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Climate change and the cost of going green

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1 Climate change and the cost of going green

With the pandemic of Covid 19 under control, the media has turned its attention again to climate change. One might be forgiven for thinking there is now a headlong rush to become green and carbon neutral but at what cost.

2 The predictions

The climate models currently in use predict only the future to 2100. Beyond that date there are just too many uncertainties; global warming by more than 8 degrees, the worst-case scenario by the end of the century, could result in chaotic behaviour. Although mid level stabilisation at 4 degrees by 2150 is probably more realistic[1], see figure 1.

[1]This corresponds roughly to a maximum of 800 parts per million of carbon dioxide in the atmosphere or double the present value

Warming oceans and sea-level rise should result in more carbon sequestration by forests and phyto-plankton in the sea while also generating more clouds and increasing the albedo thus reducing greenhouse heating. However, it is possible that too much warming will prevent the formation of clouds and result in a runaway heating effect, much has happened in the Paleocene-Eocene thermal maximum event of some 56 million years ago after the dinosaur extinction[2]. Temperature rise of 12 degrees and CO_2 concentration of 3000 parts per million occurred as a result of intense volcanic activity. Eventually the planet cooled after about 100,000 years and the ice ages occurred. The direction of travel for the planet at the end of this century is therefore very uncertain but until then, models predict steady global warming and sea-level rise; probably only by 3 degrees or maybe less than 2 if CO_2 is substantially reduced.

The pandemic resulted in an almost 20 percent reduction in CO_2 emissions during 2020 but had little effect on temperature. The analogy of a bath full of water with just the taps turned off is misleading because the plug is still out as carbon continues to be sequestered by the forests and oceans. The moral seem to be that a substantial reduction in air and motor travel for decades will be required to have a significant impact on the apparently inexorable rise in global temperature.

3 Achievement of carbon neutrality

Currently the most activity is centred on reducing fossil fuel use in energy production, manufacturing and transport. The biggest

[2]Schneider, T., Kaul, C.M. Pressel, K.G. Possible climate transitions from breakup of stratocumulus decks under greenhouse warming. Nat. Geosci. 12, 163167 (2019). https://doi.org/10.1038/s41561-019-0310-1

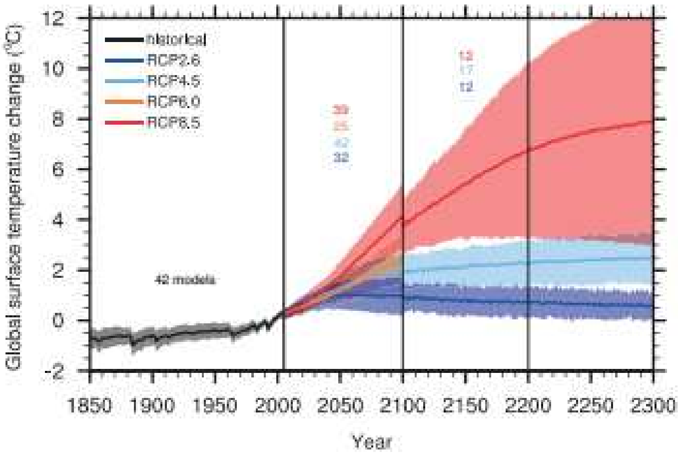

Figure 1: Long term global warming
IPCC report Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner, 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5$_{C}hapter12_{F}INAL.pdf$

carbon dioxide production globally is for energy hence the growing clamour for solar and wind power with electric transport systems. In manufacturing there will be a continued need for fossil fuels to produce steels and plastic even if all energy production by coal oil and gas is eliminated. In construction, concrete is a major source of carbon dioxide emission and in all probability the possibility of sequestering atmospheric carbon to build structures up from the atomic level using nanotechnology is many decades away. In fact, a headlong rush to build wind turbines, solar power stations and battery-powered transport is likely to increase carbon dioxide emissions significantly while the change to new technologies is completed; probably over two or three decades.

4 The cost of carbon neutrality

At a local level, the UK has committed to removing gas boilers from new housing by 2025. Currently, gas heating is a quarter the cost of heating by electricity. What impact will this have upon those in the population who can barely afford heating at present in winter in England? The attempt in 2006 under the Blair government to achieve carbon neutral housing with level V regulations was abandoned because the cost of building doubled. In fact it is now easier to raze a property to the ground rather than attempt to modify the structure to be carbon neutral.

