



Climate impacts of fossil fuels in today's electricity systems

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Synopsis

Oil, coal, and gas account for approximately 80% of global primary energy, but only a portion of total airborne CO₂^{eq} (approx. 35% at GWP₂₀ to 65% at GWP₁₀₀), even though they account for 95% of total measured CO₂ emissions. The benefits of these energy sources, as well as their related costs, are not all incorporated in current energy policy discussions. Global greenhouse gas policies must include documented changes in measured airborne CO₂^{eq} to avoid spending large amounts of public funds on ineffective or sub-optimal policies.

The authors examined airborne CO₂, which is less than half of emitted CO₂, as well as reported CH₄ emissions and the global warming potential of CH₄ as published by the IPCC for coal and natural gas. The surprising conclusion is that surfaced-mined coal appears 'better for the climate' than the average natural gas, and all coal appears beneficial over LNG. Therefore, current CO₂-only reduction policies and CO₂ taxes are leading to unintended consequences and the switch from coal to natural gas, especially LNG, will not have the desired impact of reducing predicted future global warming; in fact, quite the contrary. A large portion of anthropogenic global warming is attributed by the IPCC and IEA to CH₄, but it must be noted that CH₄ emissions from natural sources and from agriculture account for approximately 40% and 25% of annual global CH₄ emissions respectively. Energy accounts for about 20% of documented CH₄ emissions.

CO₂ contributes only approximately 35% of annual airborne anthropogenic GHG emissions after accounting for CH₄ over a 20-year horizon. At a 100-year horizon, the contribution of CO₂ increases to approximately 60%. Energy policies that do not consider all GHG emissions along the entire value chain will lead to undesired economic and environmental distortions. All carbon taxation and CO₂ pricing schemes are incorrect and need to be revised.

At IPCC's GWP₂₀ an approximately 2%¹ higher loss of CH₄ across the value chain prior to combustion of natural gas *versus* coal will lead to 'climate parity' of coal with natural gas. According to public data, natural gas value chains have high CH₄ and undocumented CO₂ losses. On a global average, using only IEA-documented CH₄ data, natural gas emits approximately 15% more CO₂^{eq} than surface-mined coal, over a 20-year horizon. This difference will increase as the use of shale gas and LNG expands.

Investors should support all energy systems in a manner that avoids an energy crisis, including intermittent renewable energy systems where they make sense. If CO₂ emissions need to be reduced, one of the most effective ways would be to install ultra-supercritical power plants with CCUS technology. However, the undisputed benefits of increased CO₂ concentrations in the atmosphere because of its promotion of photosynthesis and plant growth effects (fertilization) need to be considered in energy policy decisions as well. The authors suggest that future research and development should concentrate on reducing net emissions from fossil fuel power plants and providing cost-effective and reliable new conventional power generation capacity, utilizing clean coal and clean natural gas technology.

Keywords

fossil fuels, GHG, greenhouse gases, energy policy, climate change potential, clean coal technology.

Introduction

In 2019, fossil fuels – in order of importance oil, coal, and gas – made up approximately 80% of global primary energy (PE) production totalling approximately 170 000 TWh or 600 EJ. Despite the covid pandemic and significant wind and solar capacity additions, the percentage did not change much in 2021.

¹This coal/gas break-even number increases from approximately 2% to 5.5% loss of methane using IPCC's 100-year Global Warming Potential (GWP) instead of the 20-year GWP. Detailed calculations can be found in footnote⁴

Climate impacts of fossil fuels in today's electricity systems

This proportion has also been largely constant since the 1970s, when energy consumption was less than half what it is today. The same three fossil fuels made up over 60% of global gross electricity production, totalling approximately 27,000 TWh in 2020². It is important to note that global electricity production makes up about 40% of PE, with transportation, heating, and industry accounting for the remaining approximately 60% (see also Figure 1).

Renewables in the form of wind and solar – while not the subject of this paper – accounted for approximately 3% of global PE and 8% of global gross electricity production in 2019, and this was largely unchanged in 2020 and 2021 (refer to Schernikau and Smith, 2021, for more details on solar energy). For comparison, coal and gas combined accounted for approximately 50% of global PE and 60% of global gross electricity production.

The UN projects that global population will rise from the current 8 billion to 10 billion in the next 30 years (Roser, Ritchie, and Ortiz-Ospina, 2013), and may peak around 11-12 billion by the end of the century. Despite continued improvements in energy efficiencies, rising living standards in developing nations are forecast to increase global average annual per capita energy consumption from 21,000 kWh to 25 000 kWh by 2050 (Lomborg, 2020; BP, 2020). As a result, global PE consumption could rise by as much as 40% to 60% by 2050 (a 25% population increase and a 20% PE/capita increase translates to 50% PE demand increase). Energy demand growth is fuelled by developing nations in Asia, Africa, and South America. Developed nations are expected to consume less energy in the decades to come, owing to population stagnation or decrease, and increases in energy efficiency.

