IT POLLUTES, SO TAX IT

NEED WE SAY MORE ABOUT CARBON DIOXIDE?

Peter Hartley

With responses from Ross McKitrick and Robert Lyman

The Global Warming Policy Foundation
Technical paper 6

Carbon Taxation: The Pigou Imperative

Peter Hartley

Technical paper 6, The Global Warming Policy Foundation

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Summary

Accumulation of carbon dioxide in the atmosphere will warm tropospheric and surface temperatures and thereby change other climate attributes. The negative externality is global in scope and all countries contribute to it. The resulting collective action problem may be one reason attempts to slow CO_2 accumulation have failed. Another may be that the most efficient policy instrument for restricting emissions, namely a globally-uniform emissions tax, has not been tried. Instead of attempting to limit CO_2 emissions at the global level, however, a suite of alternative policies may achieve better outcomes while circumventing the collective action problem.

1. Introduction

Carbon dioxide emissions were designated as a type of pollutant in the late 1980s. Although CO_2 is not directly harmful, its accumulation in the atmosphere will raise average temperatures in the troposphere[1] and at the Earth's surface, with possible, potentially harmful, ensuing changes in other climate attributes.

Decades of attempts to materially limit CO_2 emissions have failed. Data from Mauna Loa on annual average concentrations of CO_2 in the atmosphere reveals annual growth rates of 0.46% from 1991–2000, 0.54% from 2001–2010 and 0.62% from 2011–2020. The main policy responses have been technology mandates and restraints, rather than placing a 'Pigouvian tax' (Pigou, 1920) on CO_2 emissions, a more efficient approach that is favoured by economists. However, three more fundamental issues have impeded attempts to limit CO_2 emissions.

The first is the global scope of the externality. Policies limiting CO_2 emissions are ineffective without the participation of all large emitters. Yet each nation has an incentive to leave CO_2 emission control to others, and beyond that to provide a haven for profitable CO_2-emitting activities shunned by others.

The second fundamental issue is that the costs of reducing emissions are borne immediately, while potential benefits mostly accrue decades hence. Furthermore, most beneficiaries will be richer than most of those paying the costs, especially when controls must be implemented in countries with large populations and low current per-capita income. Expected future benefits need to be much greater to offset the burden of near-term control costs.

The third issue, which exacerbates the other two, is that fossil fuel combustion dominates both anthropogenic CO_2 emissions and world energy supply. Specifically, the Intergovernmental Panel on Climate Change (IPCC, 2001) says that fossil fuel combustion accounts for around 75% of anthropogenic CO_2 emissions. According to the BP *Statistical Review of World Energy*, fossil fuels provided more than 83% of world primary energy in 2020. Since energy enables a force to do work, there is a strong connection between energy use and economic activity. Energy is an essential input to production, and reliable and affordable energy is essential to a modern lifestyle. As a result, there is a trade-off between reducing CO_2 emissions and increasing the living standards of the billions of people without access to modern energy sources.

The nexus between CO_2 emissions and energy supply also constrains feasible CO_2 emission-reduction policies in democratic countries. Policies that raise energy prices, reduce energy use and thus economic growth, or reduce supply reliability, erode political support. The link from energy use to economic output, and the critical importance of oil products for modern armed forces, also tie energy supply to national security.

Given these impediments, any achievable tax on CO_2 emissions would be far from ideal. Current policies are even worse. Are there practical alternatives that could do better?

To limit the scope of the discussion, we ignore anthropogenic emissions of greenhouse gases other than CO_2, and anthropogenic sources of CO_2 apart from using fossil fuels to provide energy. From the data cited earlier, CO_2 emissions from fossil fuel combustion dominates anthropogenic influences on climate via the greenhouse effect.

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1 This is the part of the atmosphere where convective over-turning and weather processes occur.

2. Overview of relevant scientific issues

Carbon dioxide is a colourless, odourless, non-toxic gas.[2] As one of the main inputs into photosynthesis, it is essential for almost all life on Earth. It is also absorbed and released by the soil and the oceans and, on a longer time frame, is naturally sequestered in rocks and fossil fuels. As fossil fuel combustion releases CO_2, all sinks absorb more, but not by enough to prevent the stock in the atmosphere gradually accumulating.

2.1 Carbon dioxide as a greenhouse gas

Atmospheric CO_2 intercepts some frequencies of outgoing infra-red radiation emitted by the Earth's surface and troposphere, creating an imbalance with incoming solar radiation not directly reflected back to space. Temperatures in the troposphere and on the surface must increase to restore balance.

Overlap of some radiation absorption bands of different greenhouse gases makes it complicated to calculate the direct radiative impact of increased CO_2. Notably, the altitudinal and latitudinal distribution of water vapour, the most significant greenhouse gas, alters the incremental insulating effects of CO_2. Nevertheless, there is wide agreement that the bands blocked by CO_2 are substantially saturated at the current concentration of 0.04% (400 ppm), so the incremental effects of a doubling to 0.08% (800 ppm) will be small.

2.2 Feedback effects

From an initial temperature increase of ΔT, general circulation models (GCMs) calculate an amplified increase that is well-approximated by $\Delta T/(1-f)$ for a feedback parameter f. Models disagree more about f than ΔT.

The most important feedback is that initial warming increases evaporation, and thus the amount of water vapour in the atmosphere. However, this effect can also change cloud cover. Clouds that reflect incoming solar radiation reduce f, while clouds that block outgoing longwave radiation increase it. GCMs do not model cloud formation directly, since it occurs at a much smaller scale than the model grid size. Measuring the effects of CO_2 on cloud cover is difficult because many other factors contribute. Andrews et al. (2012) show that differences in induced changes in the amount, geographic and altitudinal distribution, and types of cloud cover explain most differences in f across GCMs.

Temperature measurements suggest that the warming from CO_2 increases experienced to date is at the low end of the range predicted by GCMs. For example, McKitrick (2014) shows that the surface warming since 1750 is about 72% of the average value implied by data, assumptions and GCMs used in IPCC (2013). Lewis and

2 For example, submariners and astronauts live without ill effects in air with CO_2 concentrations far above feasible future atmospheric levels. Since CO_2 (molecular weight 44.009) is more dense than dry air (21% O_2, 78% N_2, 0.934% Ar, 0.04% CO_2 has molecular weight 28.96), CO_2 accumulating at ground level can preclude access to oxygen. This is a potential hazard of sequestering CO_2 that can later leak out.

Curry (2015, 2018) also conclude that a majority of the GCMs used in IPCC (2013) are inconsistent with observed warming. Their median estimate of temperature sensitivity to increased CO_2 implies future warming of 55–70% of the mean model-simulated warming. Also, Christy and McNider (2017) and McKitrick and Christy (2018) compared warming in the tropical mid-troposphere, where GCMs predict strong CO_2 warming, with both satellite and independent weather balloon measurements. They find that the GCMs overestimate this critical trend by about a factor of two on average.

Uncertainty in f asymmetrically affects uncertainty in $m = 1/(1-f)$. Figure 1 graphs two probability density functions for f, with different means but the same variances, along with the corresponding probability density functions for m. Reducing the mean of f by one third while holding its variance fixed translates into an approximately 34% lower mean, but a more than 57% lower standard deviation, of m. Variance in m is important because limiting CO_2 accumulation in the atmosphere can be seen as a type of insurance. A decrease in the likelihood of extreme outcomes reduces the value of that insurance.

