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AN EMPIRICAL ANALYSIS OF NET-ZERO EMISSION TARGETS OF CANADA AND THE EUROPEAN UNION

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ABSTRACT:

The 2015 Paris Agreement stipulates that participating countries should aim to achieve a balance of emissions and sinks of greenhouse gases by 2050. This is an essential pre-condition for a subsequent reduction in atmospheric levels of carbon dioxide. Several countries have formulated and presented their proposed pathways to this condition of net- zero emissions. Employing a methodology based on a revised Kaya Identity and the concept of emission intensity, the paper examines the feasibility of the pathways to net zero published by the Canadian government and the European Commission. By analysing the link between emissions and gross domestic product, it is shown that the path to net- zero emissions proposed by Canada is technically feasible but dependent on the deployment of a suite of negative emission technologies none of which has yet to be demonstrated at scale. In the case of the EU27, it is argued that the proposed pathway to a condition of net-zero emissions in 2050 is not a plausible scenario, and that the emissions of greenhouse gases in mid-century are likely to be more than three times higher than the level projected by the European Commission.

KEY-WORDS: Net zero emissions, Residual emissions, Energy intensity, Negative emission technologies, Kaya Identity, Canada emissions, EU emissions.

1. OBJECTIVES AND MOTIVATION

The objective of the analysis that follows is to present a coherent empirical framework for the analysis of national strategies to reduce emissions of greenhouse gases (GHG) to a point of net-zero emissions (NZE). This condition is defined in Article 4 of the Paris 2015 Agreement and stipulates that countries that are parties to the accord shall take measures to arrive at a NZE condition "in the second half of the century" (UNFCCC, 2016). Many countries, including Canada and the 27-member European Union (EU27), have published plans that purport to show how their GHG emissions will decrease to the NZE condition by 2050.

The net-zero condition assumes that a country's GHG emissions in 2050 will be balanced by measures that absorb an equal quantity of carbon from the atmosphere thus producing the net-zero condition. These measures are generally referred to as 'negative emission technologies' (NETs). They operate as carbon sinks and can be distinguished as either *natural* or *engineered*. Living biomass (primarily trees) is the most effective natural carbon sink, while engineered sinks include bioenergy with carbon capture and storage (BECCS), and direct air capture (DAC). Other less advanced and more conceptual engineered sinks include ocean fertilisation and enhanced weathering.

The net-zero condition therefore consists of a balance between a country's *actual* emissions in 2050 (its *residual* emissions), and the combined absorptive effect of the measures that compensate for those emissions. One of the objectives of the research described here, it to show that residual emissions of a country *cannot* decline to zero. It follows that the condition of net zero emissions *always* involves a point of equilibrium between residual emissions and the absorptive effects of a suite of negative emission technologies—because invariably there is more than one.

Governments that design and implement policies to reduce GHG emissions to the point of net zero are therefore faced with a interesting trade off. Driving down emissions to the lowest possible level is more costly, but these costs will be offset by savings in the deployment of negative emission technologies (either natural or engineered or both). Alternatively, residual emissions may only be reduced to the point where the incremental cost of further reductions is considered to be excessive; the deployment of negative emission technologies would then need to be of greater scale and capacity.

The question of technical feasibility also arises. Serious doubts have been raised about the efficacy of BECCS and Direct Air Capture. The natural sinks are more reliable but are at risk of degradation from wildfires and the destructive infestations of insects. A consideration of the precautionary principle may therefore lead governments to propose that residual emissions should be brought down to an absolute minimum, thus reducing the risk of the net-zero condition being unattainable due to the limited efficacy of the proposed carbon sinks.

This paper seeks to address the issues and answer the questions outlined above, and to examine the pathways to net zero emissions published by the government of Canada and the European Commission. In each case, the emission of greenhouse gases in 2050 is balanced by the deployment of a set of negative emission technologies that are intended to fully offset the residual emissions. The degree to which this objective is likely to be achieved is examined.

The methodology presented below is applicable to all countries that have formulated a pathway to a condition of net-zero emissions by 2050. It outlines an empirical approach that examines the feasibility of a country's proposed program to reduce its emissions of greenhouse gases to a level where they may be realistically balanced by the combined effect of a set of negative emission technologies.

2. INTRODUCTION

The concept of net-zero emissions of greenhouse gases is a foundational element of the 2015 Paris Agreement. In Article 4 it is stipulated that Parties shall aim '*to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of the century…*' (UNFCCC, 2016). But the articulation of this requirement does not indicate if anthropogenic emissions should decline to a particular level, only that they should be balanced; although Article 4 also advises that '*developed country Parties should continue taking the lead by undertaking economy-wide absolute emission reduction targets*' (UNFCCC, 2016).

