Reducing the risk of climate disequilibrium: material balances and costs for alternative low emissions energy sources

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1 Introduction.

Scientists tell us that to avoid potentially dangerous shifts in the dynamics of the climate we have to find some way to cool the planet or cut anthropogenic emissions of greenhouse gases by 80 percent or more on current figures. The first option is ignored in what follows except for a brief note. Concentrating on the second, energy usage accounts for about 75 percent of anthropogenic emissions. The remainder comes from agriculture and forestry. At a rough first order approximation this means that energy production has to be achieved at nearly zero emissions. In order to try understand what this would require I make some approximate calculations on the energy sources available. As far as possible I have calculated from primary data on energy and other physical constants. I have relied on secondary material for things that cannot be calculated from the ground up, for example mortality rates. In these cases I have tried to use such sources as the US Department of Energy, WHO, UN scientific reports, OECD, UK Government Reports, the International Energy Agency and so on. I also make some cost comparisons. Since costs are not a hard barrier to deploying energy sources it is only large differences in the costs of different technologies that are of interest and cost data has not been given a great deal of attention.

The same units of energy are used for all calculations and one unit of thermal energy from, say, burning wood or oil is treated as equivalent to one unit of electrical energy. This is explained below. It is assumed throughout that electrical energy can be transformed into the form required for manufacturing and transport and other activities.

The calculations include assumptions with a wide range of uncertainty and the data at the level of aggregation that interests us often has large variations. For example, we can only guess at the the global growth rate for the next twenty five years. Emissions from coal fired power plants depend on the mix of types of coal and the type of plant. Solar power will depend on cloud cover, and biomass on plant conversion ratios etc.

With these uncertainties in mind I am satisfied with estimates and predictions within a margin of error of up to 25 percent. The figures could be improved locally but we probably won't do a lot better for the global problem.

I am only concerned with the parameters of possible responses to the problem and do not set out to argue for or against any particular form of energy.

2 The problem

2.1. The basic structure

The problem of emissions reduction can be understood in terms of energy use and efficiency. More formally let α be total emissions, e be total energy, y be total output of goods and services and n be total population. Then

$$\alpha \equiv \frac{\alpha}{e} \times \frac{e}{y} \times \frac{y}{n} \times n$$

This gives the following possibilities for reducing emissions.

1. n. For practical purposes it is difficult to do much about population in the relevant time period.

2. $\frac{y}{n}$ is consumption per capita. It is also difficult to change this in the short run. Developed countries have not shown much enthusiasm for serious cuts in consumption and it seems unlikely that developing and underdeveloped countries would be prepared to arrest their growth.

3. $\frac{e}{y}$ is energy per unit of production. It is possible to reduce this through technological improvement and energy savings. It is difficult to assess how far these reductions might take us but clearly their are upper limits imposed by physical laws.

4. $\frac{\alpha}{e}$ is emissions per unit of energy. In this case the question becomes: can we get the energy we need in order to maintain existing levels of consumption and provide for future growth without exceeding the level of emissions that will produce dangerous shifts in the climate?

2.2. Geo-engineering

The problem of climate change might also be solved by finding some way of offsetting the effects of increased emissions by reflecting solar radiation or of capturing carbon dioxide and other greenhouse gases from the atmosphere by, for example, encouraging phytoplankton blooms. The first type of solution, and many of the second types, are usually referred to as geo-engineering. Much of the literature has focussed on various techniques to reduce the incidence of received radiation and I concentrate on this .[1] In most of the literature geo-engineering is seen as a means of assisting emissions reduction programmes or a last ditch emergency measure [20], although there is a literature that is more enthusiastic about adopting it as a solution [21, 17]. It is technically feasible but it also generates a number of issues if used as anything other than an emergency measure. These issues are of such a magnitude that geo-engineering solutions are not pursued here. Among the most important of these are:

[1] Carbon capture and storage from the atmosphere is much less feasible than from emission sources so I ignore it. The capacity of the ocean to absorb carbon dioxide through phytoplankton blooms is not clear.

1. A geo-engineering solution would have to continuously increase the rate of cooling to match increased climate forcing from emissions, unless the emissions problem were solved.
2. Any geo-engineering solution would have implications for international relations and raise issues of sovereignty over resources.
3. Among the arguments for geo-engineering are that there is insufficient political will to change patterns of consumption [21]. This seems to make the error of identifying the problem as consumption, rather than emissions. It then mixes up a plausible statement about consumption with an implausible statement about energy. It then assumes that the international will to undertake large planet reforming exercises would substitute for the lack of will to undertake less disruptive changes in energy production.

If on the other hand geo-engineering is seen as an emergency fix then the issues under consideration are different, but the need to reduce emissions remains.