The cost of electric cars is still more than double those of the petrol equivalent although this is reducing. However, the increased use of electricity will require changes to the infrastructure and place greater demands on electricity generation. Moreover, the loss in petrol tax income for the government is likely to result in some form of mileage charge for car usage.

Finally at a local level, the life-cycle of car batteries is still uncertain with recycling of the small battery elements very labour intensive. However it is hoped that the increasing use of lithium and rare earths in electric cars will be from recycling although initially more mining will be required.

5 The global cost

The main global contributors to carbon dioxide are from burning coal, gas and oil and producing steel and cement. The reactions are:

Coal (221C), natural gas (CH_4) and oil (e.g. C_8H_{18}), summarized as

$$C + O_2 \rightarrow CO_2 + \text{heat} \ , \tag{1}$$

and

$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O + \text{heat} \ , \tag{2}$$

The heat of combustion is used to generate electricity, propel motor vehicles, etc. Other important activities include the manufacture of cement, most typically by the reaction:

$$CaCO_3(\text{limestone}) \xrightarrow{\text{heat}} CaO + CO_2 \ ; \tag{3}$$

which requires a great deal of heat, The generation of iron and steel:

$$Fe_2O_3(\text{haematite}) + \tfrac{1}{2}O_2 + C \xrightarrow{\text{heat}} 2Fe + 2CO_2 \ : \tag{4}$$

the production of glass:

$$Na_2CO_2 + SiO_2 \xrightarrow{\text{heat}} Na_2SiO_2 + CO_2 \ , \tag{5}$$

and of silicon:

$$SiO_2 + C \xrightarrow{\text{heat}} Si + CO_2 \ ; \tag{6}$$

these reactions also require heat in order to proceed at a reasonable rate (mixing sand with powdered coal at room temperature does not produce silicon), which is usually provided by the combustion of fuel. One may note that all the reduction activity needed for extracting metals from ores is due to our oxidizing atmosphere having been at work for thousands of millions of years.

Calculation of carbon released in metric tons and energy generated in mega Joules (MJ) by fuels gives:

$$\text{Cton} = \text{Fton}/\text{MolCrel} \times 10^6, \tag{7}$$

and energy released:

$$\text{Ej} = \text{FtonHj} \times 10^3; \tag{8}$$

where Cton is the carbon released to the atmosphere in metric tons, Fton is the mass of fuel or mineral in metric tons, Mol is the molar mass of the fuel or mineral in grams, Crel is the number of carbon atoms released in the reaction, Ej is the energy in mega Joules(MJ) of the reaction and the specific heat of the fuel is Hj in MJ per kg. Note 1 J = 1 Ws.

The results for fuels are shown in table 1.

Table 1: Carbon and Energy release from 1 metric ton of fuel

Fuel	molar Mol g	no C Crel	Hj MJ/kg[a]	Cton tons	Energy Ej MJ
Coal(221C)	3142	221	20	0.8440	4.47×10^4
Gas(CH_4)	16	1	50	0.7500	5.06×10^4
Oil(C_8H_{18})	114	8	45	0.8421	4.47×10^4

[a] World Nuclear Association: Heat Values of Various Fuels, https://world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx

For minerals the carbon released from producing the useful product is shown in table 2

Table 2: Carbon release from 1 metric ton of mineral

mineral	molar Mol g	no C Crel	Cton tons
Cement(Ca CO_3)	100	1	0.1200
Steel(Fe2O_3+C)	160	1	0.0750
Glass(Na_2 CO_2+SiO_2)	136	1	0.0882
Silicon(SiO_2+C)	60	1	0.2000

Globally the situation from 2019/20 data for fuels is shown in table 3, where carbon released is in giga tons (Gtons). Energy produced is in the form of electricity generated assuming 60 percent of fossil fuel is used and the average efficiency of generation is 50 percent.

Table 3: Global carbon release and electricity energy generated in 2019/20

Fuel	mass Fton tons	C Gtons	Energy MJ
Coal[a]	8.00×10^9	6.752	4.80×10^{13}
Gas[b]	2.05×10^9	1.538	3.08×10^{13}
Oil[c]	4.47×10^9	3.764	6.03×10^{13}
Total		9.30	1.39×10^{14}

[a] IEA, Coal 219: Analysis and Forecasts to 2024, https://www.iea.org/reports/coal-2019

[b] IEA, Natural Gas Information: Overview; Detailed and comprehensive annual data on natural gas supply, demand and trade, July 2020:https://www.iea.org/reports/natural-gas-information-overview