However, it should be noted that recent models by McKinsey (McKinsey Energy Insights, 2019, 2021) estimate that global PE demand will only increase by 14% by 2050, while the International Energy Agency's (IEA's) 2021 Net-Zero Pathway (IEA, 2021) models a reduction by approximately 10% by 2030 to reach 'net zero' CO₂ emissions (not CH₄ emissions) by 2050, although this is questioned by the authors. The same reports estimate that global power generation will almost double from 2020 to 2050 (McKinsey Energy Insights, 2019), also driven by the projected electrification of transportation. The Institute for Energy Economics in Japan (IEEJ) predicts global PE demand to increase by 30% by 2050, while the American Energy Information Agency (EIA) predicts a 50% increase (IEEJ, 2019; EOA, 2019, 2021) in line with the authors' analysis.

It is prudent to assume that wind and solar alone will not be able to generate enough energy to match the expected demand

²40% of 170 000 is not 27 000; the difference comes from energy lost during electricity production. Only a fraction of energy put into a system is usable after conversion, the remainder is lost as heat. Authors' Research and Analysis based on the following sources:

IEA. 2019. Installed power generation capacity in the Stated Policies Scenario, 2000-2040. <https://www.iea.org/data-and-statistics/charts/installed-power-generation-capacity-in-the-stated-policies-scenario-2000-2040> [accessed 25 October 2021].

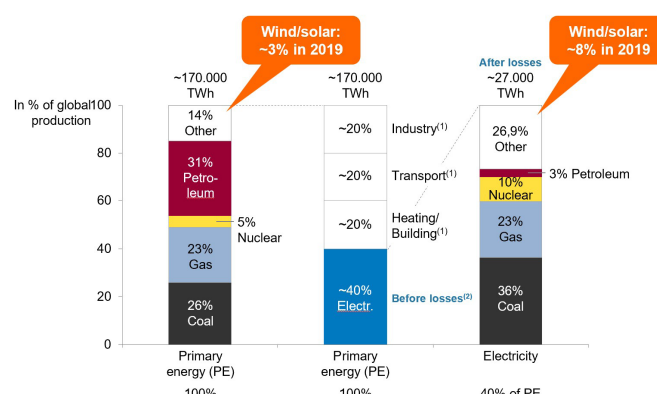
IEA. 2021b. Key World Energy Statistics 2021. <https://iea.blob.core.windows.net/assets/52f66a88-0b63-4ad2-94a5-29d36e864b82/KeyWorldEnergyStatistics2021.pdf> [accessed 25 October 2021].

BP. 2021. Statistical Review of World Energy. 70th edition. <https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf> [accessed 25 October 2021].

BP. 2020. Statistical Review of World Energy. 69th edition. <https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf> [accessed 25 October 2021].

REN21. 2021. Renewables 2021 Global Status Report (GSR). <https://www.ren21.net/reports/global-status-report/> [accessed 25 October 2021].

Smil, V. 2017. Energy Transitions: Global and National Perspectives. Praeger, Santa Barbara, CA.



Notes: (1) Only the portion of industry/transport/building that is not included under electricity (2) Assumed worldwide net efficiency of about 33% for nuclear, 37% for coal, 42% for gas, assume average. ~40% efficiency => 27 000 TWh becomes 68 000 TWh or 40% of 170 000 TWh

Sources: Schernikau, analysis based on IEA Energy Technology Perspectives 2020

Figure 1—Overview of global primary energy and electricity

increase to 2050. This is confirmed by the IEEJ's October 2020 report (IEEJ, 2019; EIA, 2019, 2021) forecasting an absolute increase in fossil fuels' share in PE in its reference case by 2050. In July 2021, the IEA (2021) confirmed that '...[renewables] are expected to be able to serve only around half of the projected growth in global [electricity] demand in 2021 and 2022'. Over 60% of global electricity growth during 2021 was fuelled by coal and natural gas (NG), and only 30% from renewables. For PE growth, the renewable share will be only a fraction, about 20%, as about 2/5th of PE is for electricity. Schernikau, Smith, and Falcon (2022) provide more details on the global energy landscape, including a discussion on the pros and cons of using PE with increased penetration of renewable energy.

Even if wind and solar were to fulfill all future increases in PE demand, it becomes clear that for the next 30 years and beyond we will continue to depend on conventional energy resources for a large portion, if not the vast majority, of our global energy needs. Therefore, given the relevance of coal and natural gas to the future energy scene, this paper examines the global warming impact of such fossil fuels.

Which fossil fuel is 'best for the climate'?

Coal and natural gas are the main fuels for electricity generation, while oil is the main fuel for transportation. Nuclear's share reaches about 10-11% for electricity and 5-6% for PE (see Figures 1 and 2). Nuclear energy is not discussed further in this paper despite its many benefits and challenges. Given the importance of coal and NG, especially for electricity but also for energy as a whole (approx. 60% of electricity and 50% of PE), the authors review the impact of both coal and NG on global warming, relying on reported data by the IPCC, the IEA, and Our World in Data.

Introducing greenhouse gases and global warming potential

It is undisputed that (1) the average global temperature has increased since the 1800s – the end of the Little Ice Age, and that (2) humans have contributed to global warming in the past and will continue to do so. It is also undisputed that (3) CO₂ is a greenhouse gas (GHG) and that increasing airborne CO₂ levels contribute to global temperature change, in concert with other climate forcings.