2.3. Note on units of energy

Some clarification on units of energy might be useful. There are several different measures for power and energy such as the barrel of oil equivalent, horsepower, British Thermal Units and so on. I use the kilowatt (kW) and its multiples. One $kW = 10^3$ watts. I will take a standard power station as roughly the average coal, gas, or nuclear facility and round this to one gigawatt-electric (1GWe) or $10^9 watts\ electric$.

A small bar radiator, an electric iron, a micro-wave oven or a hairdryer usually has a capacity of about one kW. If one of these appliances is run for an hour its total energy usage is $1kWhour$. A clothes dryer with a capacity of $4kW$ would use $1kWhour$ in fifteen minutes.

2.4. Energy

The total energy consumption for the world including thermal energy in the form of heat from chemical reactions produced by burning stuff and electrical energy is about

$$150 \times 10^{12}\ kW\ hours/year$$

and, before proceeding, we need to consider how the different forms of energy in this figure relate. Electrical energy can be transformed directly into thermal energy whereas it usually takes more than two units of thermal energy to produce a unit of electrical energy. This might seem to justify rating a unit of electrical energy as worth two or three units of thermal energy and arguing that this level of consumption could be met with maybe half this amount of electricity. My reason for treating a unit of thermal and a unit of electrical energy as equal and not scaling in this way is that the conversion does not reverse. Turning electrical into thermal energy, by putting it into batteries for cars or using it for cooking, for example, will not produce two to three units of thermal energy.

Since much of the discussion is in terms of solar, wind and nuclear energy as electricity producers nothing much is lost with this assumption. Biofuels are the only exception and will be discussed directly in terms of thermal energy.

To produce this amount of energy would require a production capacity of approximately

$$17 \times 10^9 \ kW$$

Under the assumption that all forms of energy as equivalent and using the one-to-one conversion ratio this requires about 17,000 standard power stations operating at full capacity. This would require about

$$21,000$$

power stations at .8 capacity.

Since the US uses about 20 percent of this it needs about 4,000 standard power stations.

To get some order of magnitude, an average US consumer uses about

$$250 kW hours/day$$

or the equivalent of running 250 bar radiators for an hour or about ten bar radiators for a full day.

A standard power station running at full capacity would produce enough energy for about 100,000 US consumers.

An average EU consumer uses about

$$125 kW hours/day$$

2.5. Growth and efficiency and total consumption

Since total demand will be affected by efficiency and growth we need to consider what figures we should work with. It might be assumed, for example, that if we take efficiency into account and reduce the $\frac{e}{y}$ we could produce the same amount of stuff using 100×10^{15} $Watt\ hours/year$. On the other hand we need to allow for growth. Assume that the world's economy grows at 2 percent per year between now and 2050 and approximately doubles. This gives a new total energy requirement, after allowing for efficiency of

$$200 \times 10^{12} \ kW \ hours/year$$

with the obvious variation between regions.

This tells us that growth can quickly wipe out efficiency gains. For this reason I will simply go ball park and work with current energy use.

2.4. A few rough figures

Some rough figures might help put the problem into context. I use metric tons although the difference between metric and imperial is not significant for our purposes.

1. Electricity consumption is a bit less than 20 percent of total energy use in the developed world. This might be expected to increase with shifts in consumption and in the energy profile of transport with the fastest increase in developing countries.

2. A standard coal fired station burns more than $10,000$ tons of coal a day although this varies considerably with the type of coal and the type of station. It may be as much as 1.5×10^4 tons. This means a standard station burns about 5×10^6 tons of coal a year and produces an equivalent amount of waste. Solids are about one thirtieth of this waste and include about fifteen tons of radioactive material. They also include arsenic lead and mercury. The rest is mostly emissions from combustion. This gives a total of about

$$17 \times 10^6 \; tons \; CO_2 \; per \; year$$

if we ignore emissions from mining and transport.

3. A standard slow neutron reactor on a once through cycle burns about 25 *tons* of fuel a year and this is the bulk of its solid waste, if we ignore mining and refinement. Waste from a fast neutron or breeder reactor may be as little as 1 *ton* per year, depending on type. Ignoring mining and fuel fabrication greenhouse gas production is approximately zero.

4. Without land use change the average per capita production of greenhouse gases per year in tons are approximately [40]

US	24.3
Australia	25.6
Germany	12.3
Britain	11
France	8.8
China	3.9
OECD average	10.5

5. Assume an elephant has a mass of 5 tons and that the average life expectancy of a US citizen is eighty years. It follows that, under the current technology mix, an average American will produce a mass of greenhouse gases equivalent to about

$$400\ elephants/\ person/\ lifetime$$

6. It is difficult to predict the volume of emissions if all energy were produced using wind and solar as a primary source. This will depend on the assumptions made about the back up facilities.