[c] IEA, Oil Information: Overview; A comprehensive reference on current developments in oil supply and demand, July2020, https://www.iea.org/reports/oil-information-overview

The global effect of mineral processing is shown in table 4

6 Wind energy

The global change as a percentage of carbon released by building wind turbines over time t yrs may be described by the following:

Table 4: Global carbon release from mineral processing 2019/20

Mineral	mass Fton tons	C Gtons
Cement[a]	4.40×10^9	0.528
Steel[b]	1.90×10^9	0.143
Glass[c]	3.50×10^7	0.003
Silicon[d]	5.00×10^6	0.001

[a] Constructech; Global Cement Consumption; https://constructech.com/global-cement-consumption

[b] World Steel Association: Crude Steel Production APRIL 2021: https://www.worldsteel.org

[c] ICG; Towards an International Year of Glass in 2022: https://www.iyog2022.org/images/files/77-economicsiyog-200925.pdf

[d] statistica; Silicon - Statistics and Facts, Sept 2020: https://www.statista.com/topics/1959/silicon/ - dossierSummary

$$\text{Ctot} = (\text{PdotTton}/\text{Co}+((\text{Edot}-\text{Pdot}3600\times12\times365)\text{t}+\text{Eo})/\text{Eo})10^2; \quad (9)$$

where Ctot is the percentage change of carbon released to the atmosphere per year, Pdot is the production rate of construction of turbines in number per yr, Tton is the carbon released in Gtons in constructing a 1 MW turbine, Edot is the rate of increase in global electricity demand in MJ per yr, Eo is the energy base usage for 2019/20 in MJ (the total from table 3), while Co is the base carbon released in Gtons from fossil fuel electricity production, also from table 3. It is assumed that the turbine operates on average at full capacity for 12 hrs per day[3].

Note that this equation 9 makes no reduction in the use of fossil fuel for electricity generation unless Ctot is decreased because of greater supply than demand, in which case it may be assumed that the reduction in carbon emitted is due to a pro rata decrease in fossil fuel used: otherwise the wind energy mostly

[3]National Wind Watch:https://www.wind-watch.org/faq-output.php

satisfies the increasing demand. This reduction will only be possible if electricity demand growth decreases while increased Ctot implies more electricity is supplied by fossil fuel burning.

Wind turbines require significant raw materials to construct, mainly concrete and steel which in production generate atmospheric carbon. This is shown in table 5 for a typical 1MW tower.

Table 5: 1 MW wind turbine resources and carbon released in construction

Steel tons	Cement tons	C released Tton tons
100[a]	500[a]	67.50

[a] Wikipedia; Wind Turbine: https://en.wikipedia.org/wiki/Wind turbine

Global electricity growth is shown in table 6.

Table 6: Global electric energy demand

2007 MJ	2020 Eo MJ	growth Edot MJ[a]/yr	%increase/yr
1.75×10^{14}	2.28×10^{14}	4.04×10^{12}	1.78

[a] IRENA; RENEWABLE ENERGY TECHNOLOGIES: COST ANALYSIS SERIES, June 2012Wind Power: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2012

The current 2020 growth rate for wind farms is some 100 GW per yr[4], see figure 2. Even doubling this rate barely achieves neutrality.

However, if global electricity demand grows by a third the 2020, table 6, rate to 0.6% per yr then there is hope for some carbon neutrality, see figure 3.

From the graphs, 2 and 3 it is apparent that increasing the number of wind farms globally just releases more carbon and merely

[4]IRENA; Wind Energy: https://www.irena.org/wind

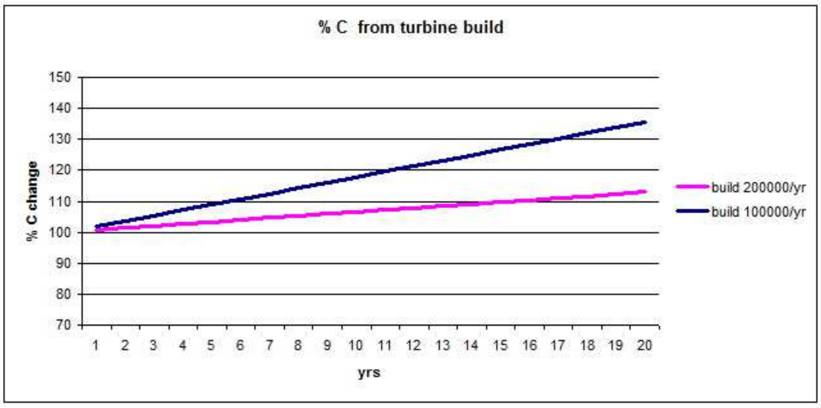

Figure 2: Global change as a percentage of carbon released by building wind turbines over time