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Several countries have published reports which set out how they envisage reducing their GHG emissions to a condition of net zero by 2050. For example, the EU27 pathway to NZE shows emissions declining from 3740 million tonnes of carbon dioxide equivalent (MtCO2e)[1] in 2015 (Per capita greenhouse gas emissions including land use, 2024a) to residual emissions of about 500 MtCO2e at the point of net zero in 2050 (European Commission, 2024). The pathway published by Canada shows emissions falling from about 700 MtCO2e in 2000 to 165 MtCO2e at the net zero point in 2050 (Canada Energy Regulator, 2023).

Residual emissions must be balanced by negative emission technologies (NETs). In Europe, the principal NET is land use, land use change and forestry (LULUCF), while a sink labelled as 'Industrial removals' (presumably BECCS and direct air capture) makes a small contribution. In Canada, four negative emission technologies are proposed: LULUCF, direct air capture; hydrogen production; and bioenergy with carbon capture and storage (Canada Energy Regulator, 2023).

A country's residual carbon emissions cannot decline to zero. A comprehensive review of over 180 countries over the last 25 years shows that a country's emissions are proportional to its Gross Domestic Product (GDP). The proportionality changes as economies electrifiy and become more energy efficient but it can be shown that the ratio of GHG emissions to a dollar of GDP has a lower bound of approximately 50 gCO2e/$GDP.[2] This limit is confirmed by a consideration of the global carbon cycle. Emissions of carbon from land use change continue even if all economic sectors are 100 per cent electrified and emission-free—which is itself unrealistic in any modern economy.

What this means is that a country that strives to move down a pathway to net zero emissions must necessarily compensate for its residual emissions by deploying one or more negative emission technologies. The question is which?

Four technologies are generally proposed as the means of removing carbon from the atmosphere and thus balancing the residual emissions of a country and achieving the net zero condition: Afforestation and reforestation; land management to increase soil carbon; bioenergy with carbon capture and storage; and direct air capture. Other more imaginative interventions have been proposed, including ocean fertilisation and enhanced weathering. However, ocean fertilisation is judged to have very high levels of uncertainty and ecological risk, while enhanced weathering requires the mining, transport and utilisation of very large quantities of minerals: between 1 and 3 tonnes of rock for every tonne of carbon removed. Moreover, neither technology is judged to be capable of operating at the minimum level of carbon capture and removal required (European Academies Science Advisory Council, 2018).

2.1. Afforestation and Reforestation

The global carbon cycle includes the absorption of carbon dioxide by the world's forests and natural landscapes as trees and other biomass photosynthesize carbohydrates. However, counting on the world's forests, wetlands, mangroves and other biomes to continue to absorb several billion tonnes or more of carbon dioxide from the atmosphere is not without risk. The world's forests continue to be cut down as agriculture encroaches onto forest lands, while wildfires and infestations by insects are increasing in scope and intensity as global temperatures continue to climb. In many places, wetlands and mangroves are also being slowly incapacitated (FAO, 2024). In 2023, wildfires emitted 6.7 billion tonnes of carbon dioxide—more than double EU emissions from the burning of fossil fuels (FAO 2024). Rates of deforestation, although declining, have averaged 4.7 million hectares a year over the last decade (FAO, 2024). This pessimistic analysis does not lead to the conclusion that the land sink is likely to collapse. On the contrary, the European Academies Science Advisory Council concluded that "regarding the role of **afforestation, reforestation and other natural climate solutions**, this remains the least costly and most easily deployable existing CDR (carbon dioxide removal) technology" (emphasis in original) (European Academies Science Advisory Council, 2019).

2.2. Land Management

Industrial agricultural practices are generally detrimental to the quality of the soil: which is why there is so often a heavy reliance on chemical fertilizers. But agriculture can be regenerative and

[1] 'Carbon dioxide equivalent', CO2e, is a way of accounting for the environmental impact of the other greenhouse gases as equivalent units of carbon dioxide

[2] All GDP data in this report are expressed in international dollars at 2021 prices.

sustainable in which case agricultural land will absorb carbon from the atmosphere. In fact, soils hold twice as much carbon as the atmosphere—about 1.7 *trillion* tonnes (Global Carbon Project, 2024).

