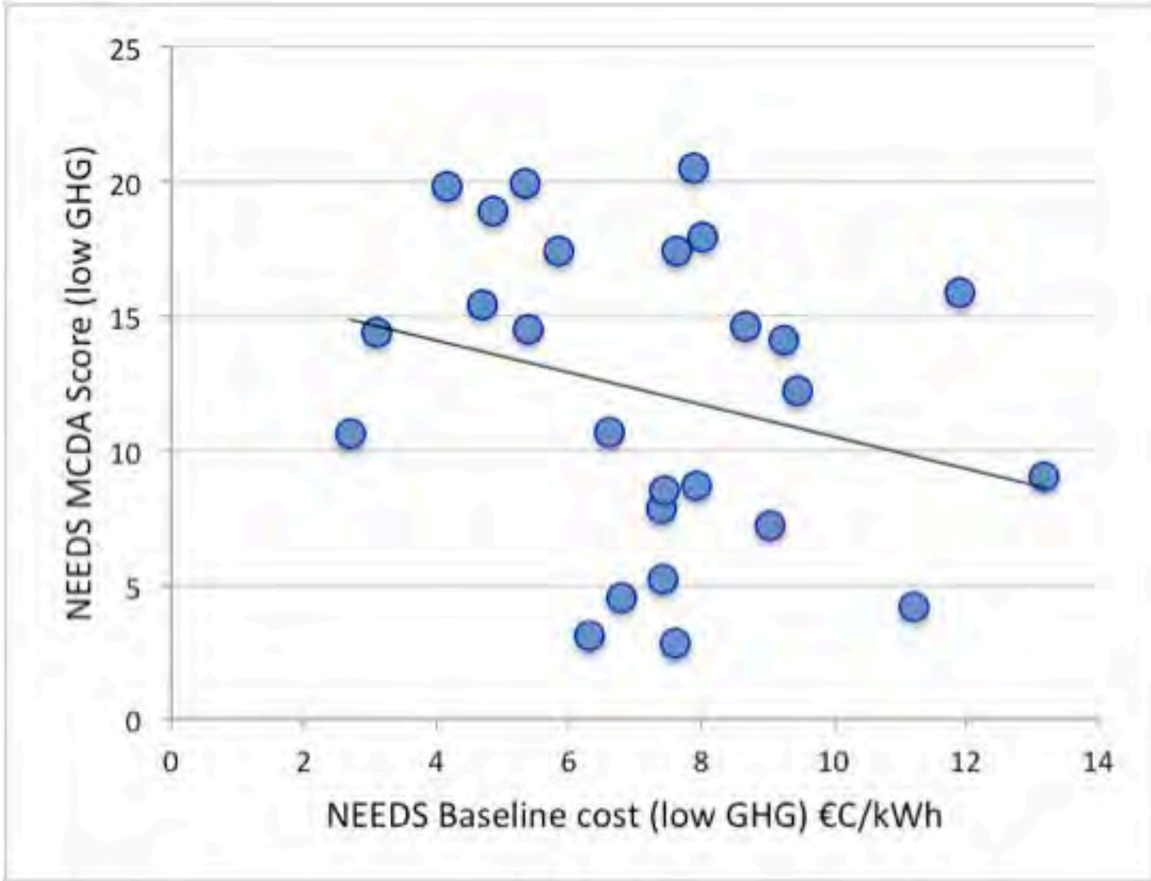


Comparing NEEDS baseline cost with NEEDS MCDA results

In tandem with their baseline cost approach, NEEDS also ran an MCDA survey. One might expect the two approaches to give similar results. In fact there is no correlation (R^2<0.1) and what correlation exists is negative.

In correspondence with Stephan Hirschberg, he explained that the baseline cost approach fails to capture public perceptions and social acceptance and that their MCDA study was specifically designed to reach a different conclusion.

Between reading correspondence from Stephan Hirschberg and the NEEDS reports, we find some alarming contradictions, statements and methodologies described.