7. If all energy were produced using nuclear reactors emissions would go to zero.

8. A once through slow neutron reactor produces about

$$20kg/\ person/\ lifetime$$

of radioactive waste. This would fit into one or two soft drink cans. If waste from refining is included then

$$200kg/\ person/\ lifetime$$

9. If we use an integral fast reactor the total waste, including that from refining is less than

$$1kg/\ person/\ lifetime$$

or about the amount that would fit into the shell of a D size flashlight battery. This is made up of fission products with a relatively short half life, and for most of it this is less than one year.

3 Comparative costs

3.1. Estimating comparative costs

The comparative costs of energy are calculated calculated per unit of energy over the life time of the project and this is called levelized cost. Let $i(t)$ be the investment at time t, $m(t)$ maintenance cost, $f(t)$ fuel and other operating costs, $r(t)$ the rate of interest and $e(t)$ energy produced at time t. The levelized cost of a project is then given per unit of energy generated over the life of the project. This is calculated as

$$c = \frac{\sum_{t=1}^{n} \frac{i+m+f}{(1+r)^t}}{\sum_{t=1}^{n} \frac{e}{(1+r)^t}}$$

and the National Renewable Energy Laboratories have a simple on-line calculator for this [23].

The value of c is sensitive to assumptions about the rate of interest. At low rates long lived technologies such as nuclear do much better than at high rates. Figures given here have used commercial rates of between 5 and 10 perrcent.

The US Department of Energy and the OECD put the cost of coal without capture and storage and nuclear as roughly equivalent with onshore wind at slightly less using levelized costs if the back up costs are not taken into account [10]. Hydro and gas without capture and storage are the least expensive. Offshore wind is more expensive and solar thermal is more expensive again. If carbon capture and storage and grid costs are taken in to account gas, onshore wind and nuclear remain roughly equivalent and are the least expensive after hydro with offshore wind and solar thermal about two times more expensive [27]. Other studies give similar figures, for example ([7], p.27).

Here is a table that combines the US Department of Energy projected levelized cost in dollars per MWh (that is one thousand kWh) and the OECD figures for grid level costs [10, 27]

gas	95
on shore wind	106
advanced nuclear	110
coal with CCS	138
solar pv	173
solar thermal	289

The Royal Academy of Engineering attempted to make a comprehensive survey of all costs for the British Government [29]. This put wind coal and nuclear at about the same levelized cost without carbon capture and storage, systems costs or back up facilities. If all additional costs are included wind and coal are twice as expensive as nuclear and solar is six times more expensive.

A recent study by the Bureau of Energy and Resource Economics in Australia puts nuclear less expensive than all technologies except gas from landfill and roughly equivalent to gas turbine generation and to onshore wind on 2012 average figures. It is about one third the cost of solar thermal. See AETA: Projected technology cost ranges (2030) [4].

3.2. Direct cost comparisons

These figures can be checked with some direct estimates. The worst case for nuclear is the Olkiluoto station in Finland being built by Areva. This is a first of a kind and has had a series of delays and cost increases. Its final cost is about $\$6.5 \times 10^9$ per GWe capacity [41]. A South Korean consortium is building four power stations in the United Arab Emirates at $\$3.6 \times 10^9$ per GWe capacity [47] and the Chinese are currently building the Westinghouse AP1000 at betweeen \$2.1 and $\$2.6 \times 10^9$ per GWe capacity.

For comparison we can use some figures on recent installations in Spain and Australia. Capital costs for a proposed wind farm in South Australia with biomass back up are about $\$7 \times 10^9$ per GWe capacity [6]. Using figures from Moree in Australia photo voltaic is about $\$20 \times 10^9$ per GWe capacity without back up and the Gemasolar CSP plant in Andaluca concentrated solar is about 25×10^9 per GW capacity with back up [3].

On these figures the capital cost of nuclear using the most expensive case is about the same as on shore wind with back up and this is less than the two solar options.

Although wind and solar have lower operating costs than nuclear they have a shorter life with perhaps $60 - 80$ years for a nuclear plant and at best about 25 years for a wind turbine or a solar installation. This gives a slightly lower levelized cost so the figures check out.

3.3. Cost projections under uncertainty

It is sometimes asserted that solar and wind will become less expensive than alternatives. This assertion is usually based on the error of allowing the cost of one technology to decrease while assuming other costs remain constant or increase.[2]

4 Wind

4.1. Total capacity

The calculations for the total potential capacity of wind are made using highest plausible estimates. I concentrate on the US and make the assumption that the wind availability is no worse than average and probably better than most tropical areas with high populations. To make the presentation easy I will start with some figures given by Elliott [11] and then check using primary data. The areas with the greatest potential for wind energy are North Dakota, Wyoming, and Montana with a combined area of approx $807,000km^2$. It is assumed that $435000km^2$ is covered with wind farms or roughly half the total area or something like the area of California. If it is assumed that the average power density is $1.2W/m^2$ this gives approximately $4600 \times 10^{12}kWh$ which is

$$42\ kWh\ per\ day\ per\ person$$

or something approaching current electricity use or less than one fifth of total energy demand for the US.