Soil organic carbon can be increased by growing cover crops; leaving crop residues to decay and decompose naturally; applying manure or compost; using low- or no-till soil preparation; and employing other land management techniques to improve soil quality and structure (European Academies Science Advisory Council, 2018).

This approach is the basis of the '4 per mille' initiative that was started in France following COP21 in 2015. The objective is to increase soil organic carbon by 0.4 per cent a year, an increase which could potentially absorb 2 to 3 billion tonnes of carbon a year (International '4 for 1000' Initiative, Soils for Food Security and Climate, n.d.). Basic principles include no-till agriculture; intercropping; agroforestry; adaptive grazing periods and rotations; land restoration; and improved water and fertilizer management including the use of organic fertilizers and compost (International '4 for 1000' Initiative. Soils for Food Security and Climate, n.d.).

2.3. Bioenergy and Carbon Capture and Storage

Known as BECCS, bioenergy and carbon capture and storage is often the technology that policymakers call into play when their preliminary forecasts of future emissions fail to chart a pathway to a net zero condition by 2050. A BECCS module is plugged into the mathematical model and the required net-zero emission target is rapidly attained. This analytical rescue operation has been increasingly exposed as invalid and unacceptable (European Academies Science Advisory Council, 2022).

First described as a 'backstop' technology by the European Academies Science Advisory Council (EASAC) (European Academies Science Advisory Council, 2018), the Council has become increasing critical of the technology, stating in 2018: "*The role of bioenergy with carbon capture storage (BECCS) remains associated with substantial risks and uncertainties, both over its environmental impact and ability to achieve net removal of CO2 from the atmosphere. The large negative emissions capability given to BECCS in climate scenarios limiting warming to 1.5°C or 2°C is not supported by recent analyses and policy-makers should avoid early decisions favouring a single technology such as BECCS* (European Academies Science Advisory Council, 2019).

A more recent report issued by EASAC in 2022 saw no reason to change its earlier conclusion that "policy should avoid favouring BECCS and proceed first on the cost-effective nature-based solutions", which they footnote as referring to "Reforestation, afforestation, recovery of peatlands, mangroves, etc." The report goes on to state that "lowering the expectation of CDR (carbon dioxide removal) technologies adds even more pressure to accelerate conventional abatement action as rapidly as possible" (European Academies Science Advisory Council, 2019).

2.4. Direct Air Capture

Direct air capture (DAC) involves the absorption of carbon dioxide directly from the air using a chemical absorbent. Since the concentration of CO2 in the air is very low: only about 0.043 per cent, the process requires extensive structures of powerful fans to suck in and expel huge volumes of air. This work requires very large amounts of electricity. The captured carbon dioxide is then compressed and pumped underground into permanent storage: a step that also requires electrical power. We know that the technology works: carbon dioxide can be absorbed from the atmosphere. The question is whether the technology can be deployed at a scale where it consistently captures at least a billion tons of CO2 a year —which is the scale required if DAC is going to be make a serious contribution to reduce atmospheric levels of carbon dioxide.

The electricity required to absorb a tonne of carbon dioxide using either liquid or solid absorbents is estimated to be between 1800 and 2600 kWh/tCO2 respectively (International Energy Agency, 2024). A network of DAC installations capturing and sequestering 1 GtCO2 a year would therefore require 360 – 630 TWh of electricity a year; roughly the output of 140 - 240 small nuclear reactors. The amount of thermal energy is also substantial: 5.3 – 7.2 GJ/tCO2 (International Energy Agency, 2023), which converts to 168 GW of high-temperature heat for DAC systems capturing 1 GtCO2 per year. This is approximately 100 times the power of The Geysers geothermal plant in the USA (Geothermal power, 2025).

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The substantial energy consumption of Direct Air Capture technology is driven by the physical process of trying to absorb carbon dioxide at a concentration of 0.043% from a stream of air at ambient temperatures. The provision of substantial amounts of carbon-free electricity is also costly—an economic burden which direct air capture cannot avoid.

Not mentioned above is the challenge of permanently sequestering the captured carbon dioxide in underground repositories, an essential component of direct air capture, which adds another level of difficulty to the technology.

The uncertainty surrounding the viability of the two main engineered carbon sinks, BECCS and DAC, and the risks associated with a reliance on nature-based approaches based on land use and forestry argues for a policy where the need for negative emission technologies is kept to a minimum. This in turn implies that *residual* emissions should be reduced as much as possible. This conclusion has been reiterated by the EASAC, for example in 2019, when the council stated that mitigation (i.e. actual emission reductions) should be "made the first priority ahead of any reliance on future NETs." (European Academies Science Advisory Council, 2019).