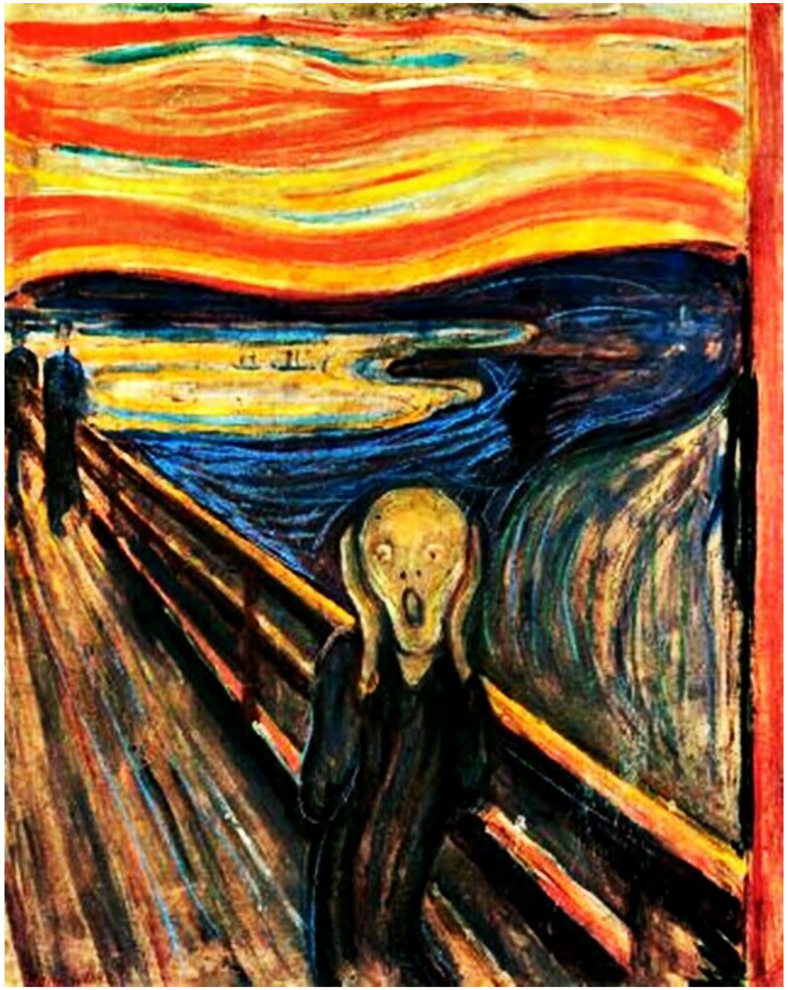
A few comments about NEEDS MCDA

- Uptake was very poor, of 2848 experts invited to participate only 275 did so and these were dominated by academics.
- The 26 technologies assessed included many esoteric technologies, such as a molten carbonate fuel cell. Our small expert group would not know where to begin evaualting this technology.
- The questions asked were impossibly difficult to answer.
- One participant did comment *“The indicators must also be understood by "normal people", right?*
- A “sophisticated” online user interface was developed where respondents could enter a score and a preference (effectively a weight) and could continuously monitor and compare the overall scores for the various technologies and adjust their inputs until they got answers perceived to be correct.
- The preferences were on an extremely aggressive scale: *a highly aggressive 7 point scale was used ranging from 1/16 through 1/4, 1/2, 1, 2, 4 and ending with 16. This provides leverage with a dynamic range of 256 where the stakeholder has the discretion to pour all the weight on a handful of criteria.*
- The questions were blatantly biased in favour of renewables and against nuclear power, one respondents comment: *“The questionnaire is one-sided in favor of renewable energies. Even fusion energy would be rated very poorly with these criteria.”*

Devoid of scientific merit

The decision-maker can see the consequences of his preferences, see whether or not the results agree with any preconceived ideas of the desired outcome, and hopefully reconcile any differences to a more consistent understanding. (in ref [19] section 2.3).

This effectively means that participants could fiddle the preferences until the desired result was obtained. As far as we can tell the NEEDS MCDA survey, part of an €11 million project, is largely devoid of scientific merit.



Has nuclear Energy a future?

Comprehensive assessments: external costs

On a cost basis, includes costs at plant, system, and societal levels.

Pollutants from burning coal (e.g., afflicting Poland and Germany) largely ignored in public debate.

Current nuclear cost-competitive. Cost of nuclear accidents not decisive, when smoothed out over time.

A full price would be substantially higher than the one we currently pay, and a market with a full price would therefore co-ordinate towards lower carbon sources, such as nuclear and PV/wind, with system costs becoming highly relevant.

Carbon taxes make a step in this direction, however being around 0.01 USD per kWh, tend to fall short of covering the true social (and grid level) costs.