Climate impacts of fossil fuels in today's electricity systems

In addition, it is undisputed – though less well known – that the global warming impact of CO₂ or any GHG declines logarithmically, thus each additional ton of CO₂ airborne has less capacity to increase temperatures (Wijngaarden and Happer, 2020). CO₂ is active in the wavelength band from about 12–18 µm, which has been essentially saturated. This works in such a way that additional CO₂ molecules can only slightly widen the wavelength band in which the molecule can impact outgoing thermal radiation. In the absence of GHGs, the Earth's surface temperature would be on average about -18°C; but with GHGs the surface reaches a temperate and livable 15°C. The 33K difference is ascribed to the so-called 'greenhouse effect' of the atmosphere (World Meteorological Organization, 2021).

The IPCC in its 5th Assessment Report AR5 gives the global warming potential (GWP) of several of GHGs over both a 20- and a 100-year horizon. These GWPs are little changed in AR6, published in August 2021. The IPCC (2014a) defines GWP as 'An index measuring the radiative forcing following an emission of a unit mass of a given substance, accumulated over a chosen time horizon, relative to that of the reference substance, carbon dioxide (CO₂)'. There remains scientific uncertainty and debate about the global warming potential, but for the sake of this paper the authors choose to use the official reported IPCC data³ (Cain, 2018; Derwent, 2020; ClimateAnalytics, 2017; Kleinberg, 2020; Lynch *et al.*, 2020). For instance, the IPCC notes the large uncertainties in the GWP of CH₄ – between about 32% and 40% (see IPCC, 2021, Table 7.SM8).

The definition of GWP is given in many sources, but explained well by Kleinberg (2020). Equation [1] shows that the GWP of a particular molecule *j* is the ratio to CO₂, denoted by *i* in the equation, integrated over time following an initial pulse of gas at *t* = 0. This metric implies that a gas which decays quickly will have a greater initial GWP than a gas which decays more slowly. Kleinberg's academic paper places the GWP in the correct physics perspective while pointing out its shortcomings.

$$GWP_j(T) = \frac{\int_0^T A_j f_j(t) dt}{\int_0^T A_i f_i(t) dt} \quad [1]$$

Considering the *urgency* of addressing global warming as well as the declared *climate crisis* by the UN, governments, and institutions, the authors use the IPCC's 20-year GWP₂₀ metric for CH₄ of 84× and illustrate the implication on energy policy if one were to accept the IPCC's GWP. For comparison, IPCC's 100-year GWP₁₀₀ metric for CH₄ is 28×. The reader can adjust from GWP₂₀ to GWP₁₀₀ by dividing or multiplying any relevant CH₄ number by 3 = 84 / 28. The GWP index is not radiative forcing but is a 'metric' intended to indicate how much 'worse' or 'better' a greenhouse gas is compared to CO₂ (GWP of 1) and its impact on global warming (IPCC, 2014). The following six main GHGs and their respective GWPs are mentioned by the IPCC (2014b, 2014c):

- Water vapour (H₂O): The most important and most abundant GHG, but not further detailed by the IPCC. The

authors are concerned that the greenhouse effect of water is not included in the IPCC analysis, apparently due to its complicated variability and energy transport effects.

- Carbon dioxide (CO₂): GWP₂₀ = 1, GWP₁₀₀ = 1, no lifetime defined by IPCC
- Methane (CH₄): GWP₂₀ = 84, GWP₁₀₀ = 28, lifetime 12,4 years
- Nitrous oxide (N₂O): GWP₂₀ = 264, GWP₁₀₀ = 264, lifetime 121 years
- Perfluoromethane (CF₄): GWP₂₀ = 4880 years, GWP₁₀₀ = 6630 years, lifetime 50 000 years
- Hydrofluorocarbon (HFC-152a): GWP₂₀ = 506, GWP₁₀₀ = 138, lifetime 1,5 years

The misconception of reported global CO₂ emissions and error in carbon taxing

A recent survey identified over 1,200 different climate laws and policies (Grant *et al.*, 2020). The vast majority of reports on global CO₂ emissions as well as most proposed climate policies, laws, and regulations, and global carbon-tax discussions centre on measured-human-energy CO₂ emissions. This is despite recent efforts by the IEA and other institutions to understand other GHGs better, primarily the shorter-lived GHG CH₄. The National Oceanic and Atmospheric Administration (Tans, 2021; Dlugokencky, 2021) notes that atmospheric concentrations of CH₄ increased from about 1630 ppb (parts per billion mole-fraction CH₄) in 1984 to 1880 ppb in 2021, an increase of 15% or 0,4% per annum. During the same time, the atmospheric concentration of CO₂ increased from approximately 345 ppm to 415 ppm, a 20% or 0,5% annual increase (Tans, 2021; Dlugokencky, 2021).

The IEA found that in June 2021, 73% of the world's countries had announced net-zero pledges for CO₂, but only 28% had policies to reduce CH₄, with no zero-CH₄ pledge. Governmental discussions on the 'social cost of carbon' (SCC) or any CO₂ tax have led to significantly distorted policies as they entirely ignore natural CO₂ uptake and other GHG emissions. GHG emission measurements should at least include CO₂^{eq} emissions from all sources, including but not limited to CH₄ emissions from livestock agriculture, energy production, or natural causes (see Table I). GHG emissions from changes in land use, nitrous oxides (N₂O), or fluorinated gases (F-gases), which together may add another 5–10% of total anthropogenic GHGs (Olivier and Peters, 2020), are not discussed in this paper.