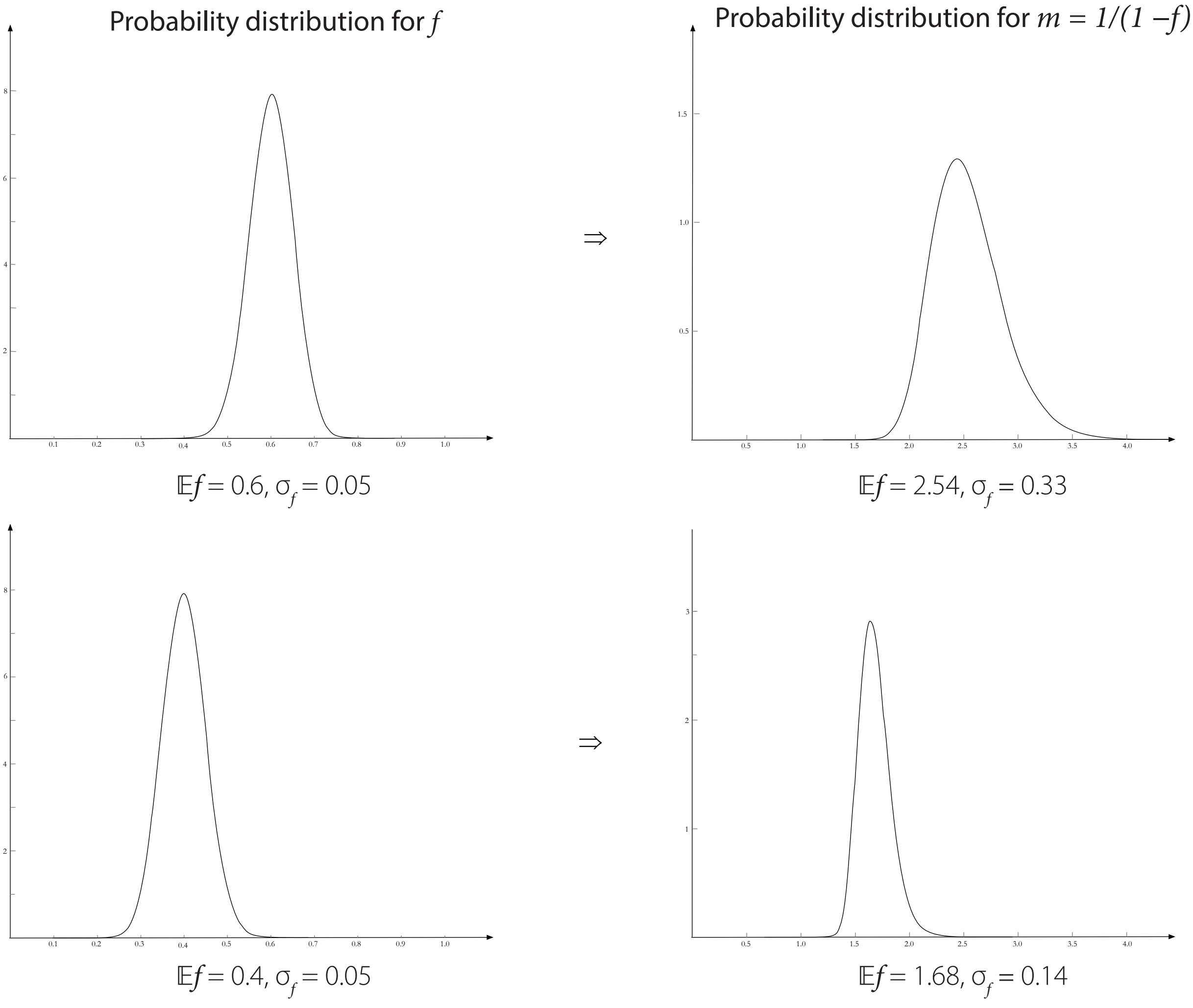


Figure 1: Relationship between the distributions of f and $m = 1/(1-f)$

2.3 Climate, weather and temperatures

Some predicted adverse effects from CO_2 accumulation arise directly from increases in surface and ocean temperatures.[3] Others are forecast to arise from changes in other climate attributes caused by the higher temperatures.

Climate is defined as the probability distributions of various weather measurements – such as temperature, rainfall, snowfall, humidity, frost-free days, hours of sunlight, cloudiness, and wind speed and direction – at a given location. The distributions are defined as *functions* of the ordinal day number within a year to allow for strong and predictable seasonal variations. To measure climate, one therefore needs a sample of multiple – traditionally 30 – years of observations of these 'climate variables'.

'Climate change' is thus a change in the distributions of the various climate variables at one or more locations. This definition has several important consequences.

First, measured climates always change as a result of sampling variation and imprecision in the underlying weather measurements. Measurements can also exhibit *bias*, and an uncorrected *change* in the bias would also be measured as climate change.

Second, in most popular discussions, the phrase 'climate change' denotes a change in 'climate,' thought of as a singular object that is not location specific, and *only* as a result of human actions. It is often used even more narrowly to mean a change in 'climate' (singular) only as a result of human emissions of greenhouse gases. The implicit claim inherent in this terminology, namely that climates were unchanging prior to the era of industrialisation based on fossil fuel use, is contradicted by abundant historical, archeological, anthropological, biological, and geological evidence. Possible sources of natural changes in climates include ocean cycles of varying periodicity[4] and cycles in the total amount and spectral composition of radiation from the sun[5] and other solar effects.[6] Some of these changes may

3 For example, higher ocean temperatures would lead to thermal expansion of ocean water, higher sea levels and increased coastal flooding. Higher air temperatures could increase deaths during heatwaves, although mortality data implies higher air temperatures during cold freezes would reduce deaths by more.

4 These include the Madden-Julian, El Niño-Southern, North Atlantic, Atlantic Multidecadal, Pacific Decadal, and North Pacific Oscillations, the Indian Ocean Dipole and the Southern Annular Mode.

5 Fluctuations in the fraction of ultra-violet light affect ozone production in the upper atmosphere that could then alter lower tropospheric circulation (see, for example, Lockwood et al., 2010).

6 Changes in solar magnetic field strength modulate penetration of high energy galactic cosmic rays into the solar system. These high energy particles ionise molecules at lower altitudes of the atmosphere, and could increase low level cloud cover, which exerts a strong cooling effect. See, for example, Svensmark et al. (2021) and Zharkova (2020, 2021). Zharkova (2020, 2021), along with many others, has associated the cooling in the Little Ice Age with reduced solar activity. She is predicting reduced solar activity over the next few decades could reduce average surface temperatures by at least 1°C. Longer term, changes in the earth's orbital parameters (orbit eccentricity, angle of tilt, and precession of the axis of rotation – together known as the Milanković cycles) affect the amount and latitudinal and seasonal distribution of solar radiation and thereby the occurrence of glacial peri-

affect climates by directly changing the type, geographic distribution and amount of cloud cover without first affecting temperatures. Some of these effects could account for the finding that the models over-predict average global warming from CO_2 increases. Human influences other than the emission of greenhouse gases, such as urbanisation, land clearance, introduction of invasive plants, and large-scale irrigation, have also been shown to affect climates.[7]

Third, many costs associated with *changes* in climates are better characterised as costs of *extreme weather*. Even if policies could eliminate *changes* in the distributions of weather variables, current distributions imply high enough probabilities for extreme outcomes to make their expected costs substantial. Furthermore, many extreme weather events have not shown statistically significant trends consonant with the increase in CO_2. This includes:

- US annual landfalling hurricanes since 1900;
- Global all-hurricane (≥ 64 knots) and major-hurricane (≥ 96 knots) annual frequencies, and global and northern hemisphere tropical cyclone annual accumulated cyclone energy since 1980;
- US strong-to-violent tornadoes annually since 1950;
- Eurasia and North America monthly snow cover extent since 1967.[8]

Large natural variations may have obscured trends, but statistically significant trends have been measured in ground, atmosphere and ocean temperatures,[9] albeit below those predicted by the models, as noted in Section 2.2.

In theory, two basic mechanisms could link other climate variables to temperature changes. On the one hand, large-scale atmospheric and oceanic circulations can be viewed as a type of 'heat engine' (Ozawa et al., 2003) transferring energy latitudinally from the tropics, where absorbed solar energy exceeds infra-red emissions, to the poles, where emitted radiation exceeds absorbed solar energy. The overlap of water vapour and CO_2 radiation absorption bands

ods. In the last four inter-glacials, warm temperatures lasted about 10,000–15,000 years, while the current inter-glacial has lasted about 12,000.

7 For example, Imhoff et al. (2010) examine the effects of urbanisation, Webb et al. (2005) study effects of changes in forestation in Brazil on rainfall patterns, Lambert et al. (2010) examine the effect of invasive plants on fire in California, while Christy et al. (2006) examine the effect of irrigation in the Central Valley of California on temperatures.

8 For hurricane data https://climatlas.com/tropical/, tornado data https://www.spc.noaa.gov/wcm/index.html#data, and snow data https://climate.rutgers.edu/snowcover/files/Robinson snowdata2020.pdf. The starting dates are the beginning years for observations that were collected on a reasonably consistent basis.

9 For ground stations, daily minima have increased more than daily maxima. For example, using records from 1,114 USHCN weather stations for the period 1895–2017, John Christy from the University of Alabama, Huntsville found no significant trend in the number of days with maximum temperature above 100°F or 105°F (see https://www.drroyspencer.com/wp-content/uploads/US-extreme-high-temperatures 1895–2017.jpg).

means that CO_2 has larger *marginal* effects on dry air, such as the very cold air at the poles. An increase in CO_2 therefore could reduce the needed energy transfer and the frequency of violent weather events resulting from it. On the other hand, since water vapour is less dense than dry air,[10] evaporation into an air parcel causes it to ascend, whereupon it cools as decreasing pressure allows it to expand. Further vertical motion occurs as latent heat from evaporation, released as water vapour condenses to form clouds, further reduces density. More severe weather might then result from higher ocean surface temperatures, especially over the tropics. Increased low-level clouds, however, reflect more incoming sunlight, while fewer high-level clouds allow more infra-red radiation to escape to space (Lindzen and Choi, 2021). Taszarek et al. (2021) also present evidence that convective precipitation has declined over the last 40 years in those areas with greatest convective precipitation on average, as a result of increased wind shear, which curtails convective storm development.

Such conflicting forces might explain why other climate variables have changed less than temperature measures such as the global average of surface temperature anomalies (GSTA).[11] Even if GSTA were monotonically related to the *global average* of some other climate variable, the *location-specific distributions* need not exhibit such a monotonic relationship. Indeed, shifts in the normal paths of weather systems, for example, would alter the distributions of some climate variables positively in some locations and negatively in others. Nevertheless, GSTA is frequently used as a proxy measure, not only of 'climate change', but also of the net harm associated with it. In addition to the non-monotonic effects of temperature on the distributions of climate variables, the *net costs* of any changes *at a given location* will depend on the pre-existing conditions and vulnerabilities at that location. There is no *a priori* reason to expect these net costs to be monotonic increasing functions of GSTA.

There is another important implication of the observation that the harm from extreme weather, and the events likely to be of most concern, will vary considerably across locations. It should make market insurance against extreme weather events more effective. The profitability, and thus availability, of market insurance depends on imperfect correlation across customers of the adverse outcomes that customers want to insure against. The law of large numbers then implies that the risk of insurance company indemnity payments on a portfolio of contracts is much lower than the risk-reduction benefit of the insurance to any one customer. Customers are willing to pay more for their contracts than the insurer has to pay investors to compensate for the risk inherent in the insurance business. Increased availability of market insurance in turn alleviates the suffering from

10 Mixing water vapour into dry air reduces density since the molecular weight of water is 18.015, compared to 28.96 for dry air.

11 Temperatures depend on many factors including latitude, elevation, and distance from an ocean, and surface weather stations are far from uniformly distributed. Temperatures at each location are converted into departures from a 30-year average – 'anomalies' – at that location before averaging across locations.

adverse weather events and reduces the implicit insurance benefits from limiting CO_2 accumulation in the atmosphere.