4.2. Calculations of wind energy

To check this figure use the National Renewable Energy maps of wind speeds across the US [22]. The average in these areas is approximately $6m/s$ at a height of $30m$. Power per unit area for wind is the

[2] It could also be applied to nuclear since production technologies at scale are relatively less mature than solar or wind.

kinetic energy energy per unit of time. This is $\frac{1}{2}mv^2$ where the mass of the air is density times volume, $m = density \times velocity \times time$. So we get a power p per square metre of

$$p = \frac{1}{2}1 \times 6^3 \approx 110W/m^2$$

The maximum theoretical possibility for extracting energy by a disk type windmill is about .6. I assume we can get close to this at .5 although probably about .3 would be more plausible. Now assuming a blade diameter of $d = 25m$ the area is $\pi(\frac{25}{2})^2$ we get the average power per windmill of

$$\tilde{p} = .5 \times 110 \times \pi(\frac{25}{2})^2 \approx 27kW$$

Optimal spacing is about five times diameter so this give one windmill per $(5 \times d)^2 = 15625$ with an average output of

$$1.7W/m^2$$

which is roughly consistent with the calculation above allowing for gaps in the terrain and the generosity of the efficiency estimates.

By building taller windmills it is possible to get more power per unit but at the cost of extra spacing and less efficiency. For example with $d = 54m$ turbine load capacity would be about .3 and redoing the calculations roughly halves the watts per metre squared.

In a similar way assume we cover most of the US shallow offshore water with offshore wind farms to get an area of about $20,000km^2$. If the power density is more than twice that calculated above at $3W/m^2$ we can get about

$$4.8kWh/d/person$$

5 Solar

5.1. Large scale systems

1. Solar thermal systems. Solar thermal seems the best option for large scale production with storage capacity. The estimates here are based on a scaled up model of the Andasol 1 parabolic trough system in Spain. This is located in an area of high radiation and gives a best case and data on output and costs are readily available [23, 36, 25, 2]. This uses curved mirrors to concentrate radiation. It also has capacity for seven hours of heat storage. Although this is not full coverage and additional back up would be needed the capacity figures give a more realistic assessment of the totals required than a straight up solar photo voltaic plant with no storage.

Andasol has a capacity of $50MWe$ with a capacity factor of .4 to give an average of $20MWe$. Its build cost is $\$.5 \times 10^9$ and it covers a land area of $2km^2$ [36]. To get to a capacity of $1GWe$ we have to scale up by a factor of 50. This is near enough although area may not vary in a simple linear manner. Assume a nuclear reactor operates at an output of .9. To make solar thermal equivalent to a nuclear reactor requires about $90 - 100km^2$.

Current US energy use requires more than 3×10^{12} capacity or about $3,000$ Andasol 1's which would cover an area of $300,000km^2$. This is a square with each side roughly $600km$ or 360 miles. This is approximately the area of New Mexico or Arizona or half Texas.

World energy would require roughly five times this capacity.

Material requirements for Andasol 1 are approximately: 65,100 tons concrete; 20, 300 tons steel; 6, 700 tons glass. So scaling op to $1GW$ gives the reactor equivalent of solar as

3.2×10^6 tons concrete

1×10^6 tons steel

$.3 \times 10^6$ tons glass

To produce $3,000$ solar thermal plants of the Andasol type would require the total US concrete production for 20 years and the total steel production for 30 years at current rates.

2. Photo voltaic. The maximum theoretical efficiency of these panels is about 45% and most commercial panels are about 10%. To get some figues for large scale production consider the Topaz solar farm currently under construction at St Luis Obispo in California and expected to be finished 2014 [44] and the Nellis solar power plant with axis tracking in Nevada [37]. Topaz covers an area $25km^2$ or $9.5mile^2$. From the manufacturers data it is expected to produce about $1,100$ $GWh/year$. Nellis covers $6 \times 10^5 m^2$ and generates $30GWh/year$.

A standard power station running at about .9 produces roughly $8,000GWh/year$ so we need about eight Topaz type plants. This covers an area of $200km^2$ or about 76 $miles^2$. A similar calculation gives the same figures for Nellis.

To produce all the energy required by the US would require something like the size of Texas or twice that of New Mexico.

4.2. Rooftop photovoltaic

The National Renewable Energy gives the maximum radiation in the south western US for south oriented panels as $8 - 9kWh/m^2/day$ with an average of less than $4.5kWh/m^2/day$ across the US if we adjust for population and ignore Alaska [22].[3] Because it has axis tracking Nellis gives us the best case.

[3] There are less coarse figures but they won't make much difference at this level of approximation.