3. METHODOLOGY

Residual emissions cannot be reduced to zero, but they can be reduced to a minimum level which appears to be approximately the same for all countries at the same level of economic development. To examine this hypothesis in more detail it will be necessary to employ a form of the Kaya Identity (Kaya identity, 2015): a mathematical identity which states that emissions of carbon dioxide can be expressed in terms of four factors: population, per capita GDP, energy use per unit of GDP, and CO2 emissions per unit of energy (Bush, M.J., 2024). As an identity, the factors cancel out, but the disaggregation into groups of easily available data has proved extremely useful. In this analysis we use a variation of the identity which disaggregates per capita emissions of greenhouse gases (not just CO2) into four factors which include the generation of electricity as well as total energy consumption. It is written as:

$$\frac{CO2e}{pop} = \frac{CO2e}{elec} x \frac{elec}{E} x \frac{E}{GDP} x \frac{GDP}{pop} \qquad (1)$$

Where:

- CO2e/pop is per capita GHG emissions, tCO2e
- CO2e/elec is *total* emissions of CO2e per unit of electricity generated, tCO2e/GWh
- elec/E is the ratio of electricity generated and total energy consumption, E, (both in GWh)
- E/GDP is the energy intensity of GDP, GWh/$GDP
- GDP/pop is per capita gross domestic product, $GDP

The first three terms on the right-hand side of the modified Kaya identity shown in Equation 1 is called the Emission Intensity (EI) where:

$$EI = \frac{CO2e}{elec} x \frac{elec}{E} x \frac{E}{GDP} \quad \text{tCO2e/\$GDP} \qquad (2)$$

The identity can therefore be reduced to a simple relationship between per capita GHG emissions and per capita GDP.

$$\frac{CO2e}{pop} = EI\ x \frac{GDP}{pop} \quad \text{tCO2e per capita} \qquad (3)$$

A country's emissions can be calculated from its per capita GDP if its emission intensity is known. It follows that policies aimed at reducing emissions should focus either on reducing the EI or per capita GDP or both. Since it is almost axiomatic that a country's per capita GDP should increase over time, GHG emissions can only be reduced if emission intensity is reduced faster than increases in per capita GDP.

3.1. Emission Intensity

The values of the EI for all countries in the OurWorldInData database (Per capita greenhouse gas emissions including land use, 2024b) can be calculated from the tables of GHG emissions per capita and per capita GDP. Across 185 countries, the 2023 values range from a high of 4758 gCO2e/$GDP in the Central African Republic, to a low of 55 gCO2e/$GDP in Switzerland. Twenty-one countries, mainly African and all very low income, have EIs above 1000 gCO2e/$GDP. Low-income countries as a group have an average EI value of 1118 gCO2e/$GDP.

Of particular interest for this study are the countries that have low EI values. Table 1 shows seven countries (out of 185) that had EI values below 100 gCO2e/$GDP in 2023.

Table 1: Low EI countries in 2023

Low EIF country	EI gCO2e/$GDP
Hong Kong	84
Ireland	97
Luxembourg	90
Malta	61
Montenegro	86
Singapore	77
Switzerland	55

Source: Our World in Data database: GDP per capita and Per capita GHG emissions (Per capita greenhouse gas emissions including land use, 2024b)

4. RESULTS AND DISCUSSION

It is instructive to examine how EI values have varied over time in these low emission- intensity countries. Can the EI decline to zero and if so, over what time frame does this transition occur in a best-case scenario? Figure 1 shows the EI values for these seven countries from 2000 to 2023. The five countries grouped in the centre are labelled in declining order.