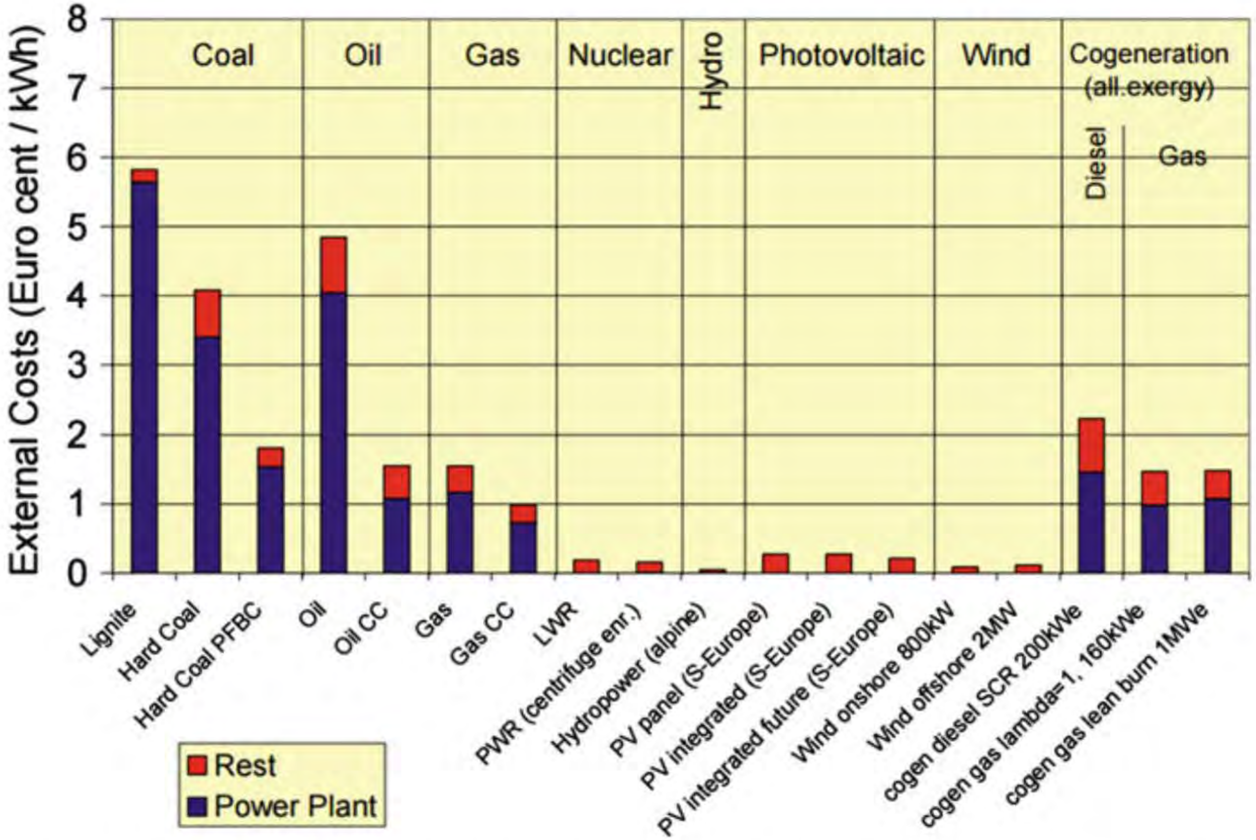


Fig. 1.15 Externalities of a range of energy sources, from the PSI and ExternE, 2005 (Dones, Roberto, et al. "ExternE-Pol Externalities of Energy: Extension of Accounting Framework and Policy Applications." Paul Scherer Institut (2005)). See the NEEDS project for further analysis. Nuclear (PWR and LWR) omits the severe accident externality

Call for exploration of future nuclear energy systems and technology

- To rely on wind and solar as the only feasible solutions is a strategic error. Carbon dioxide emissions continue to grow
- Serious outlooks and road maps support doubling nuclear capacity by 2050
- Paradox of Human Societies and Irreversibility: Need to maintain nuclear know-how to steward and resolve already existent nuclear waste problem.