The omission to include at least CH₄ emissions may be driven primarily by the simplicity of measuring or easily calculating human-energy CO₂ emissions. The chemistry and physics are simple for CO₂, assuming a certain efficiency of a given power plant as well as measuring the tons of fossil fuel combusted. From this data, one can relatively easily estimate CO₂ emissions from such a plant. For instance, 1 t of carbon equals 3,67 t of CO₂, purely based on the molecular mass. Thus, the complete combustion of coal with a 50% carbon content (as-received basis) will simply result in 50% of 3,67 t, or 1,8 t, of CO₂ per ton of coal burnt. These CO₂ emissions are detailed by country, by application, by fuel source, by income, even by activity type, and in many other ways in quite an elaborate process at a global scale. For example, recently, credit cards have become available that can manage and limit your spending based on the 'CO₂ footprint' of your purchases⁴.

One misguided result of limiting efforts on measured-human-energy CO₂ emissions is the widely accepted government policy of switching from coal to NG (in most cases to LNG) to slow or

³The authors stipulate the IPCC GWP numbers for the purpose of our energy illustrations based on data used by governments and institutions. The authors' detailed objection to GWP, as well as the scientific debate and uncertainty on GWP, cannot be detailed here due to space constraints (refer also to Cain, 2018; Derwent, 2020; ClimateAnalytics, 2017; Kleinberg, 2020; Lynch *et al.*, 2020). For instance, Wijngaarden and Happer (2020) have analysed GHG forcing in detail and conclude significantly lower climate sensitivities than those used by the IPCC.

Climate impacts of fossil fuels in today's electricity systems

limit global warming. Consequently, many international banks, institutions, and conglomerates, *e.g.*, the Tesla gas-fired power plant in its new Berlin Gigafactory (Randall, 2020) or the EU's plan to label natural gas as green (Abnett and Jessop, 2022), are withdrawing from coal but are actively supporting NG as a 'bridge fuel'. Another recent example, the world's leading coal-to-liquids company Sasol in South Africa was applauded for its announcement in August 2021 to develop NG. Global LNG export terminal capacity is also expected to more than double from 440 Mt in 2020 to over 1,000 Mt in 2030.

Most scientific studies, government reports, or any carbon tax for that matter, consider solely CO₂ emissions from combustion when recommending NG or LNG as a bridge fuel towards a net-zero future (see Figure 4). This is indisputably wrong and leads to distorted policies, as will be explained in the following pages. A wider selection of additional studies, reports, and press releases on CH₄ emissions is given in the Appendix.

Reported CO₂ and CH₄ emissions

For the purpose of this paper, the authors rely on reported CO₂ and CH₄ emissions from the IEA and Our World in Data, which in turn rely on the Global Carbon Project, the Carbon Dioxide Information Analysis Centre (CDIAC), and Saunio *et al.* (2020). The IEA notes, however, that estimates of CH₄ emissions are subject to a high degree of uncertainty. Top-down estimates used by the IEA are lower than bottom-up estimates, and estimates have been increasing steadily. The IEA's reported CH₄ emissions data is summarized in Table I.

In addition, the authors rely on the IPCC's confirmation that about half of the CO₂ emitted to the atmosphere disappears annually into global ecological and physical sinks, *i.e.*, taken up by plants through photosynthesis, fertilization, and by oceans. In fact, IPCC AR6 (IPCC, 2021) states with high confidence that 54% of CO₂ is removed and 46% remains airborne in the atmosphere. During the period 2010–2019, 31% of the emitted CO₂ was taken up by ecosystems (*e.g.*, plants) and 23% by the oceans.

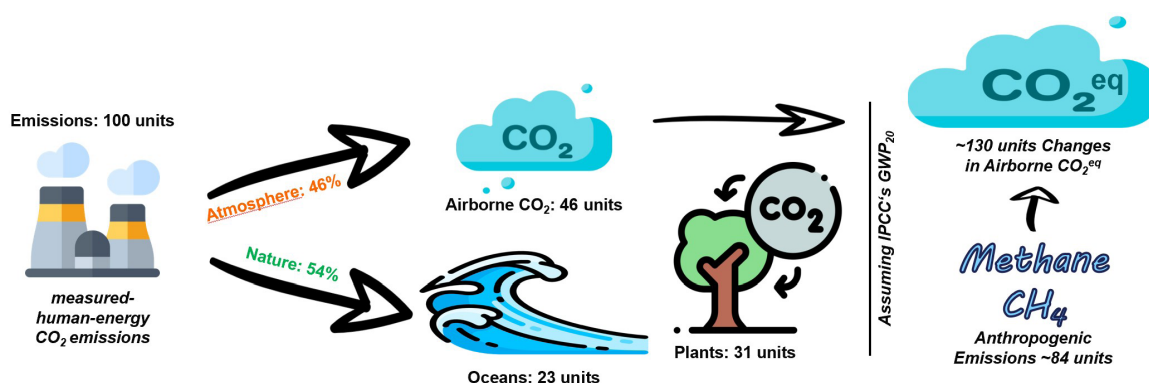
Several other studies (*e.g.* Knorr, 2009) also confirm that less than half of CO₂ emissions remain airborne. Logically, only

airborne CO₂ can contribute to the greenhouse effect. This 'natural CO₂ uptake' is highly relevant when comparing CO₂ to other GHG emissions that do not contribute to plant growth.