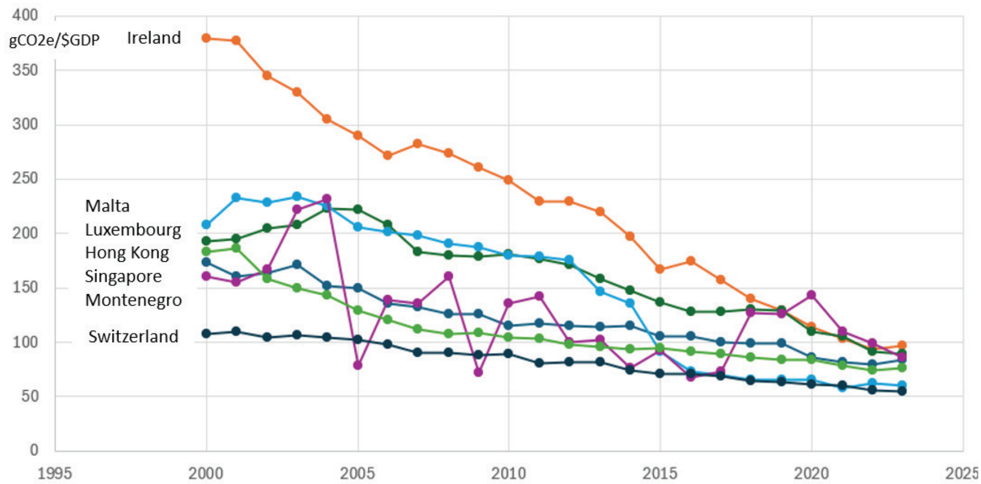

Figure 1. Emission Intensity trends in low EI countries, 2000-2023

Source : Our World in Data (per capita greenhouse gas emissions including land use, 2024c). Emission intensity is calculated from the ratio of per capita GHG to per capita GDP. All GDP values in this paper are expressed in International dollars (USD) at 2021 prices.

Immediately obvious is the indication that in all cases Emission Intensities appear to decline asymptotically to a limiting value of approximately 50 gCO2e/$GDP. This characteristic can be explained by considering the three constituent factors of shown in Equation 2. The first is the ratio of *all* GHG emissions to the amount of electricity generated. GHG emissions can never fall to zero. A country's carbon emissions are driven by the carbon cycle and they are always non-zero. The second factor is the ratio of electricity generation to total energy consumption. As an economy electrifies this element will tend towards unity. The third factor, E/GDP, is the energy intensity of GDP. This can certainly be reduced but once again it cannot fall to zero. Consider a thermodynamic explanation. GDP is a proximate indicator of the work being done by an economy. It takes a huge amount of work and energy to power up and drive forward all the physical, chemical, and mechanical processes of a modern productive economy. The greater the GDP the greater the amount of work and energy required to maintain its operations. The energy intensity of an economy can certainly be reduced: as many countries have demonstrated. But it cannot be brought down to zero—a physical impossibility.

A lower bound on the value of emission intensity has important implications for a country's proposed pathway to a condition of net zero emissions in 2050. The lower bound is not a physically defined constant. The lowest value calculated among a group of 185 countries is 55 gCO2e/$GDP: the value for Switzerland (Table 1). The lower bound could be considered as the edge of a zone of increasing

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improbability. Values below 50gCO2e?$GDP should be viewed with increasing scepticism and their validity strongly questioned.

4.1. Net Zero Emissions

Canada has published its proposed pathway to arrive at the point of net zero emissions by 2050. Figure 2 shows the projected pathway to reduce emissions from about 700 MtCO2e in 2024 to 165 MtCO2e in 2050, at which time a portfolio of negative emission technologies is proposed to offset the residual emissions. These NETs include land use, land use change and forestry; hydrogen production; direct air capture; and bioenergy with carbon capture and storage (BECCS) (Canada Energy Regulator, 2023).

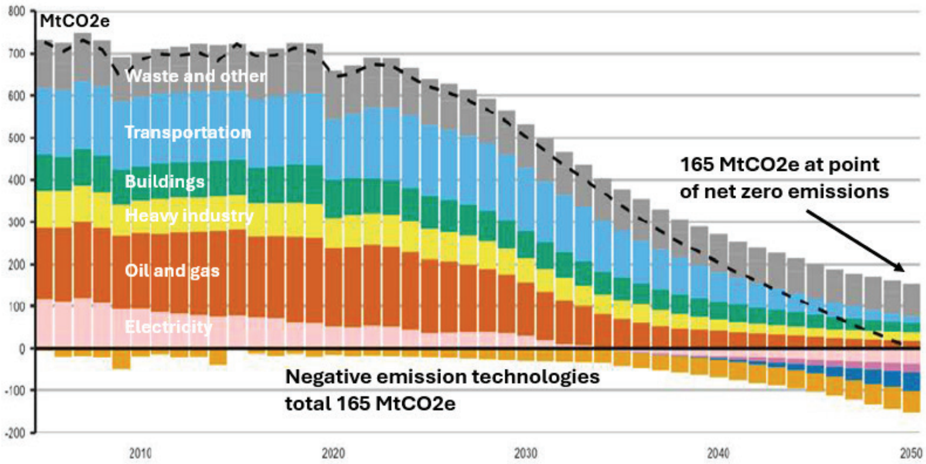

Figure 2. Canada's pathway to net zero emissions in 2050

Source: Canada's Energy Future 2023: Energy supply and demand projections to 2050 (Canada Energy Regulator, 2023). The negative emission technologies (in descending order) are BECCS; hydrogen production; direct air capture; and land use, land use change and forestry. Hydrogen produced from biomass gasification is not a negative technology (U.S. Department of Energy, n.d.).