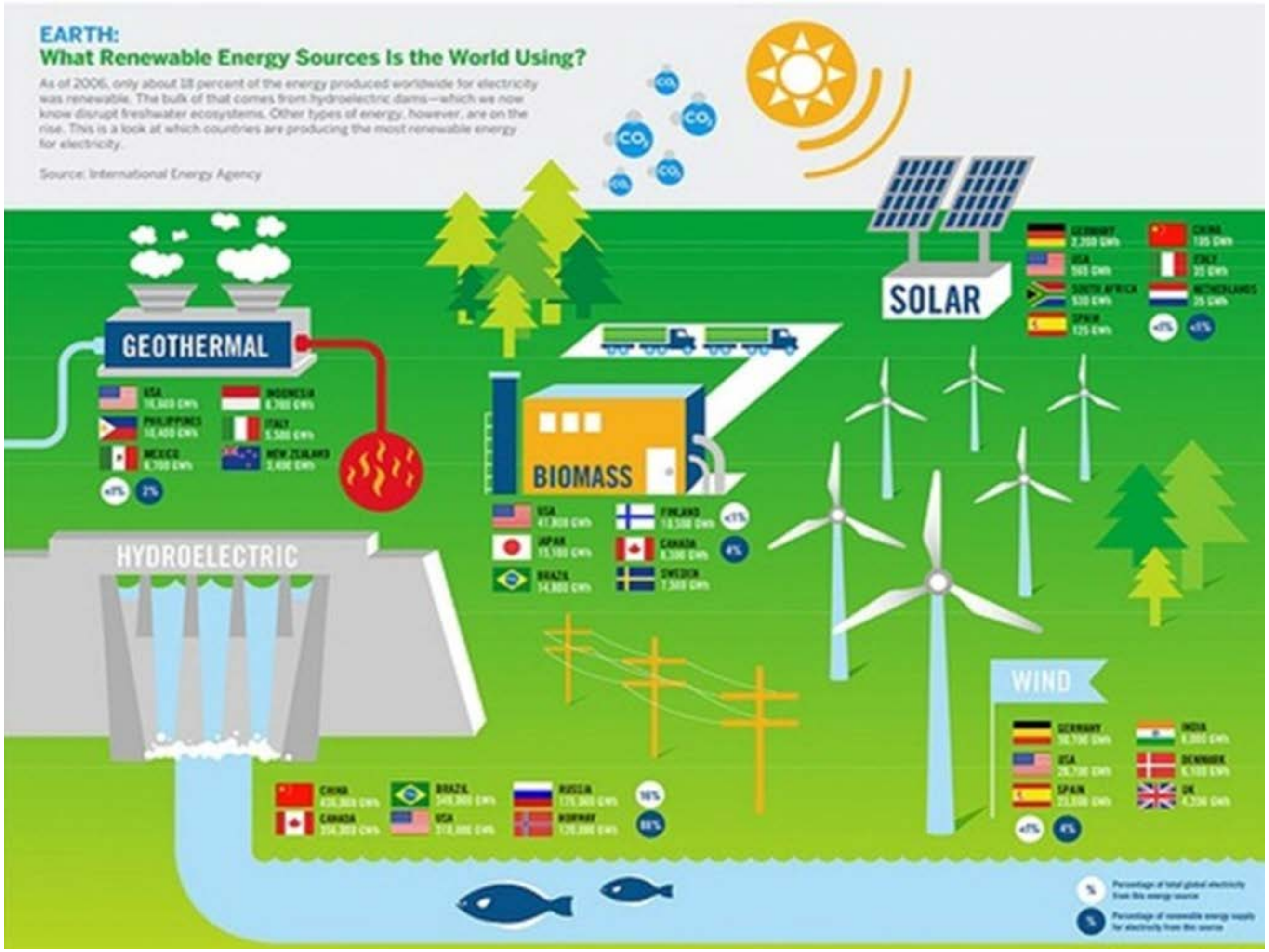
- Paris Climate Conference in 2015: Developed countries committed USD100 billion per year in climate change prevention and adaptation.
- We, along with others, call for an urgent increase in gov't and international R&D funding by two orders of magnitude—i.e., of the order of hundreds of billions of USD per year, for an international civilian "super-Apollo" program.
- This will deliver immense public benefit but also enable revolutionary innovations to be spun out that would not otherwise ever have been attained

Super-Apollo projects

WWII effort in time of “peace” but great global challenges

renewables, new materials, water, de-desertification, health, new nuclear, biotech, wetware (bio is tech), blockchain…

D. Sornette, A civil super-Apollo project in nuclear R&D for a safer and prosperous world, Energy Research & Social Science 8, 60-65 (2015)



need for **massive innovation / productivity policies** to complement / replace non-working monetary and fiscal policies globally