Thus, governments and institutions should switch from 'measured-human-energy CO₂ emissions' toward the more correct metric that the authors call 'changes in airborne CO₂^{eq}'. Figure 2 and the following section illustrate this process.

Documented CO₂ and CH₄ emissions are detailed in Table I and Figure 3. Because IPCC's 20-year global warming potential (GWP₂₀) for CH₄ is 84 times higher than that for CO₂, the calculations are straightforward and as follows (Ritchie and Roser, 2020a, 2020b):

- Global measured-human-energy CO₂ emissions totalled 36 Gt in 2019 (95% from fossil fuels), of which 40% or 14 Gt stem from coal, 34% from oil, and 21% from NG. Approximately 54% of all CO₂ emissions disappear annually, reducing 36 Gt of emission in 2019 to about 17 Gt of airborne CO₂ increase that year (6,6 Gt from coal).
- Documented anthropogenic CH₄ emissions total approximately 360 Mt at GWP₂₀, resulting in 30 Gt CO₂^{eq} – 12 Gt from agriculture, 3,4 Gt from NG, 3,5 Gt from underground coal mining, 3 Gt from oil, and 8 Gt from other sources. An additional 230 Mt of CH₄ result in 19,5 Gt CO₂^{eq} from natural sources.
- As a result, global changes in airborne CO₂^{eq} from anthropogenic sources of CO₂ and CH₄ at GWP₂₀ are approximately 47 Gt (17 Gt from CO₂ and 30 Gt from CH₄). Fossil fuels accounted for approximately 60% of total anthropogenic CO₂^{eq}. Coal itself contributed just over 20%, oil just below 20% and NG 15%. For comparison, at GWP₁₀₀ fossil fuels accounted for approximately 75% of total anthropogenic CO₂^{eq}.
- Total measured-human-energy airborne CO₂ accounted for approximately 35% of the total changes in airborne anthropogenic CO₂^{eq} from both CH₄ and CO₂ at GWP₂₀. When considering CH₄'s 100-year global warming potential GWP₁₀₀ this increases to 65%.



IPCC AR6 Page 89: "During the last decade (2010–2019), average annual anthropogenic CO₂ emissions reached the highest levels in human history at 10.9 ± 0.9 PgC yr⁻¹ (high confidence). Of these emissions, 46% accumulated in the atmosphere (5.1 ± 0.02 PgC yr⁻¹), 23% (2.5 ± 0.6 PgC yr⁻¹) was taken up by the ocean and 31% (3.4 ± 0.9 PgC yr⁻¹) was removed by terrestrial ecosystems (high confidence)."

About half of CO₂ emissions become airborne and can contribute to green-house effect

Source: Schernikau, based on IPCC (2021), AR6 – Physical Science Basis, p. 89, and IEA methane tracker (IEA, 2021)

Figure 2—Less than half of CO₂ emissions remain airborne – Illustrative comparison to anthropogenic CH₄ at GWP₂₀