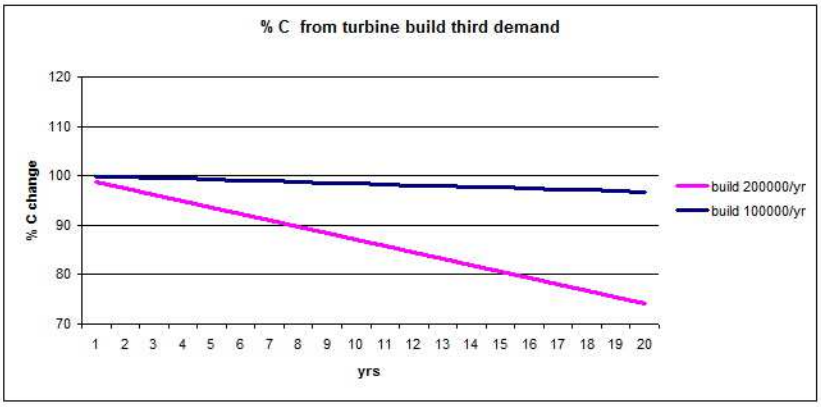

Figure 3: Global change as a percentage of carbon released by building wind turbines over time: one third demand Edot/3

supplies the increasing demand for electricity. In fact, the current trajectory for the rate of production for wind farms exacerbates the situation although it is possible that economies of scale will occur with larger 50 MW turbines and greater output with offshore installations. The only real solution is to reduce the rate of demand for electricity and even if reduced by a third, will carbon emitted in the production of electricity reduce? At this point reduction in fossil fuel generation could then also be considered. There are many assumptions in this linear prediction of anthropogenic carbon emission but it is indicative of the problems; massive investment in more wind farms by a factor two, with consequent loss of land usage unless offshore, and reduction in energy demand from the wealthiest nations while curbing the demands of those nations still developing. Although better insulation will reduce heating demand in those countries in the temperate latitudes, the push to electric transport will probably offset this gain.

7 Solar energy

A similar equation, 9, for the global change as a percentage of carbon released by building solar farms over time may be used, where typical solar farm output at capacity only occurs for 2000 hrs per yr[5].

Resources for the construction of a typical 1MW solar farm are shown in table 7.

The current 2020 growth rate for solar farms is some 25 GW per yr[6], see figure 4 for the impact on global carbon release.

[5]Wikipedia; Sunshine duration: https://en.wikipedia.org/wiki/Sunshine duration

[6]IEA, Solar PV; Renwables 2020: https://www.iea.org/reports/renewables-2020/solar-pv

Table 7: 1 MW solar farm resources and carbon released in construction

Steel tons	Cement tons	Glass	tonsC released	Tton tons
56[a]	47[a]	70.0[a]	16.02	

[a] https://solaredition.com/raw-materials-breakdown-for-building-a-1-megawatt-solar-photovoltaic-plant-2017

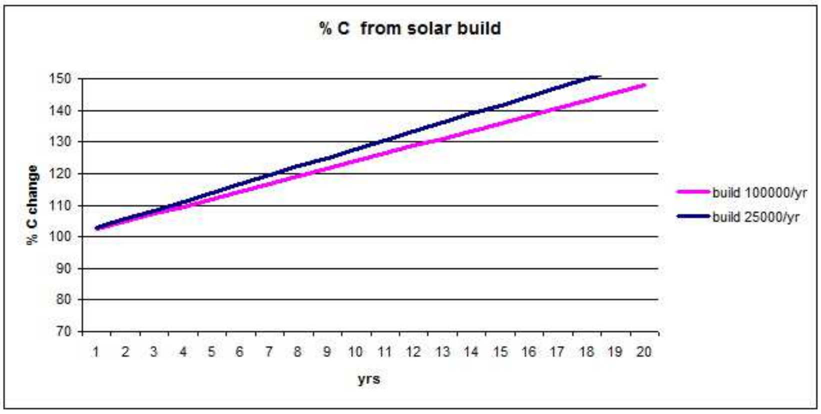

Figure 4: Global change as a percentage of carbon released by building solar farms over time

Again if global electricity demand grows by a third the 2020, table 6, rate to 0.6% then there is hope for some carbon neutrality, see figure 5.