Is this trajectory feasible? To answer this question we need to estimate Canada's per capita GDP in 2050, which is used to calculate the EI at the point of net zero emissions. Canada's per capita GDP growth rate was 0.7 % per annum (p.a.) from 2000 to 2023 (GDP per capita, 2021). Over the next 25 years, we assume the long-term trend will remain approximately at this level. Projecting forward from 2023 at growth rates between 0.7% and 1.0% p.a. gives per capita GDP in 2050 between $67,500 and $73,150.

The population that year using the M1 scenario (Statistics Canada, 2025) is 49.3737 million so emissions per capita at the net zero point are 165/49.3737 = 3.342 tCO2e. The emission intensity at the NZE point can now be calculated from these data as this value divided by per capita GDP, which gives an EI ranging from 46 to 50 gCO2e/$GDP.

These values are right at the estimated lower bound of emission intensity. Driving down Canada's EI from its present value of over 300 to 46 gCO2e/$GDP in 2050 is challenging but certainly possible (and we note that Ireland has already demonstrated a similar trajectory). We will discuss how this reduction can be achieved; but first we will examine the European plan. Europe's path to net zero emissions by 2050 is shown in Figure 3

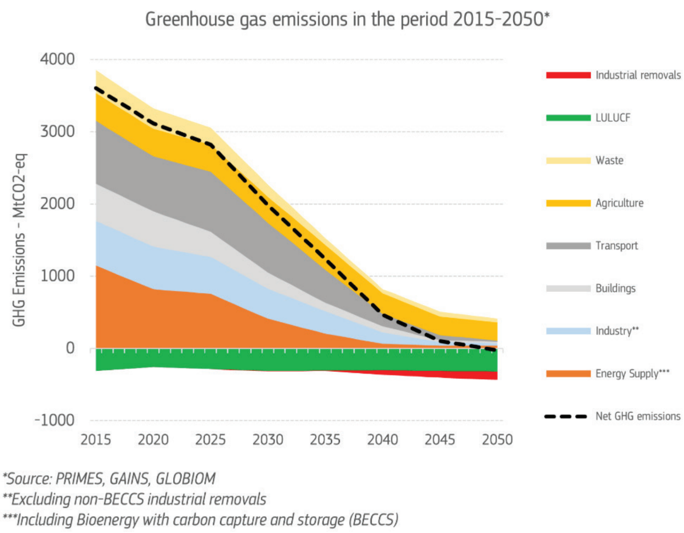

Figure 3. Europe's pathway to net zero in 2050

Source : European Commission. 2040 climate target (European Commission, 2024). https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2040-climate-target_en

The graph shows that GHG emissions on this pathway decline to approximately 500 MtCO2e in 2050. These emissions are then balanced by an equal amount of negative emission technologies: land use, land use change and forestry (LULUCF); and a technology referred to as 'industrial removals' which we assume to be either BECCS, DAC or both. The EU27 population in 2050 is projected to be 447.9 million (Eurostat, 2023), which gives per capita emissions in 2050 as 500/447.9 = 1.12 tCO2e. This is implausible. It is a value lower than the carbon footprint of the middle 40 percent demographic cohort in sub-Saharan Africa (Chancel L., Bothe P., Voituriez T., 2023).

EU27 per capita GDP in 2050 can be estimated as being in the range of $75,000-$85,000 which gives EI values of 13 – 15 gCO2e/$GDP. These figures are impossibly low and point to the troubling conclusion that the EU27 proposed pathway to achieving net zero emissions by 2050 is unrealistic: the EU is unlikely to be able to reduce its GHG emissions to 500 MtCO2e per annum by 2050. A more credible figure based on per capita GDP of $75,000; a population of 447.9 million; and with EI at its minimum value, suggests GHG emissions in 2050 will be at least 1600 MtCO2e per year.[3]

The measures proposed by the EU to "deliver the European Green Deal" are important and valid. However, there is compelling empirical evidence that the 2050 sectoral emission targets are unrealistic (European Commission, 2023). Innovative engineering solutions are unlikely to change this assessment since the lower bound on emission intensity is predominantly defined by the physical reality of an economy.