Climate impacts of fossil fuels in today's electricity systems

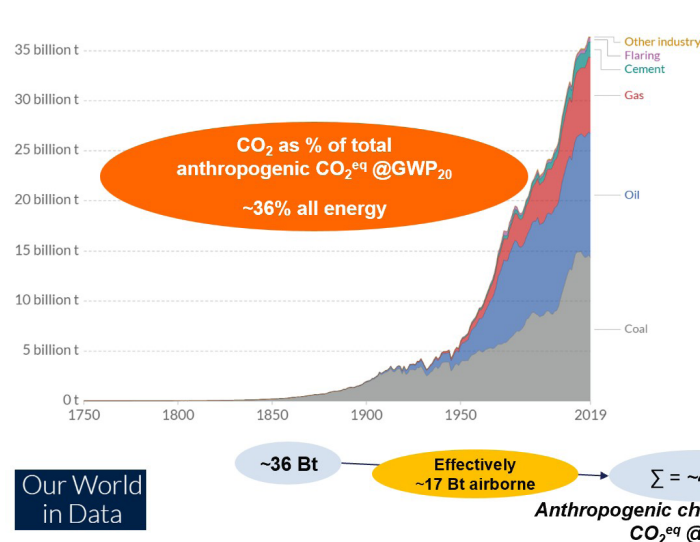
Table I

Summary of global CO₂, CH₄, and CO₂^{eq} emissions at GWP₂₀ and GWP₁₀₀

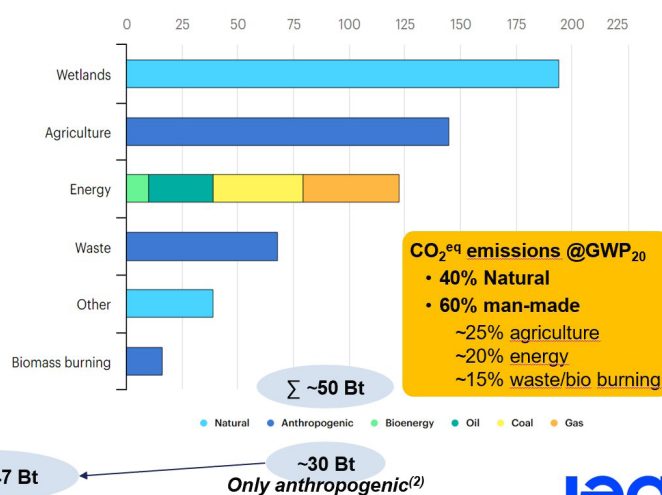
	46%			84		28				Total CO ₂ ^{eq}	
	CO ₂ emissions (Mio t)	airborne CO ₂ (Mio t)	CH ₄ (Mio t)	converting CH ₄ to CO ₂ ^{eq} @GWP ₂₀	converting CH ₄ to CO ₂ ^{eq} @GWP ₁₀₀					@GWP ₂₀	@GWP ₁₀₀
Coal	14.360 39,9%	6.606 39,9%	42,0 7,1%	3.528	1.176					10.134 15,3%	7.782 23,5%
Gas	7.620 21,2%	3.505 21,2%	41,0 6,9%	3.444	1.148					6.949 10,5%	4.653 14,1%
Oil	12.360 34,3%	5.686 34,3%	36,0 6,1%	3.024	1.008					8.710 13,2%	6.694 20,2%
BioEnergy			10,0 1,7%	840	280					840 1,3%	280 0,8%
Total Energy	34.340,0 95,4%	15.796,4 95,4%	129,0 21,8%	10.836,0	3.612,0					26.632,4 40,2%	19.408,4 58,6%
		24% of global CO ₂ ^{eq} @GWP ₂₀									
		48% of global CO ₂ ^{eq} @GWP ₁₀₀									
Agriculture			145,0 24,5%	12.180	4.060					12.180 18,4%	4.060 12,3%
Nature			233,0 39,4%	19.572	6.524					19.572 29,6%	6.524 19,7%
Waste/Biomass burning			84,0 14,2%	7.056	2.352					7.056 10,7%	2.352 7,1%
Overall Total	36.000 100,0%	16.560 100,0%	591 100,0%	49.644	16.548					66.204 100,0%	33.108 100,0%
	Primary Energy TWh	Mio t CO ₂ airborne per TWh PE	Tons CH ₄ per TWh PE	Mio t CO ₂ ^{eq} per TWh from CH ₄ @GWP ₂₀	Mio t CO ₂ ^{eq} per TWh from CH ₄ @GWP ₁₀₀					Total CO ₂ ^{eq} per TWh @GWP ₂₀	Total CO ₂ ^{eq} per TWh @GWP ₁₀₀
Coal	43.850 25,8%	0,151	958	0,080	0,027					0,231	0,177
Gas	39.290 23,1%	0,089	1,044	0,088	0,029					0,177	0,118
Global (estimate)	170.000 100,0%	0,093	759	0,064	0,021					0,157	0,114
avg coal vs avg gas	1,12 x	1,69 x	0,92 x							1,31 x	1,50 x
avg surface mined coal vs avg gas										0,85 x	1,27 x
avg gas vs avg surface mined coal										1,17 x	0,79 x
inverse		0,59 x	1,09 x							0,77 x	0,67 x

Note: all numbers were updated in December 2021 based on the latest IEA-reported CH₄ data. Previous data was based on end of 2020 IEA figures. The IEA adjustments slightly favoured gas over coal. All figures are based on 2019 except for IEA CH₄ figures, which are best estimates per annum.
Source: IPCC, IEA, author's calculations

Annual measured-human-Energy-CO₂ Emissions (in Bt)
Σ CO₂ ≈ 36 Bt



Annual CH₄ Emissions (in Mt)
Σ CH₄ ≈ 590 Mt → ~50 Bt CO₂^{eq} @GWP₂₀^(1, 2)



Notes: (1) @ GWP₂₀ means 20-year GWP defined by the IPCC; (2) anthropogenic 30 Gt at GWP₂₀ become 10 Gt at GWP₁₀₀.

Source: Schernikau, 2021 based on (left) Our World in Data based on Global Carbon Project: CO₂ emissions by fuel (<https://ourworldindata.org/emissions-by-fuel>) and CO₂ emissions ([https://ourworldindata.org/CO₂-emissions?country=](https://ourworldindata.org/CO2-emissions?country=https://ourworldindata.org/CO2-emissions?country=)); (right) IEA methane tracker database analysis (<https://www.iea.org/articles/methane-tracker-database>)

Figure 3—2019 Global changes in anthropogenic airborne CO₂^{eq}

Air pollution from coal versus gas

Coal production, transportation, and combustion adversely affect the environment in many ways, including but not limited to particulate emissions and air pollutant emissions. However, air pollution from combustion of coal is reduced to a bare minimum

in modern coal-fired power plants utilizing clean coal technology where the newest filter and waste product management systems are employed. For example, the United Arab Emirates commissioned one of the world's most advanced and newest 2,4 GW ultra-supercritical (USC) coal-fired power plants in 2021

Climate impacts of fossil fuels in today's electricity systems

(Power Technology Energy News and Market Analysis, 2021). Such modern coal-fired power plants emit virtually only water vapour and CO₂. Much investment and effort are needed to upgrade all global power plants with the newest technologies to increase their efficiency and further reduce particulate matter, SO_x, and NO_x emissions.