Taking into account a capacity factor of .2 and assuming an efficiency of .1 it works out that the plant is capturing about $5kWh/m^2/day$.

Assume that all south facing roofs in the US are covered with solar panels and that there is about $10m^2$ or about $107ft^2$ of roof per person. In this case the maximum output obtainable from solar panels with an efficiency of .2 operating under perfect conditions is $.2 \times 4.5kWh/m^2 \times 10m^2$ which gives

$$9\ kWh/person/day$$

with a more realistic figure when operating conditions are taken into account of about

$$6 - 7kWh/day/person$$

which gives less than

15% of total electricity consumption

or

3% of total energy consumption.

6 Bio-mass

The most efficient plants have a maximum capacity of about two percent in converting solar power to biomass although most are much less with the exception of sugar cane which has a potential efficiency of over three times this[38]. Converting solar radiation to energy in bio-fuels it has an efficiency of about .4 percent [8] and if we use the previous average of $5kWh/day/m^2$ this gives an energy conversion of about $1W/m^2$. Assume we convert the total agricultural land area in the US to production of energy from biomass and that there are no problems with water supplies and so on. Most plants that could be grown only have about a third the capacity of sugar cane so to be on the high side, assume that our plants have an energy yield of $.5W/m^2$. Total agricultural land in the US is less than $4,000 \times 10^9 m^2$. This gives a total yield of less than

$$.5 \times 10^{-3} \times 4 \times 10^{12} kW$$

and this gives approximately

$$160\ kWh/person/day$$

We need to make some adjustment for the energy cost of producing and transporting this biomass. Suppose it is .3 of the energy currently used in US food production. Total energy used is $300 \times 10^{11}\ kWh/year < .8 \times 10^{11}\ kW/h/day$ so .3 is $2.4 \times 10^{10} Wh/day$. Subtracting gives

$$80\ kWh/person/day$$

which is about one third of the energy needs of the average consumer.

If we assume that people want to eat a more realistic, and still generous, assumption is that about 10 percent of the agricultural land is devoted to biomass. This gives

$$8\ kWh/person/day$$

or about three percent of total energy needs.

I think even ten percent of agricultural land is a generous assumption. Such land is relatively scarce in Europe, India and Asia so we would expect the per capita figures to be less attractive.

7 Back up and transmission costs

The problem of backing up solar and wind can be solved by using either conventional power plants, batteries or an extended grid of wind and solar installations. If this is done with either bio-fuel, fossil fuel or nuclear stations it may require something in the order of $80 - 95$ percent of installed capacity for wind ([7], p. 23) and something similar for solar. This raises questions about capital cost and the running efficiency and emissions intensity of back up plants. It also raises questions about volume of emissions saved. I leave all these to one side.[4]

It is difficult to get even a not very good estimate for batteries as costs will vary with the type of storage and level of decentralization. Among the cheapest form of rechargeable batteries are lead acid and the minimum cost for a battery with a storage capacity of $2.5kWh$ is about \$200. This means it would cost about \$10,000 every ten years or so depending on battery life to provide for an average US household for one day at the 50 percent level. Other factors that we would need to consider are whether this amount of back up is adequate, the way in which costs scale for larger batteries, material balances and the grid costs of charging spikes.

What would happen if wind and solar were dispersed across a wide geographical area and energy were transmitted from points with high output to compensate for low output elsewhere? This is less straightforward than it sounds. Since solar is not available for about sixteen hours a day, a combined wind and solar system would be required. If we treat solar and wind as as independent random events there is nothing to suggest that every time the sun coin flips an off the wind flips an on coin. To continue to err on the optimistic side for solar and wind I will ignore this. If we could always get backup from somewhere in the grid what would it cost?

[4] I have so far not been able to get good technical data on the characteristics of fossil fuel and nuclear plants operating on a stop go basis.

In order to get a rough estimate of long distance transmission costs I will use the figures for the lines from France to the UK currently under construction [39]. This gives a cost of $\$5 \times 10^6\ /GW/km$ which is less than an overland line from Spain to France. To put this into perspective $1,000km$ of transmission for one GW will cost more than a nuclear reactor.

How much capacity would be needed and what distance would need to be covered? It is difficult to say without detailed calculation on weather patterns and solar storage capacity, but it might be reasonable to assume that multiple transmission lines would be needed. To get an idea let us assume that we need the equivalent of two north south and two east west transmission lines across the continental US with a capacity of $500GW$. These lines give a total distance of $10^4\ km$.

With these estimates the total cost of transmission would be $\$5 \times 10^6 \times 5 \times 10^2 \times 10^4$. This gives

$$\$25 \times 10^{12}$$

In other words, enough to build between $5,000$ and $10,000$ nuclear power stations.