2.4 Direct benefits of CO_2

Another complication for policy is that CO_2 is directly beneficial to plants. Thousands of laboratory and open-air experiments have shown that CO_2 enrichment increases plant growth, in part by reducing transpiration (see, for example, Pospisilova and Catsky, 1999). Figure 2 shows a satellite-based measure of plant growth over more than 30 years, with CO_2 aerial fertilisation likely explaining much of that growth. Since additional primary plant productivity benefits other species ultimately dependent on plants for energy and critical nutrients, increased CO_2 should benefit a wide range of ecosystems.

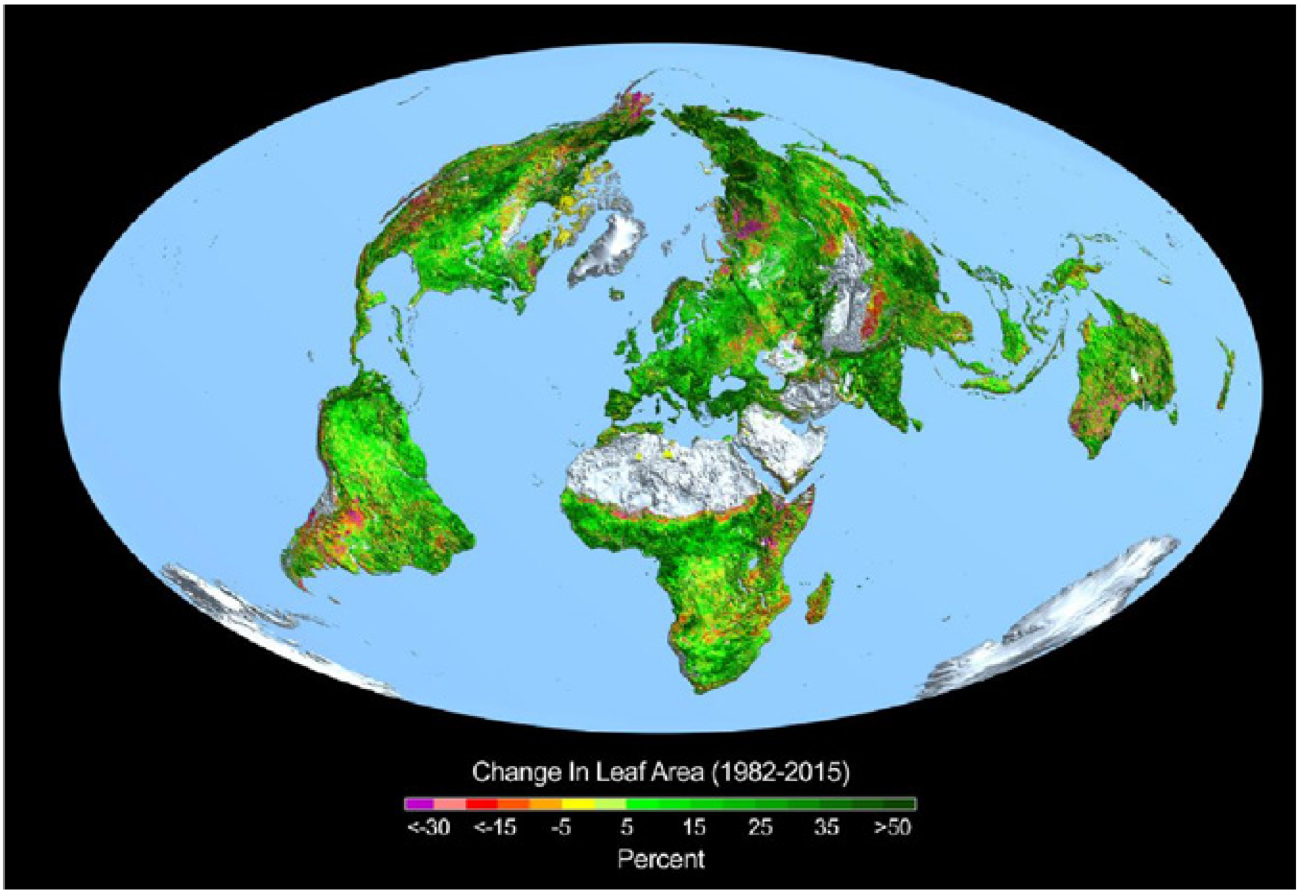


Figure 2: Satellite-based measure of plant growth 1982–2015.
Source: https://svs.gsfc.nasa.gov/vis/a010000/a012200/a012222/Change_In_Leaf_Area.tif.

Table 1 lists the results, for common plants of commercial value, of experiments that increased CO_2 concentration by 300 ppm.[12] Indeed, CO_2 is often pumped into commercial greenhouses to enhance productivity.

More generally, increased CO_2 should directly benefit agricultural enterprises around the world. Taylor and Schlenker

12 The concentration of CO_2 in the air supplied to the control varied across experiments.

Table 1: Plant dry weight (biomass) response to 300 ppm atmospheric CO_2 enrichment

Plant	Number of studies	Mean (%)	Standard deviation (%)
Common wheat	490	38.5	1.5
Rice	428	33.3	1.5
Maize	60	32.1	5.4
Sugarcane	13	35.7	5.7
Soybean	290	47.9	2.2
Potato	56	36.9	3.5
Alfalfa	89	37.3	3.6
Douglas fir	6	9.7	3.9
Loblolly pine	67	60.9	7.7
Ponderosa pine	47	63.3	11.6

Source: co2science.org

(2021) show that higher ambient CO_2 has increased maize, soybean, and wheat yields in the main US growing regions for these crops. They estimated a panel model of average yields at the county level with ambient CO_2 concentrations measured by the NASA Orbiting Carbon Observatory-2 (OCO-2) satellite as the main explanatory variable. They also include measures of temperature, precipitation, criteria pollutants (CO, NO_2, O_3, PM10, SO_2), county fixed effects and time trends, and allow the error terms to be spatially correlated.[13] They find that a 1 ppm increase in ambient CO_2 (it has increased 135 ppm since pre-industrial times) increases yields for maize, soybean, and wheat by 0.5%, 0.6%, and 0.8%, respectively.

2.5 Natural absorption of CO_2

Not only increased vegetation and other biomass, but also the world's oceans and soils, absorb CO_2 produced by fossil fuel combustion. The National Oceanic and Atmospheric Administration Global Monitoring Laboratory (2022) developed a model of global CO_2 sources and sinks called *CarbonTracker*. They find that about half of anthropogenic CO_2 emitted into the atmosphere is absorbed by natural sinks, although uncertainties associated with the underlying measurements make the model predictions probabilistic. The standard errors in the modelled annual increases are of similar magnitude to the measured increases.

3. Efficient emission control

The majority of air pollutants are most harmful immediately after emission and in the immediate vicinity of where they are emitted. Over time, various chemical, biological and/or physical processes remove them from the air, reduce their toxicity, or disperse them.

13 They show the results are not materially affected when they allow for different econometric specifications, functional forms, geographies included and a different measure of surface-level CO_2.

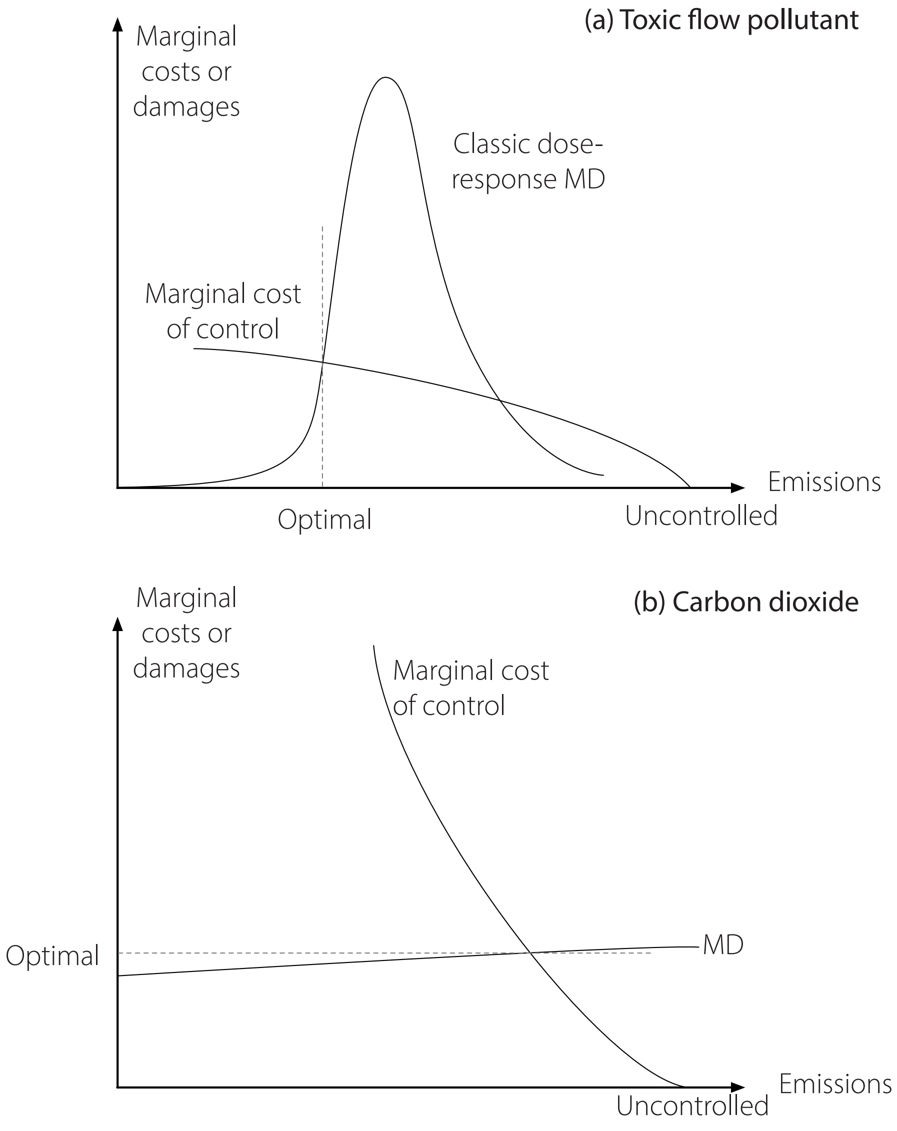
By contrast, the potentially harmful effects of CO_2 are global in extent and depend on the gradually accumulating *stock* of it in the atmosphere. The differing time and spatial dimensions affect both the marginal damages from emissions and the marginal costs of controlling them.