A similar picture emerges for solar powered farms in the two figures 4 and 5. Increasing the efficiency of photo voltaic cells is likely, although a factor four increase in number of solar farms is used here which may be achieved by technology improvements, and should alter the energy mix dependence on fossil fuels but again land use for solar farms is considerable, typically 4 acres per MW[7].

[7] Suncyclopedia; Area Required for Solar PV Power Plants: http://www.suncyclopedia.com/en/area-required-for-solar-pv-power-plants

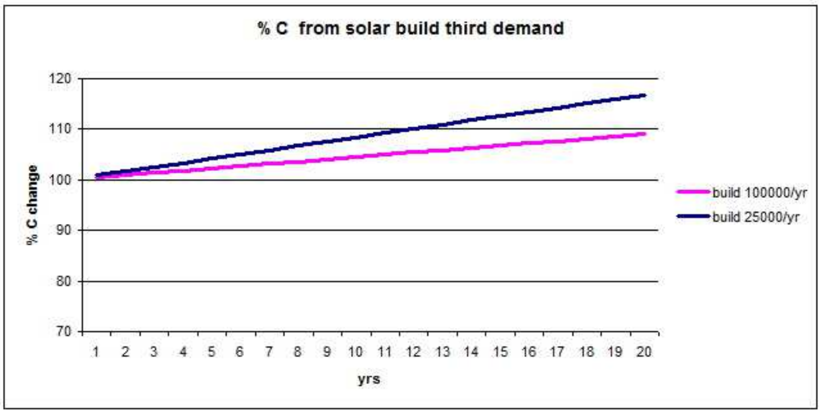

Figure 5: Global change as a percentage of carbon released by building solar farms over time: one third demand Edot/3

8 Conclusions

The foregoing is a relatively simplistic approach to answer the question, what is the cost of achieving carbon neutrality? Many of the assumptions made could change over the next two decades and technology advances may well improve the situation but it seems that real reduction in anthropogenic carbon emission in the production of energy is a goal that is barely achievable. It is likely on our current trajectory that living costs will be increased by this attempt to become carbon neutral and a temperature rise held at 1.5 degrees C over the next eight years is probably not possible.

Even combining the growth in solar and wind energy barely achieves neutrality as shown in figure 6.

As deforestation still has the greatest effect on reducing carbon sequestration[8] it may well be worth spending less on renewable energy and giving the money to those developing countries who

[8]G Holt and J Ramsden, Climate Change from First Principles, Collegium Basilea 2019: https://www.amazon.co.uk/dp/1523298138

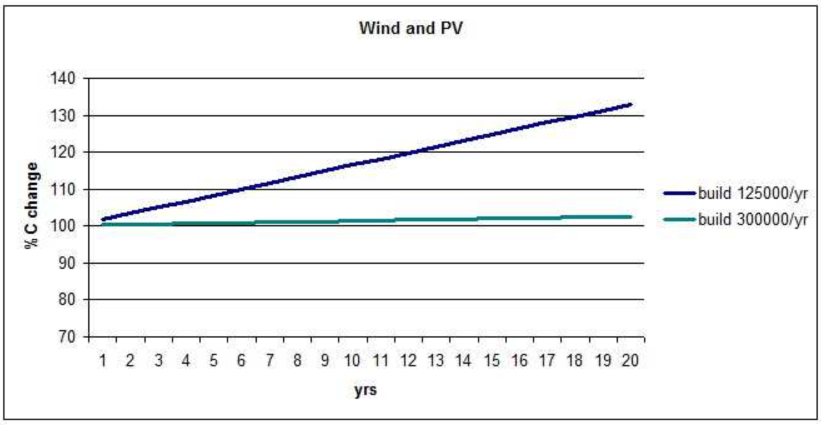

Figure 6: Global change as a percentage of carbon released by building both wind and solar farms with current electricity demand increase rate

wish to exploit the forests. Similarly nuclear fission is a big supplier without emitting carbon once built, where lessons have now been learned making it a tested technology unlike offshore wind where longevity and maintenance costs are not yet fully established. Meanwhile rising sea levels will reduce land availability and the ability to sustain life through farming. Whether or not this will reduce the global population is moot; certainly the Covid 19 pandemic has hardly dented the number and the reality is that only population decline will reduce the demand for power. The future is changing and perhaps Mars looks attractive.