How good are these figures? I am only guessing. What if they are only half the estimate? They could of course also be twice as large. If they are half and they scale then the cost would build between $2,500$ and $5,000$ reactors which would still cover all the needs of the US.

What if we assume that we only transmit one fifth of this capacity and that transmission lines can be built at half the cost. Then the cost is

$$\$2.5 \times 10^{12}$$

or about 700 nuclear reactors.

If solar power from North Africa were used for the European grid similar, or greater, orders of magnitude might be anticipated. Distances and costs would probably be about the same although the capacity of the transmission lines might need to be greater.

8 Nuclear

8.1. Introduction

The main problems associated with nuclear are waste, safety and fuel supply and beliefs about the first two of these have been amongst the major reasons for opposition to nuclear power. Capacity constraint, transmission and intermittent supply are not significant. Cost has already been dealt with. I begin with a brief description of three important types of reactors.

8.2. Characteristics of nuclear reactors

Commercial once through pressurized water reactors. Most electricity is currently produced by once through slow neutron reactors with an average capacity of about $1GW$. These typically use pressurized water as a means of heat extraction. By once through is meant that the fuel is used until all the energy that is commercially available for this type of reactor is burnt and the remainder is discarded. This is about 25 tons per year. By slow neutron is meant the speed of the neutrons in the fission process. This process burns up less than 1 percent of the energy available in the original uranium ore.

Fast breeder reactors. The term 'breeder' comes from the process whereby a reactor can increase the available nuclear fuel by converting U238 and other non-fissile elements into fissile material such as PU239. Most fast neutron reactors can be used as breeder reactors and are sometimes referred to as fast breeders. The breed ratio can be set so that the reactor creates more or less fuel than it consumes. it follows that a fast breeder reactor has the capacity to extract most of the energy from the 200 tons of mined uranium used to get fuel for a slow neutron reactor and also to use the 25 tons of waste. Taking into account efficiency losses this allows them to extract about 100 to 150 times more energy from a unit of uranium than slow neutron reactors. It is also possible to use Thorium, Th232 as a fuel, which the reactor converts to U233. This is roughly three to five times more abundant than uranium.

Fast breeder reactor have been run experimentally since the 1940's using lead or liguid sodium as a coolant. One current design is the integral fast reactor which reprocesses and recycles waste on site. It requires about $90kg$ of uranium for fuel each month, or about four to five shoe boxes.

It is also possible to use slow neutron reactors as breeder reactors. In this case the best fuel source is Thorium, Th232, which the reactor converts to U233. This is roughly three to five times more abundant than uranium.

Small nuclear reactors. Small reactors are usually considered to be anything up to about $300MWe$. These were originally developed for military use and there are active development programmes in the US, Russia, China, France, Japan and South Korea. There are now several commercial designs starting from a capacity of about $5-10$ MWe reactors. These are sufficient to supply all the energy needs of about 500 to $1,000$ people or the electricity needs of about $2,000$ to $4,000$ people at current American rates of energy use. See [49] for a complete list and description of current designs.

Small nuclear reactors can be either slow or fast neutron. Most of the newer designs are fast neutron, including the standing, wave reactor.[5]

[5] This is being supported by TerraPower with investment by Bill Gates.

There are a number of features that make small reactors interesting. Among these is that they can be massed produced and shipped to site. It would be expected that this will dramatically reduce costs per unit of capacity. They can also be used as 'plug and play' power units or to operate as U-batteries with the capability to run for at least ten years without refueling. In addition they can be shipped to unstable regions as closed units and replaced as needed.

8.2. Waste problems

As with other toxic substances waste needs careful management but it is difficult to find any significant issues, that is issues that cannot be solved with current technologies and within reasonable cost parameters. See the previous discussion of using waste as fuel.

8.3. Safety

It is often claimed that nuclear reactors are inherently unsafe or present an unacceptably large threat to health and the environment. Here is a brief sample of the claims used to support this position.

1. Almost a million people have died as the result of the accident at Chernobyl with potentially more dying as the result of Fukushima [14, 28].

2. Reactors can create a nuclear explosion and/or Fukushima and Chernobyl were nuclear explosions [45]

3. Fukushima has caused moose and deer in the united states to die and has increased cancers in Alaska, California, Hawaii, Oregon and Washington by 28 percent [18]

4. Fukushima could result in a nuclear explosion that would wipe out Japan completely and cause the West Coast of America to be evacuated [18, 30]

5. Fukishima is a disaster that is comparable to the tsunami that killed $19,000$ people and to Hiroshima [13].

6. A nuclear power plant could be struck by a hijacked plane causing widespread radioactive damage and rendering large areas of land uninhabitable [15].

7. A dirty bomb made of nuclear waste and conventional explosives could create catastrophic consequences [9].

How realistic are these claims?