3.1 Marginal damages

The harmful effects of air pollutants are often close to zero at low concentrations, but rise very steeply once concentration reaches a threshold where many individuals find it toxic. After most of the damage has been done, *marginal* damages from *additional* emissions level off and then decline (MD in Figure 3a). Marginal damages from emissions over a short time period therefore critically depend on how much is already being emitted at that time. By contrast, the present value of damages from CO_2 emissions depends on the entire path of emissions over an extended period of time. Marginal damage from changing emissions *in any one year* will be insensitive to emissions already occurring *in that year*, giving the relatively flat MD in Figure 3b.

Figure 3: Optimal emissions

(a) toxic flow pollutant, and (b) CO_2.



3.2 Marginal costs of emission reduction

Emissions can usually be reduced in many ways. For example, changes in the production process or type of fuel used can lessen exhaust toxicity. Devices like precipitators, scrubbers, or catalytic converters can clean the pollutant from the exhaust. Cutting output will also cut emissions at a cost of control equal to the forgone benefit from lost consumption minus the explicit (excluding the external costs) cost saving from reduced production.

Emissions reductions should begin using the lowest marginal cost method. Starting from a competitive equilibrium without any taxes or subsidies, the marginal benefit to consumers from the produced output would equal the marginal explicit cost of production. Hence, the marginal cost of cutting output may be zero at first, while the marginal costs of changing the production process or type of fuel, or installing control devices, would normally be positive. As output falls, the difference between the (rising) marginal benefit of consumption and the (falling) marginal explicit cost of production is likely to quickly increase. Once the marginal costs of using different methods are equal, further emission reductions should use all those methods while keeping their marginal costs equal. The result will be a function, as graphed in Figure 3, relating the *minimum* marginal cost of control (hereafter called simply 'marginal costs of control') to emissions.

The principle that the marginal costs of different control methods in active use should be equal is known as the *equimarginal* condition. It is usually violated by policies mandating specific technologies to control externalities. By contrast, firms subject to an emissions tax, or possessing marketable emission permits that impose an opportunity cost on emitting analogous to a tax, would minimise costs by satisfying the equimarginal condition.

3.2.1 Initial marginal costs of CO_2 control

The marginal costs of control curve for CO_2 (Figure 3b) starts from zero when emissions are uncontrolled. This is equivalent to assuming that the marginal benefit of energy derived from fossil fuels equals the explicit marginal costs of supplying fossil fuel energy *plus* the cost of non-climate externalities, *but excluding any climate damages* since these are calculated separately by the MD curve. It would be true, for example, in a competitive market without taxes, subsidies or non-climate externalities. A complicating factor is that fossil fuel energy is not a homogeneous commodity supplied in a unified global market. The conditions regarding non-climate externalities, market competitiveness, and taxes and subsidies differ by fuel type and jurisdiction.

Focus first on the oil market in OECD countries, where the largest component of demand – transportation fuel – is taxed more heavily than average. Parry and Small (2005) examined gasoline taxes in the UK and the US, noting that the UK tax rate is among the highest in industrial countries, while the US rate is among the lowest. They give three arguments supporting fuel taxes over and above their effect on climate damages. First, fuel taxes are a 'second-best' way of internalising environmental externalities from local toxic pollutants.[14] Second, by raising driving costs, fuel taxes are a 'second-best' way of reducing traffic congestion and accident externalities.[15] Third, since fuel demand is relatively inelastic, fuel taxes may be a relatively less inefficient way to raise revenue.

Parry and Small find the congestion externality to be the largest component of a 'second-best optimal' tax, while the pollution component is the smallest. They also find that the tax in the UK is about double, and that in the US is about half, the 'optimal' rates they compute. Apart from taxes, fuel efficiency and other mandates partially address the pollution externality, while road and bridge tolls, central city parking taxes, and public transport subsidies partially address the congestion one. In summary, for transportation fuel use in industrialised countries, the initial marginal cost of cutting CO_2 emissions from the uncontrolled level may approximate zero.

Unlike industrialised countries, many oil exporting countries subsidise oil-product consumption. A subsidy would normally imply marginal cost of production exceeds marginal benefits of consumption, making initial marginal costs of CO_2 control negative. Many of the countries subsidising oil products consumption, however, are members of OPEC, which restricts oil supply to increase its price. Even the subsidised domestic price is likely to exceed the relatively low marginal cost of production in many OPEC countries. As a result, the initial marginal costs of CO_2 control via cutting OPEC oil *production* are likely to be positive. *Shifting consumption* of existing output from OPEC to non-OPEC countries by eliminating subsidies, however, would raise efficiency. Such a shift would probably also reduce total oil consumption and production. The reduction in OPEC consumption from increased prices would exceed the rise in non-OPEC consumption from smaller decreased prices, while higher OPEC exports would displace some non-OPEC production. If CO_2 emissions do fall, the initial net social marginal costs of reducing CO_2 emissions via such a policy would be negative. The policy is then said to involve 'no regrets', even though it can impose losses on some domestic interests.

Turning next to natural gas and coal, the main uses are as inputs into electricity generation and industrial processes (fertilisers, chemicals, and metallurgy) and, for natural gas, heating water and indoor air. Subsidies and anti-competitive behaviour are less significant in these markets. In developed countries, environmental externalities from local toxic pollutants are mostly internalised by anti-pollution

14 Directly taxing emissions would be more efficient because vehicle maintenance, for example, can alter the relationship between fuel use and pollutants produced. In most OECD countries, vehicles must pass an emissions test while idling. Sensors that can measure the exhaust gases of vehicles travelling at normal driving speeds have been developed and could be used to impose an emissions tax on the registered vehicle owner.

15 Directly taxing *vehicle miles travelled* would be more efficient because differing fuel efficiencies weaken the link between gasoline or diesel consumption and vehicle use (including zero liquid fuel consumption when using an electric vehicle).

devices installed either as a result of regulations or in response to taxes or tradable permit schemes. In many developing countries, environmental externalities from local toxic pollutants produced by coal combustion remain uncorrected. The initial marginal costs of controlling CO_2 by reducing coal use in those countries would be negative.

3.2.2 Elasticity of marginal costs of carbon dioxide control

Unless research into new technologies (discussed in Section 6) succeeds, the marginal cost of control curve is likely to rise steeply as CO_2 emission constraints tighten. Technologies for removing CO_2 from exhaust gases, currently in their infancy, are costly and not ready to be deployed at scale. In addition, safely sequestering the captured CO_2 has proved expensive, except where it is used for enhanced oil recovery.[16]

Energy supplied by fossil fuels can be decreased by reducing overall energy demand. If this is achieved via taxes, the low elasticity of energy demand implies that the foregone marginal benefit of reduced energy use will rise steeply as use is curtailed.[17] New technologies, or improvements in processes, that increase energy efficiency can also reduce energy demand. However, the rebound effect implies that the ultimate reduction in energy demand from an improvement in energy efficiency is less than the immediate reduction.[18] Furthermore, energy efficiency improvements alter the *level* of energy demand, whereas continuing improvements are needed to offset energy demand *growth*.

Finally, fossil fuel use could be reduced via electrification of industry, transportation, and space and water heating, accompanied by alternative methods of generating electricity. Currently, electrification is not possible in many applications,[19] while in others it still tends to be more expensive or inferior to fossil fuels on other grounds. Using nuclear, wind and solar to generate electricity also has proven to be quite expensive. 'Command and control' regulations have focused on promoting wind and solar as an alternative to fossil fuels, so we discuss them in more detail.

The average load factor for existing wind farms is at best around 35%, and for existing utility-scale solar plants at best around 25%, compared to over 90% for nuclear plants and up to 70% for coal

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16 A National Energy Technology Laboratory database of CCS projects worldwide currently lists 44 existing, active plants that capture and/or store a total 121,438 metric tonnes/day. This is about 0.14% of the CO_2 released by fossil fuel combustion according to BP statistics. About 40% of the volume of captured CO_2 is used for enhanced oil recovery where about 90-95% of the injected CO_2 remains underground.

17 Under an emissions tax, but not a permit system where permits are given away, these losses could be offset by efficient use of the tax revenue. This is called a 'double dividend' from emission taxation.

18 Increased energy efficiency lowers the cost of engaging in energy-intensive activities, spurring demand for them. The resulting increase in energy use can, at least in part, offset the initial declines in energy use.

19 For a summary of issues in electrifying industry see https://www.nrel.gov/docs/fy18osti/72311.pdf.

plants operated to supply baseload as intended.[20] Lower load factors raise capital costs per megawatt hour of electricity output.

Absent transmission constraints, wind and solar farms are sited first in the most favourable locations. Realised average load factors therefore are likely to decline as total capacity expands. Although new transmission lines can offset this, they often are long and also tend to be used at low load factors, making them expensive per megawatt hour transported.

The relatively low energy density of wind and solar energy also raises land requirements per megawatt of generating capacity. This is less of an issue where land has fewer high-valued alternative uses, such as in west Texas, but then much longer transmission lines are needed to get the power to market.