5. INTERNATIONAL CONTEXT AND RELEVANCE

Over 190 countries have signed up to the 2015 Paris Agreement and thereby committed to achieving a condition of net zero emissions by 2050, which is defined in Article 4 as "*a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty*."(UNFCCC, 2016)

A country's Nationally Determined Contribution (NDC) is intended to "communicate ambitious efforts" to achieving this objective. An NDC should therefore explain what measures a country intends to take in order to arrive at a condition of net zero emissions in 2050. This report should also include estimates of the residual emissions in 2050 and the negative emission technologies that will be employed to compensate for them. The methodology described in this paper provides a simple analytical procedure for conducting a first test of the validity of a country's proposal. It is applicable to all countries that publish annual socio-economic data and information on the level of their emissions of greenhouse gases. However, other indicators that assess the effectiveness of measures to achieve a condition of net zero emissions are also relevant (Angekumbura, M., 2024).

Emissions of greenhouse gases cannot be substantially reduced unless a country's emission intensity is brought down close to its minimum possible level. There are three ways to accomplish this task. As shown in Equation 2, emission intensity is the product of three factors:

1. **The factor CO2e/elec,** is the ratio of *all* GHG emissions to the level of electricity generation. This element can only be reduced to a minimum value if the generation of electricity is reliant on emission-free technologies. These would be predominantly renewable sources of energy, or a combination of renewables and nuclear energy. Although nuclear is a mature technology and capable of generating gigawatt-scale power, it is well established that solar and wind even with energy storage are substantially less costly (Lazard, 2024). The current enthusiasm for small modular reactors is unlikely to change this assessment (Ramana, M.V., 2024). In countries where all power generation is 100 percent emission-free, this factor declines to a low level—but it cannot decline to zero because every country has areas of trees and other biomass which emit carbon dioxide as part of the carbon cycle. Other greenhouse gases including methane from organic waste and nitrous oxide from fertiliser runoff may also be present. Fossil-fuel power generation with carbon capture and storage (CCS) is also technically feasible. However, a thorough

[3] The calculation is $75,000 (2050 per capita GDP) x 50 gCO2e/$GDP x 447.9 million (2050 population) = 1680 MtCO2e or 3.75 tCO2e per capita

investigation by the Institute for Energy Economics and Financial Analysis conducted in 2022 concluded unequivocally that "CCS is not cost competitive with renewables and storage as a climate change mitigation option for the power sector." (Robertson, B., Moussavian, M., 2022).

But the policy implications are clear: electrical power generation must transition to emission-free sources of energy.

2. **The second factor, elec/E,** is the ratio of electricity generation to *total* energy consumption. This element measures the degree of electrification of all economic sectors. It makes little sense to generate emission-free electricity if economic sectors rely on fossil fuels. Every economic sector, starting with transportation, buildings, and manufacturing, should eventually become 100 per cent electric. Electrification of heavy industry is more challenging but certainly possible. Over time, and under a continuing policy of electrification, this factor will trend to a value close to unity.

3. **The third factor, E/GDP,** is the energy intensity of GDP. It is a metric often showcased because it has declined significantly in many countries as they have become more efficient in their use of energy (often due to higher levels of electrification). However, it cannot fall to zero. The idea of 'absolute decoupling' is valid up to a point: the consumption of energy can indeed fall while GDP continues to grow. But the ratio cannot fall to zero. Low-income African countries have values as low as 0.24 kWh/$GDP (Rwanda), while among modern economies Switzerland is the lowest with 0.52 kWh; Ireland is at 0.60 kWh; and Hong Kong at 0.61 kWh per dollar of GDP (all three are among the low EI countries shown in Figure 1) (Energy Intensity, 2022). Policies to reduce this metric should focus on the efficiency with which electricity is used. For example, heating a home with electric baseboard heaters works perfectly well, but it is much more efficient to install a heat pump. Similarly with lighting: not all electric light bulbs are the same. LED lights use only a small fraction of the electricity consumed by an incandescent bulb. Smaller electric vehicles consume less energy than electric SUVs. Other measures that reduce the value of this metric include retrofitting buildings to improve their thermal efficiency and the widespread installation of rooftop solar.

These three programmatic elements: emission-free electricity generation; the electrification of economic sectors, and greater energy efficiency, are the keys to achieving a condition of net-zero emissions by the middle of the century. Each one is essential.