The first point is that a nuclear reactor cannot create a nuclear explosion without violating the laws of physics and to claim by association that it has some parallel with Hiroshima is simply wrong. If the laws of physics don't impress you look at the photographs of Hiroshima and Fukushima. This means we can ignore 2 and the premises of 4 and 5 above. What of the claim that Japan may be lost and the West Coast of America may need to be evacuated or that the effects of Fukishima are comparable to the tsunami?

Threats to health. For estimated fatalities and incidences of illness we can look at the reports from the United Nations the World Health Authority and related organizations. These are based on a linear no-threshold model which it is thought may significantly overestimate the effects of small doses of radiation [26].

Chernobyl Some two decades after the explosion 47 workers had died of acute radiation syndrome and nine children died of thyroid cancer. The Chernobyl Forum, comprising a number of UN agencies including the International Atomic Energy Agency, the World Health Organization, the United Nations Development Programme , other UN bodies and the Governments of Belarus, the Russian Federation and Ukraine, used the Linear Non Threshold Model to put the estimated number of possible deaths in the highest areas of exposure at 4000 [19]. This was later upgraded to $9,000$ to cover a larger area [43]. Without the linear no-threshold extrapolation the death toll remains at 56. It was also reported that mental health problems resulting from lack of accurate information about risk was the largest public health problem created by the accident. Figures for fatalities from mental health causes were not given [19].

Fukushima The World Health Organization report in 2013 found no observable increases in cancer and estimated that there would be no observable increases in future in the general population. It estimated some increase in baseline rates amongst the most affected emergency workers[46]. The United Nations Scientific Committee drew on 80 scientists from 18 countries. It found that there have been no cases of radiation sickness and no attributable health effects. It also stated that it is unlikely that there will be any attributable health effects at any future time [34].

Comparisons. Here are some typical figures based on recorded deaths and estimates of deaths from respitory illnesses, carcenogenics and the like [12]. To get some idea of the figures a million GWh is about the amount of electricity produced by 100 standard power stations in a year.

Energy Source	**Mortality Rate** (deaths/millionGWhr)
Coal global average	170,000
Coal China	280,000
Coal U.S.	15,000
Oil	36,000
Natural Gas	4,000
Biofuel/Biomass	24,000
Solar (rooftop)	440

Wind	150
Hydro global average	1,400
Nuclear worst case estimates	90
Nuclear - commercial power plants only	0

It is tangential but might put the nuclear figures in perspective to look at the bombings of Hiroshima and Nagasaki. The pre-bombing population was approximately $450,000$. Some $200,000$ were killed as the direct result of the bombing. Of the remaining $250,000$ approximately $2,000$ died of cancer caused by radiation. There was no noticeable increase in the rate of birth defects.

Terrorist attack. A number of studies have shown that nuclear plants are not vulnerable to terrorist attack. One obvious reason is that they are difficult to hit and much less attractive than other targets, such as large public gatherings.

Consider the worst and most implausible case of a terrorist attack. Assume something of the size of a fully-fuelled Boeing 767-400 of over 200 tonnes hits the dead centre of the outside of a round containment vessel at 560 km/h. A study carried out by the US Electric Power Research Institute estimated that this could not penetrate any part of the outer containment [51]

Dirty bombs. Although dirty bombs sound dramatic the vast majority of deaths would be from the conventional explosion with few if any from radiation and there is nothing to suggest that large areas of land would need to be quarantined. Some psychological damage may result from mis-information about the danger of radiation.

8.4. Proliferation issues

It is sometimes claimed that there is a link between nuclear energy and weapons proliferation. This is not currently an issue because:

1. Nearly all the major producers of greenhouse gases are states that already have nuclear weapons.
2. Waste from once through reactors is not immediately deployable as weapons grade material without enrichment facilities and, in this case, it is simpler to enrich something else.

If fast neutron reactors are used in future or states without nuclear weapons build enrichment facilities there may be an issue with proliferation. To say this, however, does not mean there is an uncontrollable danger any more than there is with the more high risk activity of commercial flight.

Among the management protocols that could easily be adopted for states that do not currently have nuclear weapons are:

1. Continuous monitoring of fast reactors and fuel use;
2. Guaranteed nuclear fuel replacement to prevent the need for enrichment;

3. Providing reactors with locked down fuel systems that prevent entry or tampering in potentially high risk or unstable regions.

8.5. Fuel supply

It is sometimes claimed that there is insufficient fuel to run enough nuclear reactors to reduce emissions. How much is there?

Measured resources of ore bodies depend research effort which responds to price. About 7.1 million tons of uranium reserves that can be extracted at less than $\$260/kg$ are currently known [50]. There are about 400 reactors currently operating and each requires somewhat less than 200 tons of ore a year. This means the current fleet requires about $70,000\ tons/year$ of ore. It follows that, without any further exploration, there is enough ore to run the current fleet, or its technological equivalent, for about 100 years at near to existing prices.