Another cost is that realised load factors of wind and solar farms can fluctuate by large amounts over short periods. Electricity grids where wind generators supply an average of just 10% of output have experienced serious reliability problems when wind speeds are too low or above cut-out level, or turbines freeze. The biggest crises occur when wind generation is more significant locally and transmission constraints limit electricity imports. Unanticipated falls in electricity supply can impose substantial costs on customers. Unless hydroelectricity based on stored water is available, backup thermal capacity currently is needed.[21] Open-cycle gas turbines, which have relatively high operating costs, are most often used for this purpose. The thermal technologies with lowest marginal costs are unsuitable for backing up intermittent renewable generation. Traditional nuclear plants are designed to operate at full capacity except when they are refuelling, and it can be costly, and hazardous unless specifically allowed for, to quickly cycle them up and down (Lokhov, 2011).[22] Cycling coal plants can result in worse SO*x* and NO*x* pollution because control equipment is designed to operate when the plant runs at full capacity (Bentek Energy LLC, 2010). For all plants using steam turbines, the need to maintain a head of steam means that energy is often wasted when they are cycled. Using baseload plants at less than full capacity also means that the substantial fixed costs are spread over fewer gigawatt hours of output, raising unit costs.

The production, installation and disposal of the non-renewable capital needed to harvest renewable energy, or any transmission lines needed to connect remote generators to the grid, are not free

20 Using data from the Energy Information Administration, the average load factor for coal plants in the US has declined from over 66% in 2010 to almost 40% in 2020. Operating them as backup for intermittent renewables may explain some of this, but increased competitiveness of natural gas plants has also played a role. Also, many of the coal plants are aging, making them less reliable and less competitive.

21 Utility-scale batteries can also backup renewables. However, they are currently expensive and, while they have proved effective for providing very short-term ancillary services, they are not suitable for longer-term storage cycles. The latter also are needed to support seasonality in renewables generation output.

22 Tight regulations and associated long construction times also have made construction of new plants using current nuclear technology very expensive. Newer nuclear technologies under development may solve some of these problems.

of CO_2 emissions. Furthermore, many minerals needed to produce wind turbines, solar panels and batteries are found in low concentrations, so many tonnes of rock need to be extracted to obtain a tonne of ore (see Table 2).[23] Most of this mining, and the associated energy-intensive processing, shipping and refining, uses fossil fuels.[24] Moreover, a massive expansion of wind turbines, solar panels and batteries would greatly increase the costs of critical mineral inputs because exploitation of lower-grade and/or more remote resources will be required.

The costs of wind turbines, solar panels and batteries also need to include the costs of other environmental externalities. These could include bird and bat kills, the despoliation of vistas, and adverse health effects from noise and infrasound. Mining and processing mineral inputs into wind turbine, solar panel, and battery production also produces local toxic air or water pollution. Wind turbines, solar panels, and batteries also yield substantial toxic waste after they are dismantled.

As argued in Hartley (2017), limiting production of fossil fuels in western democracies creates significant energy and national security externalities by increasing reliance on OPEC and Russia. Russia's invasion of Ukraine in February 2022 highlighted the risks for European nations in importing significant volumes of Russian natural gas, the use of which to back up intermittent wind and solar generation makes the electricity supply – along with indoor heating and much of industry – vulnerable to supply disruptions. Basing electricity supply on wind, solar and batteries also increases imports of critical components or inputs from China. According to the International Energy Agency *Photovoltaic Power Systems Program*, in 2019 China accounted for 68% of global polysilicon production, 96% of global photovoltaic (PV) wafers production, 76% of PV cell production and 71% of PV module production. The GWEC *Global Wind Blade Supply Chain Update* for 2020 ranks China as the largest producing country for wind turbines. Chinese firms, either as independents or as OEMs for large international firms, are responsible for more than 50% of global wind blade production capacity. In a 2021 report, the US International Trade Commission reported that China is now the leading exporter of wind-powered generating sets, accounting for about 10% of the market outside China. Finally, Table 2 shows that China dominates production of many minerals critical to the manufacture of wind turbines and solar PV. Although the requirements for lithium-ion and other batteries are not given in Table 2, China is also the dominant producer of many of those inputs.

3.3 Efficient control levels and taxes versus permits

A necessary condition for efficient emissions control is equality between marginal costs of control and marginal damages. For the toxic

23 For example, leading spodumene (a lithium ore preferred for producing LiOH used in batteries) mines typically contain ores with 1–2% concentration of Li_2O.

24 On the other hand, whereas renewables require mineral inputs only at the investment stage, fossil, and to a lesser extent nuclear, generation requires ongoing mining and transportation of fuels.

Table 2: Critical mineral inputs per MW of generating capacity

Mineral	Wind (kg/MW)	Solar (kg/MW)	Nuclear (kg/MW)	Major supplying countries
Aluminum	—	100	—	Smelter prod. China (56%) India (6%) Russia (6%) Canada (5%)
Boron	1	—	—	Turkey (39%) US (23%) Chile (14%) Kazakhstan (10%)
Cadmium		40	0.5	Ref. prod. China (33%) S. Korea (20%) Japan (8%)
Chromium	800	—	427	S. Africa (39%) Turkey (23%) Kazakhstan (9%)
Copper	2000	2000	60	Chile (28%) Peru (12%) China (8%) US (6%) Congo (6%)
Gallium	—	3	—	China (97%)
Indium	—	50	2	Ref. prod. China (39%) S.Korea (32%) Japan (10%) Canada (8%)
Lead	—	250	4	China (47%) Australia (10%) Peru (6%) US (6%)
Manganese	50	—	—	S. Africa (29%) US (17%) Gabon (13%) Ghana (7%)
Molybdenum	120	—	70	China (45%) Chile (19%) US (15%) Peru (10%)
Nickel	600	—	256	Indonesia (30%) Philippines (16%) Russia (10%) Australia (7%)
Niobium	—	—	2	Brazil (88%) Canada (10%)
Rare earths	188	—	0.5	China (63%) US (12%) Myanmar (10%) Australia (10%)
Selenium	—	40	—	Ref. prod. China (33%) Japan (28%) Germany (11%)
Silicon	—	15	—	China (64%) Russia (9%) Norway (5%) US (5%)
Silver	—	12	8	Mexico (23%) Peru (14%) China (13%) Russia (8%)
Tellurium	—	50	—	Ref. prod. China (62%) Japan (12%) Russia (9%) Sweden (9%)
Tin	—	450	5	China (27%) Indonesia (26%) Myanmar (17%) Peru (6%)
Titanium	—	—	1.5	China (28%) S. Africa (12%) Australia (11%) Canada (9%)
Tungsten	—	—	5	China (82%) Vietnam (6%) Mongolia (2%)
Vanadium	—	—	0.5	China (55%) Russia (25%) S. Africa (11%) Brazil (10%)
Zinc	5200	30	—	China (33%) Peru (12%) Australia (7%) India (6%) US (6%)
Zirconium/ Hafnium	—	—	32	Australia (39%) S. Africa (26%) US (7%)

Sources: World Bank and USGS. Refining shares are given where the minerals are co-produced. Co-products that are the main output then often drive supply. The inputs are for 'representative' technologies and relate to generating capacity. Since the capacity factors for solar and wind are 25–40% of those of nuclear plants, and the plants have lifespans about 40% of that of a nuclear plant, inputs per unit of energy generated over the life of the plant would be much more unfavorable for wind and solar. The table also ignores required energy, steel, cement, land and water inputs.

flow pollutant in Figure 3a, two intersections are likely, but only the left-hand one is relevant, because marginal damages exceed marginal costs of control at all emission levels between the two. More importantly, the steep marginal damages curve around the 'threshold level' implies that the optimal *quantity* of emissions does not vary much as the marginal costs of control curve varies. For CO_2 emissions in Figure 3b, the optimal *marginal damage* does not vary much as the marginal costs of control curve varies. The marginal costs of control curve will frequently vary in both cases, because fuels differ in toxic flow pollutant and CO_2 emissions per unit of energy produced and relative fuel prices vary substantially and often.

As the marginal costs of control curve varies, either a fixed Pigouvian emissions tax or a fixed supply of tradable emission permits will lead to efficiency losses relative to the instantaneous optimal values *for that configuration of marginal costs*. The marginal costs curve varies much too frequently, however, for tax rates or permit supply to respond. Either scheme will lead to efficiency losses. As shown by Weitzman (1974, 1978) and subsequent authors, the relatively steep MD curve around the *average* optimal level in the toxic flow pollutant case then implies the permit system will be more efficient *on average* than the emissions tax. Conversely, the relatively flat MD curve and steep MC curve in the CO_2 case implies that an emissions tax is likely to be more efficient *on average*.

If a permit scheme is nevertheless used for CO_2, the MC curve becomes the permit demand curve. As it varies, the price equilibrating demand to the fixed permit supply also will vary. The inelasticity of permit demand means that a large change in permit price is needed to eliminate a small excess demand. If the number of permits is reduced over time, or permit demand increases while supply is held fixed, the *average* permit price will rise. Conversely, the price will fall if additional mandated renewable generation reduces the demand for permits. Unstable policies therefore increase permit price instability. In practice, European CO_2 permit prices have been notoriously variable. A variable CO_2 permit price in turn makes long-term investments in energy-using or energy-producing industries more risky. This reinforces the case for using an emission tax rather than permit scheme for controlling CO_2 emissions.

3.4 Carbon dioxide as a global externality

When emissions from many locations contribute to the same externality, the equimarginal condition requires identical marginal cost of control across all emitting locations. Either an emissions tax uniform across locations or a global emissions trading scheme with a uniform permit price could enforce the equimarginal condition, but sovereign nations have an incentive to opt out and leave control to others. Global emission control becomes extremely difficult, as has been proven by the never-ending – and mostly symbolic and fruitless – rounds of international negotiations on the issue.

