Net Zero: what, why and when?

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China has set a goal of “carbon neutrality” by 2060; the European Union is aiming for “climate neutrality” by 2050, but has left open the implications for methane policy; while many other countries, cities and companies, including the UK and USA, are aiming for “net zero emissions” by or before mid-century. All of these phrases refer in some way to Article 4 of the Paris Agreement: “In order to achieve the long-term temperature goal (LTTG) … Parties aim … to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century”. While “carbon neutrality” is relatively unambiguous, at least at a global level, when multiple climate forcers are involved, the appropriate definitions of “balance”, “climate neutrality” and “net zero emissions” that are consistent with the LTTG depend on the interpretation of the LTTG itself, and in the context of the ultimate objective of the UNFCCC, the LTTG takes primacy.

Fortunately, the science is straightforward. The IPCC Special Report on 1.5°C (SR1.5) stated: “Reaching and sustaining net-zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing would halt anthropogenic global warming on multi-decadal timescales (*high confidence*). The maximum temperature reached is then determined by cumulative net global anthropogenic CO_2 emissions up to the time of net zero CO_2 emissions (*high confidence*) and the level of non-CO_2 radiative forcing in the decades prior to the time that maximum temperatures are reached (*medium confidence*).”

Expressing these statements quantitatively and in terms that are well-established in the IPCC and UNFCCC, human-induced warming ΔT over any multi-decade time-interval Δt depends on three quantities, in descending order of importance, both in absolute terms and in explaining differences between scenarios of future emissions:

1. Net cumulative CO_2 emissions added up over that time-interval, $\overline{E_C}\Delta t$, $\bar{E}$ being average annual CO_2 emission rate over the time-interval and Δt is its duration in years;
2. The impact of any change in global energy imbalance, or radiative forcing, due to non-CO_2 climate drivers between the beginning and end of the time-interval, ΔF_N;
3. The slow adjustment to a persistent non-CO_2 radiative forcing, $\overline{F_N}\Delta t$, where $\overline{F_N}$ is the average non-CO_2 radiative forcing over the time-interval.

$$\Delta T = \kappa\left(\overline{E_C}\Delta t + \frac{\Delta F_N}{\alpha} + \frac{\rho\overline{F_N}\Delta t}{\alpha}\right), \qquad (1)$$

where κ is the Transient Climate Response to Emissions, $\alpha = \mathrm{AGWP}_H/(\gamma H)$ where AGWP_H is the H-year Absolute Global Warming Potential of CO_2, $\gamma = (1 - e^{-\rho H})/(\rho H)$, and ρ reflects the rate at which CO_2-induced radiative forcing declines under sustained net zero CO_2 emissions (approximately 0.33% per year, which is also the rate required to maintain constant global temperatures). Noting that this expression applies to multi-decadal changes, ΔF_N can be defined as the difference between the average over the decade prior to the beginning of the time-interval, and the decade prior to the end (even the “fast” climate system adjustment is not instantaneous).

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Despite its simplicity, equation (1) accounts for future warming to well within the range of internal variability across a broad range of scenarios. Hence, we could interpret achieving net zero and climate neutrality as reducing the right-hand-side of this equation to zero, maintained over a multi-decade time-interval, hence halting the increase in global average temperature. Another way of expressing this would be achieving net zero CO_2-warming-equivalent emissions, defined as the quantity in parentheses above, or the CO_2 emissions that would give the same warming as results from a combined CO_2 and non-CO_2 forcing series. There are a number of ways of estimating CO_2-warming-equivalent emissions, but in all cases they must equate a change in emission rate of a short-lived climate pollutant with a one-off pulse emission or removal of CO_2.

How soon do we have to achieve net zero CO_2-warming-equivalent emissions in order to meet the Paris LTTG of "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C"? Again, this is simply a matter of geometry (and the interpretation of the LTTG), since the rate of human-induced warming equals the rate of CO_2-warming-equivalent emissions multiplied by the TCRE. The SR1.5 estimated human-induced warming in 2020 had reached 1.1°C, increasing at 0.2°C per decade, implying that a steady reduction in CO_2-warming-equivalent emissions (or deceleration in warming) to reach net zero (halt) in 2060 would limit peak warming to about 1.5°C. Revised historical temperature and forcing datasets indicate human-induced warming in 2020 has reached 1.2°C, increasing at 0.3°C per decade, which means limiting peak warming to 1.5°C would require net zero CO_2-warming-equivalent emissions by 2040, although whether the 1.5°C referred to in the LTTG should also be revised to reflect the same post-2015 warming that the Parties thought they were aiming for at the time of signing would be a matter for the Parties.

Either way, halting global warming by 2050, or achieving net zero global CO_2-warming-equivalent emissions by that date, although clearly challenging, remains a plausible operationalisation of the goal of limiting the increase in global average temperature to 1.5°C. Given the current rate of warming, every decade's delay in reaching net zero, even assuming CO_2-warming-equivalent emissions begin to decline immediately, adds a further 0.15°C to peak warming, so even limiting warming to "well below 2°C" requires net zero CO_2-warming-equivalent emissions by 2070.

An alternative interpretation of net zero has emerged in climate policy circles, as net zero CO_2-equivalent emissions aggregated using a particular greenhouse gas metric. This cannot be related unambiguously to any temperature outcome but at a global level is generally seen as more ambitious, and hence preferable, than "just" halting human-induced global warming. It may, of course, be necessary to aim for a long-term decline in global temperature, or some $\Delta T < 0$ over the second half of this century. If that is decided, then equation (1) remains applicable to determine what emissions are needed to deliver this more ambitious goal. As we see it, however, the concept of net zero emerged from our understanding of how CO_2 affects global temperatures and what it would take to achieve a temperature goal, not vice versa, supporting an interpretation in terms of CO_2-warming-equivalent emissions.