International Atomic Energy Association figures put total known reserves at about 13 million tons if the price cap is removed with roughly an additional 22 million tons in unconventional reserves. This gives enough to run the current fleet for about 500 years.

To get a more realistic long term assessment we need to consider all available fuel sources and technologies.

1. Fast neutron reactors use uranium 50 to 100 times more efficiently than the current once through cycle. If we assume an efficiency of 50 we have enough fuel to get the equivalent output of our existing fleet for $25,000$ years. Alternatively we could run $20,000$ fast reactors for about 500 years.

2. If Thorium is used as fuel we can run $20,000$ reactors for an additional $1,500$ years to give a total of about $2,000$ years.

3. It is also possible to extract uranium from the oceans with current technology. If ten percent of the estimated $4,000 \times 10^6$ tons of uranium in the ocean is extracted we can run $20,000$ reactors for about $12,000$ years.

I think any estimates beyond this are bordering on meaningless and have not included guesses for new discoveries or extraction technologies.

8.4. Rate of build

It is sometimes claimed that we cannot build nuclear reactors fast enough to deal with the problem of emissions [16].

There are some problems with the logic of this claim when it is used to draw the conclusion that we should, therefore, get energy from sources that are probably even slower to build.

To get some idea of the possibilities, take the most recent example of a large scale programme. France built nuclear reactors at the rate of about six a year between the 1970's and 1990's with about five percent of the world's GDP. This equivalent to about four of our standard reactors. This gives us about one a week globally. If, for example, we had started to built reactors at this rate starting in 2000 we would have $2,500$ plants by 2050. This is enough to cover all current electricity needs or about 25 percent of emissions. A much faster rate would be attainable with a modest programme based on mass production.

8.5. Land area comparisons

In many places population densities are higher than the US and using land for energy is costly in terms of its alternative uses in growing food or in preserving forests and habitats for endangered species. Land can be put to more than one use with wind turbines although this may not be compatible with forests and nature reserves. Some land areas have already been calculated but it is worth reflecting on some rough estimates of the area required to replace a standard power station operating at a .9 load in view of alternative environmental and other uses.

Wind. From the previous this would require a windfarm of about

$$600\ km^2$$

or about $230 sq\ miles$ if we assume a power density of $1.5W/m^2$.

This is a square with sides $25km \approx 16$ miles long. It would cover an area more than seven times the size of the island of Manhattan. Fifteen wind farms would take an area about the size of Yellowstone National Park.

Solar. From my previous figures on scaling up the Andasol solar thermal plant we need about

$$100\ km^2$$

or about $40 sq\ miles$.

This is a square with boundaries of $10km$. This is about one and a half times the area of Manhattan. If photovoltaic is used we need a square twice this size.

Nuclear. A current generation reactor takes an area of about

$$.05km^2$$

and it we add an exclusion zone we get

$$2km^2$$

or maybe .4 km^2 if we site reactors in clumps. This could presumably be used as a reserve.

9 Remarks: a personal note

My remarks in this section are independent of the main paper in which, as far as I could, I have stuck with the arithmetic. These are largely driven by my belief that maintaining anything close to existing levels of emissions caries a high probability of changing the dynamics of the climate in ways that may be extremely costly, or even catastrophic for current living standards and the hopes of the underdeveloped world. This weighting of risks and cost is, of course, a subjective matter.

1. Based on the calculations I believe that, if we want to do something about climate change, we need to undertake a programme of building nuclear reactors. There is room for all renewable sources, but my guess is that wind and solar could not meet more than about $20 - 30$ percent of our total energy needs in a reasonable manner. I would want to make more detailed analysis of grid level costs and back up before making a firm statement. My personal estimate of the dangers associated with climate disequilibrium is such that I would simply go straight for nuclear at the highest economically sustainable rate. Other people may have a lower estimate of the dangers of shifting the climate and a preference for other options including extending solar and wind beyond something like the 20 percent level. It should be made clear, however, that this is a personal preference based on opposition to nuclear and has nothing to do with climate change, safety or cost.

2. I have not provided calculations for carbon capture and storage. Not only are there problems with scaling the technology and with storage capacity and with cost, but there are issues with the logic of digging up stored carbon and then trying to store it again. My rough figures indicate that capture and storage may require an additional fuel loading of up to 50 percent of the original burn up rate for a coal plant.

3. I have not dealt with the argument that nuclear is not economically viable because private investors are reluctant to take riks. This seems to be based on confusing economic cost with what is in the interests of maximizing profits in a particular market.

4. I have been disappointed by much of the anti-nuclear material. Much of it is based on the fallacy of believing that a problem with energy source A means that the alternative is better, or the energy fairy fallacy. Some is simply misinformed and, in many cases, it is recklessly misleading.

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