The economic policies that will induce a decline in emission intensity are well established although infrequently applied in a coherent manner. There are three tools in the toolbox: regulation, incentives, and disincentives. For example, inducing utilities to phase out fossil-fueled power generation may require a combination of carbon pricing, caps on emissions, and incentives that provide attractive financing options for alternative sources of carbon-free energy. The electrification of the transport sector requires all three measures: limits on tailpipe emissions coupled with incentives for the purchase of electric vehicles and an increased excise tax on gasoline and diesel fuel. The thermal efficiency of new construction should be tightened through straightforward revisions to code which also ban connections to fossil gas for all new buildings. The electrification of industry should be promoted by carbon pricing and by the availability of preferential financing options. In all cases, the active involvement and leadership of governments at all levels is essential. Apart from enabling and facilitating the carbon pricing initiatives, and managing the programs of incentives and disincentives, governments must facilitate the permitting procedures and expedite the megawatt-scale installations of solar farms and onshore and offshore wind power. Finally, governments have an essential role to play extending the high-voltage direct-current electrical transmission systems that are essential for the distribution of the greater amounts of power that electrification will require.

The inevitability of residual carbon emissions at significant levels in high-income countries in 2050 once again raises the question of how to compensate for these emissions so as to achieve a condition of net zero. To answer this question, we should examine the carbon cycle.

5.1. The Global Carbon Cycle

The Global Carbon Project shows a detailed graphical representation of the 'anthropogenic perturbation of the global carbon cycle'. The salient points are shown in Table 2 for the period 2014-2023.

Table 2: Anthropogenic perturbation of the global carbon cycle

Anthropogenic flux	Emissions GtC/yr	Sink GtC/yr
Fossil carbon dioxide	9.7 ±0.5	
Land use change	1.1 ±0.7	
Land uptake		3.2 ±0.9
Ocean uptake		2.9 ±0.4
Total flux	10.8 ±1.2	6.1 ±1.3

Source: Global Carbon Project. https://globalcarbonbudget.org/gcb-2024/

The difference between the total of these fluxes is the absorption by the atmosphere, where its carbon content of roughly 800 Gt is increasing by about 5.2 Gt a year (Global Carbon Project, 2024).

The almost complete transition to emission-free electrical power generation by 2050 will remove the largest source of emissions of carbon dioxide: fossil fuels. If emissions from land use change remain unchanged, the global land sink is approximately 2.1 ±0.9 GtC per year,[4] which converts to a sink of between 4 and 11 billion tonnes of carbon dioxide a year.

Even at the lower value, this scenario presents the possibility of a significant capture of carbon dioxide from the atmosphere--a flux that *at a minimum* is almost four times as large as those generally attributed to the potential global capacity of BECCS or DAC—technologies which are assumed to be realistically capable of capturing only about 1 GtCO2e a year.

6. CONCLUSION

A condition of net-zero emissions is unlikely to be achieved unless a country's emission intensity is reduced to a low level. The reduction of emission intensity depends on three fundamental policies that must be carried out concurrently. The first is the phasing out of all electricity generation fueled by fossil fuels. All electricity generation must be based on renewable sources of energy: solar energy, wind power, hydropower, and geothermal energy. Nuclear energy is also an option. The second is focused on the electrification of all economic sectors starting with transportation (already underway), followed by buildings, industry, and agriculture. The third policy is aimed at improving the efficiency of electricity consumption by incentivising the adoption of the most efficient technologies for electric heating, cooling, and lighting.

Residual emissions at the point of net zero are unavoidable. Greenhouse gas emissions can never be completely eliminated. This means that the deployment of negative emission technologies under a condition of net zero emissions is a requirement. The natural carbon sinks include forest lands, wilderness and wetlands areas, and coastal zones where mangroves are abundant. These areas must be protected, managed, and if possible expanded. Regenerative agriculture that stores soil organic carbon also plays a role. Engineered carbon sinks such as bioenergy with carbon capture and direct air capture may eventually prove to be effective but the evidence so far is not persuasive.

The Canadian government has presented a scenario where GHG emissions decline from about 700 GtCO2e in 2023 to 165 GtCO2e in 2050. A realistic estimate of per capita gross domestic product in that year suggest that Canada's emission intensity will need to fall to about 50 gCO2e/$GDP. Although ambitious, this is a feasible scenario.

For the European Union, the analysis leads to a troubling conclusion. Under plausible assumptions of GDP per capita in 2050, the proposed emission intensity for EU27 is less than 15 gCO2e/$GDP: well below the minimum level demonstrated by the empirical data and confirmed by the physical basis of the metric. The European Commission should urgently re-evaluate its forecast of the group's residual emissions in 2050 and re-assess its proposals for a program of negative emission technologies intended to compensate.

[4] Assuming the larger range is applicable.

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