Large-population developing countries are forecast to dominate CO_2 emission increases in coming decades for several reasons. First, the large populations mean that a small increase in per-capita energy use greatly increases total energy use. Second, the mechanisation of agriculture, industrialisation, urbanisation and development of infrastructure accompanying early stages of rapid economic growth greatly increase the energy intensity of production. Third, in prioritising economic growth, these nations will prefer the cheapest and most reliable energy sources, which as of now are fossil fuels. Developing countries may also use low-cost energy to attract energy-intensive activities shunned by others. Moving such industries, however, may result in faster CO_2 emissions growth and a larger ultimate CO_2 accumulation if CO_2 emissions per unit of energy used are higher in exempt locations and energy-intensive international transportation of bulky commodities increases.

4. Defensive measures

Reducing CO_2 accumulation in the atmosphere is not the only option for reducing damages. As noted at the end of Section 2.3, market insurance may be effective at reducing the net costs of many extreme weather events. Other private actions and government policies are also available.

Actions, classified as self-protection by Ehrlich and Becker (1972), can reduce the likelihood of harmful consequences from extreme weather. Examples of such policies include:

- making indoor temperature control available and affordable to more people;
- building dykes or levees to protect vulnerable coastlines or floodplains;
- building dams to help protect against flooding and droughts;
- improving evacuation procedures ahead of threatening weather events;
- improving weather forecasts to give better warnings to take precautions;
- improving urban drainage systems and mitigating urban heat island antecedents;
- burying power lines to make them more resilient to storms;
- changing building codes to increase structural integrity;
- developing crops more resilient to weather extremes; and
- removing subsidies to living on vulnerable flood plains or coasts.

These measures can defend against adverse weather events whether or not the distributions of those events have changed, either as a result of CO_2 accumulation or natural causes.

Other actions, classified as self-insurance by Ehrlich and Becker (1972), can lower the costs of adverse weather events after they have occurred. Examples of such policies include:

- better disaster relief including improved cooperation between different jurisdictions;

- training and equipping volunteer rescue services;
- Improved emergency medical facilities; and
- improved civil reconstruction capability.

Such measures can also reduce the costs of other disasters that have nothing to do with adverse weather, such as earthquakes, tsunamis, volcanic eruptions, terrorist attacks, and major industrial accidents. This would raise their benefit/cost ratios.

Hereafter we refer to self-protection and self-insurance policies together as 'defensive measures'. These are a *policy* concern because they are a public good or have a public good element in their provision. Others require changes in existing policies. In addition, individuals and firms can undertake various *private* self-insurance and self-protection actions that also reduce the expected costs of extreme weather.

Since defensive measures provide insurance, greater uncertainty about future extreme weather increases their value. This includes uncertainty that arises *even if the distributions of those events do not change* or, if they do change, what caused that change. Any changes that do occur will vary by location, as noted in Section 2.3. Each locale can tailor defensive measures to counter the harmful weather events most relevant to them. Unlike emission controls, defensive measures are not inherently adversarial and do not compromise energy and national security. Any nation can benefit from taking such measures and global agreement is not required for it to do so. If changes in the distributions of some weather variables are at least partially beneficial, defensive measures can counter the harmful effects while retaining the beneficial ones.

Reducing CO_2 emissions might also insure against possibly harmful future weather events, but in a less targeted and less reliable way. Errors in predicting effects of CO_2 emissions on accumulation (Section 2.5), CO_2 accumulation on GSTA (Section 2.2), and GSTA on the distributions of other climate variables (Section 2.3), produce a very uncertain link between emission control and weather. A policy should be used less aggressively when its effect on a desired outcome is more uncertain (Brainard, 1967). In addition, a *single* global CO_2 accumulation target must be chosen. Controls should be less stringent if *even some* locations desire a higher GSTA and/or experience higher direct marginal benefits from CO_2. Greater use of defensive measures would also raise the most desirable global CO_2 accumulation target.

The equimarginal condition implies that the marginal cost (normalised for effectiveness, and after subtracting any non-climate marginal benefits) of all defensive measures being used at each location should be kept equal. Since there are many measures, the marginal cost should increase gradually with use. By contrast, as argued in Section 3.2.2, the marginal cost of controlling CO_2 emissions is likely to rise steeply as emissions are curtailed. Furthermore, just as the marginal costs of defensive measures should be *reduced* when they provide other benefits that have nothing to do with extreme weather, the marginal costs of reducing CO_2 emissions should be *increased* to account for the forgone aerial fertiliser benefits of CO_2 discussed in Section 2.4.

5. Time profile of costs and benefits

Whereas the effects of CO_2 on temperature build gradually over time, the costs of reducing CO_2 emissions are immediate. As Stern (2007) emphasised, CO_2 emission reductions are thus an investment with a net present value strongly affected by the time discount rate. Stern observes that the 'risk free' discount rate depends on both the 'pure rate of time preference' and the anticipated change in per capita consumption over time.[25] He accepts that higher per-capita consumption of future, relative to current, generations yields a positive discount rate, but claims we should assume a pure rate of time preference of zero for public policy that redistributes costs and benefits between generations.

The great uncertainty about the link between CO_2 emission controls and weather makes emission control a *risky* investment. Hence, the appropriate discount rate needs to include a risk premium, as all investments with the same risk profile ought to yield the same rate of return. Privileging CO_2 emissions reduction relative to other investments of equivalent risk would misallocate scarce capital.[26]

The possibility that research could reduce uncertainty about the CO_2 cycle, climate science, capture and sequestration technologies, and energy technologies, implies that waiting to reduce CO_2 has a real option value. Greater uncertainty about any of these future prospects increases that option value. For the same ultimate accumulation, a time path of emission reductions that delays the largest reductions until later would be preferable to one that front-end loads the emission cuts.

Expenditures on defensive measures are also investments, but they start protecting immediately. There is also little uncertainty about their costs and potential benefits. They therefore will have a lower real option value from delay, and are likely to have a lower risk-adjusted discount rate.

25 A positive pure rate of time preference results from a marginal preference for current over future consumption when consumption in the two periods is equal. It arises because people prefer to consume earlier than later, not least because they may die in the interim. Decreasing marginal utility of consumption combined with economic growth also contributes to a positive risk free discount rate. The cost of using per capita resources for an investment today is, to a linear approximation, the marginal utility of per capita consumption today times the per capita investment. The gain in future welfare from a reduction in per capita climate costs is, again to a linear approximation, the marginal utility of consumption at that time multiplied by the per capita cost reduction. Economic growth means per capita consumption is expected to be much higher in the future, and decreasing marginal utility of per capita consumption then implies that future marginal utility will be less than marginal utility now.

26 Making a poorer current generation pay so richer future generations are better off could also be considered inequitable. Furthermore, there is no way for richer future generations to agree to transfer wealth backward to earlier generations to address the inequity.

6. Direct subsidies for new energy technology

As noted in Section 3.4, economic growth in large-population developing countries will dramatically expand demand for fossil fuels. Despite serendipitous discoveries and new production technologies that temporarily increase supply and/or reduce production costs, depletion of the most favourable deposits will tend to raise real fossil fuel prices. Simultaneously, research into alternative energy supply technologies is lowering their costs. A world where alternatives to fossil fuels supply most primary energy is inevitable, although when that will occur is uncertain. The time it takes will be a primary driver of the *stock* of CO_2 that ultimately accumulates in the atmosphere.

Many authors have claimed that there is a paucity of financial support (a 'valley of death'):

- for proving the commercial viability of promising energy technologies compared to support for early-stage R&D;
- for deploying new technologies once proven commercially viable.

Hartley and Medlock (2017) examine the efficient transition between fossil fuels and alternative energy sources when capital is required to deliver energy services.

Infrastructure for delivering alternative energy services is needed at the transition but, for some preceding period, capital used to deliver energy services from fossil fuels is a sunk cost. The efficient energy price therefore need only cover the *operating costs* of fossil fuel technologies. For some time both before and after the transition it will not cover the long-run costs of providing energy services using the new technology. The transition may thus be difficult to achieve using decentralised markets.

Research into alternative energy technologies could also suffer from an inadequate level of investment as a result of a *positive* externality. Once research has been done it can be copied at low cost. Knowing that, firms have a reduced incentive to invest in R&D.

Patents or research subsidies have traditionally been used to alleviate under-investment in R&D. Patents are preferred for technology close to producing a marketable product. They encourage R&D into those technologies considered more likely to deliver benefits to users. Direct subsidies are more useful for more basic research, where results of commercial value are more uncertain or delayed. Basic research may also have wide application, which makes the temporary monopoly status granted by patents more inefficient. The panels of scientific experts awarding research grants also may be better informed about fundamental scientific problems than about the immediate market potential of research.

Taxing CO_2 emissions, or mandating or subsidising the currently most viable alternative to fossil fuels, is more akin to a patent. Directly subsidising new basic science research, and then the required new delivery infrastructure, could instead develop technologies with greater long-term potential to substantially displace fossil fuels.

Hartley (2018) examined strategies for displacing fossil fuels in

Texas. Using technology cost estimates from the Energy Information Administration, a weighted average real cost of capital of 7.5%, and assuming electricity storage suitable for Texas could be provided at the cost of pumped storage,[27] Hartley found that supplying the Texas 2016 load with wind and storage would be about 28% more expensive than using nuclear and storage.[28] The explanation is that electricity storage is very expensive and the wind system, because of intermittency and a poor correlation of wind generation output with load, requires 96% more storage capacity. In the nuclear system, storage is used only to smooth demand. Natural gas generation can provide backup at a much lower cost than storage. At a low CO_2 tax rate, Hartley therefore found that wind with natural gas generation as backup was less costly than nuclear with natural gas backup, but even moderate increases in tax rates made nuclear with natural gas backup, and then nuclear with storage, less costly. More R&D into new nuclear technologies could increase their long-term advantages.