The 10–15% concentrated CO₂ stream from coal plants could, in principle and if required, be captured and utilized, or stored (Tramošljika *et al.*, 2021). Carbon capture utilization and storage (CCUS) at fossil power plants would be more effective than any direct air capture (DAC) from the 0.04% CO₂ content of the atmosphere or reducing CO₂ through other means. Qvist *et al.* (2020) present a case study for Poland.

Coal mine methane (CMM) leakages are associated primarily with underground coal mining. This is the CH₄ which is released during exploitation of coal seams and is vented to the atmosphere. Coalbed methane (CBM) can be extracted for commercial utilization from unmined coal seams. This extraction is usually done either by drilling vertically into the seam (SIS methane drainage) or drilling directionally along the seam (UIS methane drainage) (Zheng *et al.*, 2019). CBM projects that utilize the CH₄ are supported under the Kyoto Protocol and investors can claim CO₂ credits, either using them to offset their own emissions or by selling them on the open market.

Underground coal mines, once production is halted and the mine is abandoned, may continue to leak CH₄. This leakage is referred to as abandoned mine methane (AMM) (Kholod *et al.*, 2020). CH₄ migrates into the abandoned mine from connected coal deposits. If not prevented by an adequate sealing, the liberated gas will migrate to the surface and escape to the atmosphere through natural and mining-related fractures and other conduits. On average, the CH₄ content per ton of coal mined increases with increasing depth.

It is important to note that surface coal mines rarely emit CH₄. Even if the coal seams had collected, emitted, or stored CH₄ during burial, when the pressure is reduced or at shallower depths, the gas escapes. As a result, CH₄ from coal seams closer to the surface was vented over the past millions of years. Hence, irrespective of coal quality, coal seams closer to surface and mined by opencast methods will not normally emit CH₄ (Lloyd and Cook, 2005; Cook, 2013).

Much effort and investment are required to further reduce the negative environmental impact of coal production, processing, transportation, and combustion; although the technology mostly exists today. Generally, the combustion of coal causes more air pollution than NG, due to the emission of particulate matter, SO_x, and NO_x. Coal ash may be useful for certain industrial processes such as cement manufacturing, but is often of significant environmental liability. Also, the production and transportation of coal usually effects the environment more than NG does (other than CH₄). Any unutilized leaked or 'fugitive' CH₄ from coal mining can be considered a component of air pollution and contributes to the GWP of CH₄.

Pollution from natural gas other than CH₄ also includes SO_x and NO_x. Unconventional gas production generally affects the environment more than conventional gas, *e.g.*, from chemicals used during fracking and/or drilling. Furthermore, it is understood that CH₄ does not only have climate impacts but also affects air quality because it is an ingredient in the formation of ground-level ozone, a dangerous air pollutant that can cause respiratory and cardiovascular diseases. Other toxic gases and hazardous air pollutants are also emitted along with CH₄; these can lead

to long-term health effects or even death (CATF, 2021). CO₂, on the other hand, does not affect human health unless average ambient concentrations continuously reach levels 10 to 100 times higher than current atmospheric concentrations of about 420 ppm, at which may then cause drowsiness, tiredness, and headaches. Humans exhale about 40 000 ppm (4%) of CO₂. CO₂ concentrations in buildings vary from 400 to 2 000 ppm (author's own measurements).

Comparison of coal and natural gas GHG emissions

Surface-mined coal versus natural gas

With the introduction of a new metric, anthropogenic 'changes in airborne CO₂^{eq}' using IPCC's GWP metric and IEA data, it is necessary to summarize and re-assess discussions on energy policy. Both coal and NG have benefits and issues. When choosing coal *versus* NG, all economic and environmental benefits and problems should be compared appropriately based on available data. NG is an important and favourable energy resource and is much needed for a stable and affordable energy system, as are coal, nuclear, hydro, and other resources.

Applying changes in airborne CO₂^{eq}, the authors calculated the following GHG impacts, with and without CH₄ emissions, using the IPCC's GWP₂₀ and IEA primary energy data (see Tables I and II):

- Pure combustion with zero energy-related fugitive CH₄ emissions: 0.09 Mt CO₂ per TWh for NG *versus* 0.15 Mt CO₂ per TWh for coal. NG emits about 40% less CO₂ than coal. This is the typical global ratio.
- With fugitive energy-related CH₄ emissions: 0.18 Mt CO₂^{eq} per TWh for NG *versus* 0.23 Mt CO₂^{eq} per TWh for coal. NG emits about 20% less CO₂^{eq} than coal. This is the actual global ratio based on known data.
- NG *versus* surface-mined coal: 0.18 Mt CO₂^{eq} per TWh for NG *versus* 0.15 Mt CO₂^{eq} per TWh for surface-mined coal. NG emits about 15% more CO₂^{eq} than surface-mined coal.