7. Concluding comments

A Pigouvian tax on CO_2 emissions is often advocated as the most efficient policy for reducing external costs from CO_2 accumulation in the atmosphere. Since emissions from all locations contribute to a single global accumulation, minimising the cost of CO_2 emission reduction requires equating the marginal costs of control across all locations. For this reason, and also to prevent 'leakage' of CO_2-emitting activities from disfavoured to favoured locations, an emissions tax would need to be levied at the same rate in all countries. Getting over 100 nations to agree on, and enforce, such a tax faces enormous obstacles.

The cost of controlling CO_2 emissions depends on the cost of reducing fossil fuel use, which produces around 75% of anthropogenic emissions while supplying over 83% of world primary energy. So-called 'no regrets' policies, mainly the removal of subsidies, can reduce CO_2 emissions while delivering other efficiency gains, but their

27 Since Texas is unsuited to pumped storage, this would require substantial further improvements in battery technology. It probably also would require limited alternative demands for battery storage capacity at the same time so that the cost of raw material inputs into batteries stays low.

28 See also the concept of 'levelised full system costs of electricity' developed in Idel (2022). Essentially, Idel observes that electricity generated by a wind or solar farm is not the same product as electricity generated by a thermal power plant. The value of electricity to consumers depends especially on where on the network and when it is made available (and also other characteristics such as its ability to stabilise frequency, but location and time are the key variables). Most wind farms, for example, can be sited in a limited number of locations, often remote from load, and produce an output that fluctuates substantially with exogenous wind speed (and, for un-weatherised turbines, temperature). By contrast, thermal power stations can be placed almost anywhere on the network and can generate a wide range of output up to their capacity limit on demand. Wind farm output can be made equivalent to the output from a thermal plant by adding batteries at appropriate places on the network, and possibly also new transmission lines. However, the costs of any additional facilities needed to supply a comparable product need to be included in the levelised cost calculations.

impact would be minor and transitory. Alternative technologies that can supply energy on a massive scale are needed, not only to replace current energy from fossil fuels, but also to increase the welfare of billions of people still living without modern energy services. Available technologies deliver energy that is often less affordable, reliable, controllable, storable, transportable, or convenient than energy provided by fossil fuels. A tax on CO_2 emissions indirectly incentivises some needed R&D. However, it favours technologies that are currently most competitive with fossil fuels and not alternatives, such as nuclear energy, that could be more effective in the long run. For that, direct R&D subsidies would be preferable.

The major claimed benefit of cutting CO_2 emissions is a reduced likelihood of harmful weather events such as floods, droughts, hurricanes, tornadoes, heatwaves and deep freezes. The link between CO_2 emission reductions and the likelihood of such events is, however, quite uncertain. Unmeasured or poorly understood aspects of the CO_2 cycle weaken the link between emission control and CO_2 accumulation. There is also substantial doubt about the effects of CO_2 accumulation on climate variables, especially at regional levels. A policy with uncertain effects should generally be used more cautiously. Furthermore, the likelihood that uncertainty could be reduced implies there is an option value to waiting, strengthening the case for moderation in the short run.

Accumulating evidence suggests that GCMs, which have provided the main cause for concern, exaggerate the effects of CO_2 on temperatures and therefore also the effectiveness of CO_2 emissions control as a policy instrument. Defensive measures that reduce the expected cost of damage from adverse weather events are a major alternative. Such measures are worthwhile, whether or not the probability distributions of weather events change and no matter the source of any changes. Measures that reduce the costs of damaging weather events after they occur, such as improved disaster response, are likely to yield additional benefits when responding to other, non-weather, events such as earthquakes, tsunamis, volcanic eruptions, major industrial accidents and terrorist attacks. This would further increase their desirability. Defensive measures also deliver more immediate expected benefits, which will raise the present value from their deployment.

Each locale can tailor defensive measures to counter the types of extreme events it finds most threatening while retaining benefits from continued fossil fuel use and any beneficial effects from CO_2 accumulation. The latter include the stimulative effects of CO_2 on plant growth. It is also most unlikely, however, that CO_2-caused changes in distributions of weather events will always and everywhere only increase expected harm.

Finally, defensive measures can be implemented in a decentralised way without requiring international agreement. Their greater use, along with private self-insurance and self-protection actions of individuals and firms and greater use of market insurance, would further lower the benefits of reducing CO_2 emissions.

Given the formidable vested interests that have developed around technology mandates and restraints, justified as effective ways to control weather outcomes, it may be unrealistic to expect politicians in developed democracies to abandon them. Nevertheless, the defects of such policies will continue to exert pressure to change course.

Investing in explicit R&D and defensive measures are superior approaches for many reasons.

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Comment by Ross McKitrick

The short answer to the question posed in the title is 'Yes'; the long answer is the essay itself. It is a wide-ranging and well-argued piece that brings great clarity to the discussion around optimal climate policy.

Hartley begins with a review of some of the pertinent issues in the underlying physical science. I didn't see anything I would dispute, but, given the disputatious nature of the topic, I suspect other readers would demand more footnotes and citations to back up the claims. At several points the essay put me in mind of Steven Koonin's book *Unsettled* (including Hartley's later argument in favour of primarily relying on adaptation rather than mitigation). The scientific topics surveyed and the points made are well-established and could, with the expense of some tedious effort, be systematically referenced to numerous sources, chiefly the IPCC reports themselves. Since they are also pretty much the exact opposite of the prevailing conventional wisdom, many readers will gasp at what he says and assume it must be wrong. Thus while adding the apparatus of footnotes and line-by-line citations was not necessary for a reader like me, it would be useful to forestall other predictable counterattacks.

Hartley then provides an intuitively clear statement of the basic precepts of environmental policy, namely the equimarginal principle and the theory of the optimum. I often say to my students, upon explaining these ideas, that once you have grasped them they are so simple and even self-evident that it hardly seems necessary to point them out. Yet they are so routinely violated in environmental policymaking (especially in climate policy), resulting in an epidemic of monumental wastage of public and social resources, that we economists find it necessary to make the effort over and over again to promulgate them. I do caution students, however, that once they have grasped the principle of the optimum they will thereafter think like an economist and quickly discover how few others do. When it comes to the idea of pollution control, stating the theory of the optimum, despite it being perfectly sound and inescapably obvious, could lead to their expulsion from polite society.

The climate change issue has many aspects and a discussion that starts in one place at a general level can quickly end up deep in minute details of another topic altogether; thus Hartley soon finds himself explaining some rather specific issues in the economics of wind energy. It is not a digression, but a natural consequence of the equimarginal principle. If an appropriate carbon tax were charged, that would be a sufficient policy for dealing with the climate issue. And it is a safe bet that no one would respond to it by flinging vast amounts of money at wind or solar energy. In most cases the costs of such systems far exceed the money saved from not having to pay carbon taxes on fossil energy-based generating options. Yet windmills and solar panels are everywhere a blight on the landscape, each one a monument to government folly.

Which brings me to one of the additional points Hartley should have made. In answer to the question in his title, a carbon tax is only optimal if it is used alone. Once governments have littered the policy landscape with regulations, mandates and standards, the economic case for carbon taxes is destroyed. It would make sense to repeal all the regulatory measures and replace them with a carbon tax, but it does not make sense simply to add the tax on top of what is already there.

But this raises an uncomfortable point that would stall any such effort. The optimal carbon tax, based on the mainstream estimates of the social cost of carbon, would not yield more than a modest reduction in carbon dioxide emissions. It would not get us anywhere near the Paris targets and certainly would not put us on a path to Net Zero. It would leave us on a path of fossil fuel consumption barely distinguishable from doing nothing at all. You might conceivably get climate campaigners interested in a regulation-for-tax swap, up to the moment when you explain that the result will be an increase in emissions and a return to something close to business-as-usual fossil fuel consumption. Then they will protest that we need to raise the carbon price higher and higher until we get back to the Net Zero path. But the rejoinder is the principle of the optimum: the carbon tax should not exceed the social cost of carbon, which is too small to justify such a path. At which point, as I have already said, one is likely to be expelled from polite society.

One point I do dispute in Professor Hartley's essay concerns the prescription of a uniform global carbon price. While the social cost of carbon is globally uniform (because of the global mixing of carbon dioxide into the atmospheric stock), the optimal carbon price is not. According to the Sandmo rule (Sandmo 1975; Bovenberg and Goulder 1996) the optimal tax on pollution emissions is the marginal social cost deflated by the marginal cost of public funds. The latter is the loss of economic welfare (measured in dollar terms) required to raise one additional dollar for the public budget. It is typically above 1.0, and in some economies much higher, which means the optimal carbon tax is smaller than the social cost of carbon. Since the marginal cost of public funds varies from country to country, so must the optimal carbon tax. This is a point I have never heard discussed in the current debates about carbon border charges, but it matters acutely. It may very well be that a country with a relatively low carbon price would be justified in charging tariffs against a country with a high carbon price; what matters is how the country's carbon tax compares to its own domestic optimum, not its neighbour's.

Thus we need to say more. At the same time, sometimes less is more. There is a great need for well-informed analysts like Professor Hartley to emphasise the basics. Policymakers must aim for the optimum and equate the marginal costs of different efforts. Select policies that accomplish these things automatically, and avoid policies that destroy efficiency. Supplement the basic pricing instrument with some assistance to technological research where there is a public good associated with innovation. For a long time, the determination of policymakers to flout these rules had no apparent consequences because the imposition of the costs was still far in the distance. But now the costs are beginning to be felt, and the ground is shifting rapidly. Protests against climate policy overreach have convulsed Europe and toppled the government of Sri Lanka. They have figured into major political upheavals in Canada and the UK. And with energy-cost-driven inflation contributing to a collapse in the political fortunes of the Biden presidency, a major policy shift appears inevitable in the US. We may very well be approaching a day when it is possible to explain the principle of the optimum in polite society.

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Comment by Robert Lyman

Professor Hartley has contributed an excellent paper that provides an analysis and overview of the issues confronting policy makers who seek to design and implement carbon dioxide taxation systems that will attain, at the global level, the benefits of a Pigouvian tax on CO_2 emissions favoured by economists.

My background is that of a long-time policy advisor on energy, transportation and environmental issues operating within the Canadian federal government. The advice given to and taken by ministers on climate policy and other economic/environmental policy matters unfortunately rarely conforms with the principles of economic theory. My experience thus does not permit me to judge, or to critique, the learned discussion offered by Professor Hartley. I may, however, suggest some additional considerations that Professor Hartley may wish to reflect in his paper.

The first is that the actual use of carbon dioxide taxes, or their cousins, emissions trading systems, do not in practice often align with the theoretical ideal relating to the marginal costs and benefits of global emissions reduction. For example Canada, where I live, has not adopted a single carbon dioxide tax regime, but rather a balkanised set of regimes that apply differently in each province of the federation. In those parts of Canada in which the federal standard applies, the rate of the carbon tax was not set to accord with the theoretical optimum, but rather to rise annually at rates designed to avoid undue political opposition and to reach levels that, in theory, will be sufficient to attain a pre-conceived emissions-reduction target. In other words, the level of the tax is set based on short-term political considerations married to longer-term quantitative emission reduction targets that are entirely arbitrary.

The second point is that the benefits of carbon dioxide taxes in promoting economically efficient outcomes are usually based on the assumption that they are the only, or the primary, mechanism used to incentivise changes in consumer and producer behavior. In practice, and certainly in Canada, carbon dioxide taxes are only one of several hundred different measures used by government, including direct subsidies to renewable energy producers and purchasers, subsidies for infrastructure and manufacturing plants, tax deductions and exemptions, mandated electricity rates, regulations to reduce or prohibit the production, transportation and distribution of hydrocarbon-based energy services, and several other direct-action measures. In these circumstances, it would be difficult to determine, or assess the benefits of, the marginal behaviour changes motivated by carbon dioxide taxes. Canada is not alone in this practice.

The third point is that the design of carbon dioxide tax regimes often falls victim to other political considerations. The World Bank reports periodically on the use of carbon dioxide taxation and emissions trading systems globally. Its 2021 report indicates that:

- Forty-six countries have implemented various forms of carbon pricing regime (out of 196 countries that have signed the Paris Accord in 2015).

- Most of the countries and sub-national jurisdictions that have established such regimes are in OECD countries.
- The rate of carbon dioxide taxes charged varies widely, from \$137 per tonne of CO_2 equivalent in Sweden to \$4 per tonne in China and \$3 per tonne in Japan. Most countries have rates at or below \$25 per tonne.
- The scope of coverage of the regimes (i.e. the share of the economy subject to the tax or emissions trading price) also varies widely. Generally, in European countries, the scope of coverage ranges from 30–40%; in the United Kingdom it is 23%, in Mexico 23%, and the figure is unlisted but very low in the US.
- Similarly, there is a broad range of practices with respect to the use of the revenues received from carbon dioxide taxes and emissions trading permit sales. Only in a minority of cases are the revenues returned to the public in ways that might stimulate increased activity in the broader economy.

These issues of design indicate that carbon dioxide taxes, in practice, rarely have a common inspiration or similar effects. I leave it to Professor Hartley's judgment as to whether he wishes to comment on this in his paper.

A response to Ross McKitrick and Robert Lyman

I thank both commenters for their perceptive and valuable comments. There is some overlap in their criticisms, which can be summarised intro three points. McKitrick says:

> [A carbon dioxide tax] is only optimal if it is used *alone*. Once governments have littered the policy landscape with regulations, mandates and standards, the economic case for carbon [dioxide] taxes is destroyed. It would make sense to repeal all the regulatory measures and replace them with a carbon [dioxide] tax, but it does not make sense simply to add the tax on top of what is already there.'

This is echoed by Lyman:

> In practice…carbon dioxide taxes are only one of several hundred different measures used by government…In these circumstances, it would be difficult to determine, or assess the benefits of, the marginal behavior changes motivated by carbon dioxide taxes.

McKitrick says that, since the optimal tax would yield only a modest reduction in emissions, it will lead to calls for raising the rate, because proponents of reducing CO_2 emissions believe that the prospective damages require larger reductions than any acceptable tax could achieve. Similarly, Lyman notes that the theoretically ideal Pigouvian tax on CO_2 emissions, as proposed by economists, would in practice lead to a 'balkanised set of regimes' and rates that are:

> …not set to accord with the theoretical optimum but rather at levels…designed to avoid undue political opposition [and with a desire] to attain a pre-conceived emissions-reduction target. In other words, the level of the tax is set based on short-term political considerations married to longer-term quantitative emission reduction targets that are entirely arbitrary.

Both commenters also address difficulties associated with the notion that a theoretically ideal Pigouvian tax on CO_2 emissions would need to be international in scope. McKitrick observes that an important complication in setting the theoretically optimal rate is that the marginal cost of public funds differs across countries. Lyman observes that, 'The design of carbon dioxide tax regimes often falls victim to other political considerations…carbon dioxide taxes, in practice, rarely have a common inspiration or similar effects' across countries.

The first thing to say in response is that the superiority of economic instruments – Pigouvian emission taxes or marketable emission permits – to command and control measures, such as technology mandates and restraints, is not a controversial claim among economists. Even when we allow for the fact, emphasised by McKitrick and Lyman, that policies proposed by economists are never cleanly implemented in the way that the proponents envision, command and control policies have repeatedly proved less effective and more costly than taxes or marketable permits where the latter have been used instead. As was stated in the introduction to this paper, any *achievable* tax on CO_2 emissions would be far from ideal, but current policies are even worse.

Second, I agree with McKitrick and Lyman that given the situation we are now in with a policy landscape 'littered…with regulations, mandates and standards' and formidable vested interests reliant on the preservation of those policies, a proposal to introduce a tax on CO_2 emissions is likely to be added to existing policies and not replace them. In this respect, policies such as the 'conservative climate solution' proposed by the Climate Leadership Council[29] are unwise. It is worth quoting the rationale they give for their policy (amended to generalise their language to make it applicable to any democracy):

> While the extent to which climate change is due to man-made causes can be questioned, the risks associated with future warming are too big and should be hedged. At least we need an insurance policy. For too long, many [conservative politicians] have looked the other way, forfeiting the policy initiative to those who favor growth-inhibiting command-and-control regulations, and fostering a needless climate divide between [conservative political parties] and the scientific, business, military, religious, civic and international mainstream.

They go on to say that conservatives need to:

> [P]romote a climate plan that showcases the full power of enduring conservative convictions. Any climate solution should be based on sound economic analysis and embody the principles of free markets and limited government…[S]uch a plan could strengthen our economy, benefit working-class [people], reduce regulations, [and] protect our natural heritage…These benefits accrue regardless of one's views on climate science.

There are four pillars to their plan. The first is a tax on CO_2 emissions. The second is that all revenue raised by the tax would be paid to residents as a per-capita income transfer. A third pillar is taxes on international trade (called 'border adjustments') to compensate for differences in CO_2 emission control policies across countries. The fourth pillar involves eliminating all regulations on economic activity justified as 'climate policy' that 'are no longer necessary'.

The arguments of McKitrick and Lyman suggest that, in practice, the taxes would be added to existing policies, not replace them. In addition, any revenue raised by the tax would most likely be used for politically-favored purposes of dubious value, or, if it is returned to individuals, redistributed based on political criteria rather than on a per-capita basis. Finally, legitimising trade intervention policies would likely mean that the usual vested interests would drive policy outcomes rather than any high-minded concerns about equalising

29 See https://www.clcouncil.org/media/2017/03/The-Conservative-Case-for-Carbon-Dividends.pdf.

international differences in taxes on CO_2 emissions. In short, there is zero chance that the Climate Leadership Council plan would ever be implemented, and attempting to implement it is likely to do more harm than good.

To give the Climate Leadership Council their due, however, looking the other way and 'forfeiting the policy initiative to those who favor growth-inhibiting command-and-control regulations' is also unacceptable. Many voters are demanding a positive agenda to address their concerns about CO_2 as a greenhouse gas, and to cope with the massive anticipated increase in energy demand as high population developing countries enter the early stages of rapid economic growth. What else might politicians who favour 'sound economic analysis…free markets and limited government' propose?

The key point made in this paper is that, in contrast to toxic flow pollutants, controlling emissions, whether by taxes or by inferior measures, is not the only way to limit potential harm from CO_2 accumulation in the atmosphere. In particular, market insurance, self-insurance and self-protection measures can substantially reduce net costs resulting from CO_2 accumulation. In addition, such 'defensive measures' are consistent with free markets, limited government, and domestic democratic control over policy.

Defensive measures also allow benefits from CO_2 accumulation to be retained. These include the stimulative effects of CO_2 on plant growth, but also any beneficial changes in some climate variables in some locations as a result of increased CO_2. It is also important to counter the claim that distributions of climate variables would not change, and extreme weather events would not occur, in the absence of human emissions of greenhouse gases. Defensive measures are worthwhile whether or not the probability distributions of weather events change and no matter the source of any changes.

The paper also argued that many lines of evidence suggest that climate models have exaggerated the potentially harmful effects of CO_2 accumulation on temperatures and other climate variables. This means that we have more time to develop technologies that can supply massive amounts of reliable, controllable, storable, and transportable energy at acceptable cost (including the cost of *all* externalities). This is needed, not only to replace current fossil fuel use, but also to satisfy the needs of billions of people who want to enjoy the many fruits of a modern, developed economy. The most likely candidates are nuclear technologies, because energy density matters greatly for costs *per unit of energy produced*. Many firms are attempting to develop the required breakthrough technologies.

The main policy changes they require are reduced regulatory burdens and the removal of subsidies and mandates for unreliable and uncontrollable generation. The latter raise the costs of nuclear technologies by requiring them to cycle and by lowering their capacity factor.

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