Based on the calculations above and the fact that surface coal mines rarely emit CH₄, it can be demonstrated that at GWP₂₀, on a global average, surface-mined coal emits about 15% less CO₂^{eq} than NG. This figure increases as the use of shale gas and LNG expands. For completeness, at a 100-year horizon, at GWP₁₀₀ surface-mined coal still emits about 25% more CO₂^{eq} than average NG when comparing primary energy supply. However, for LNG the situation does not look as favourable even at GWP₁₀₀ where coal is on par with NG at approximately 5% additional CH₄ loss prior to LNG combustion (see Table I and calculations in Ritchie and Roser, 2020a). It must be noted that if one were to use electricity production, rather than primary energy, as the basis for comparison, the ratios further improve in favour of coal since gas causes higher CH₄ emissions for less electricity produced. However, it is difficult to detail the non-electricity energy contributions of gas and coal, and therefore the authors chose to use PE only, which is also more conservative and relevant to this analysis.

In addition to CH₄, CO₂ is also emitted during NG (and especially LNG) production and processing. These CO₂ emissions are currently not considered in the life-cycle analysis of the gas chain; neither are they included in the reported global CO₂ emission data nor in the analysis herein. The Institute for Energy Economics and Financial Analysis (IEEFA, 2020) presented a detailed analysis of the Australian LNG industry and associated CO₂ emissions with the subtitle 'Increased Emissions

Climate impacts of fossil fuels in today's electricity systems

Table II

Comparison of coal and NG global measured CO₂^{eq} emissions

	Global CO ₂ from combustion only	CO ₂ ^{eq} @GWP ₂₀ from measured methane emissions only	Global total CO ₂ ^{eq} emissions @ GWP ₂₀
Coal	14.360 Mt CO ₂ less 54% = 7.600 Mt CO ₂ airborne ▪ 43.850 TWh PES ▪ Ratio = 0,15 Mt CO₂/TWh	3.530 Mt CO ₂ ^{eq} <small>primarily from underground mining</small> ▪ 43.850 TWh PES ▪ Ratio = 0,08 Mt/TWh	10.000 Mt CO ₂ ^{eq} airborne ▪ 43.850 TWh PES ▪ Ratio = 0,23 Mt/TWh
Natural Gas	7.620 Mt CO ₂ less 45% 3.500 Mt CO ₂ airborne ▪ 39.290 TWh PES ▪ Ratio 0,09 Mt/TWh	3.440 Mt CO ₂ ^{eq} ▪ 39.290 TWh PES ▪ Ratio 0,09 Mt/TWh	7.130 Mt CO ₂ ^{eq} airborne ▪ 39.290 TWh PES ▪ Ratio 0,18 CO₂^{eq} Mt/TWh
Global Sum (inc. natural, oil, agriculture, other)	16,5 Bt CO ₂ airborne (total emissions 36 Bt CO ₂) ▪ Coal share = 40 % ▪ Gas share = 21 %	49,5 Bt CO ₂ ^{eq} (590 Mt CH ₄) ▪ Coal share = 7,1 % ▪ Gas share = 6,9 %	66 Bt CO ₂ ^{eq} airborne ▪ Coal share = 15 % ▪ Gas share = 11 %

Surface-mined coal
~15% "better for climate"
than average natural gas

Gas better
Coal/Gas = 1,7x
Coal better
Coal/Gas = 0,9x
Gas better
Coal/Gas = 1,3x

Coal has lower CH₄ emissions @GWP₂₀: Gas/Coal "climate" breakeven if ~2% or more CH₄ is lost along the value chain

Note: PES = Primary Energy Supply
 Source: Schernikau Illustration and calculations based on IEA, Our World in Data, IPCC (Ritchie and Roser, 2020a, 2020b)

[from LNG] Have Offset Any Gains From Renewables' Rise in Electricity Generation'. The IEFFA reports that new Australian LNG projects emit on average 0,7 t CO₂ per ton LNG during production only. For example, according to the report, the Darwin LNG Barossa field may even emit 2,4 to 3,6 t CO₂ per ton LNG, thus 'the total project could become a CO₂ venting factory with an LNG by-product'. Another documented example is the CO₂ emissions of the Western Australian Gorgon LNG project. The Conservation Council of Western Australia (2019) documented in 2019 that Western Australian LNG operations emit on average approximately 0,6t CO₂ per ton LNG produced. The CO₂ streams stem from the raw feed gas extracted from the oceans that is vented to the atmosphere. This stream of CO₂ was planned to be captured but this was not fully implemented by 2021 (Milne, 2019; Morton, 2021) (see also Figure 4).

We reiterate, the analysed CO₂^{eq} figures in this paper do not consider any CO₂ emissions associated with LNG production, processing, or transportation and thus underestimate the total CO₂^{eq} emissions of natural gas.

Total global natural gas versus coal

It is important to keep in mind that fugitive CH₄ must include all CH₄ sources and not only those from energy. Sources of CH₄ must include agriculture, wetlands, waste disposal, thawing permafrost, and others as documented by the IEA (see Figure 3). Natural CH₄ emissions amount to about 40%, and agriculture to about 25%, of total annual fugitive CH₄ (see Table I). The GWP then dictates the global warming potential of CH₄ from all sources other than from energy. These non-energy CH₄ emissions dominate CO₂^{eq} emissions from all coal. The competition is not even a close race, and little can be done to alter this ratio since wetlands and agricultural sources are inviolate in the global ecology and in the sustenance of human populations. Ocko *et al.* (2021) conclude that CH₄ accounts for 'at least a quarter of today's gross warming' and also detail estimates of natural CH₄ sinks. The IEA (2021) stated

in 2021 that 'Methane has contributed around 30% of the global rise in temperature today'.

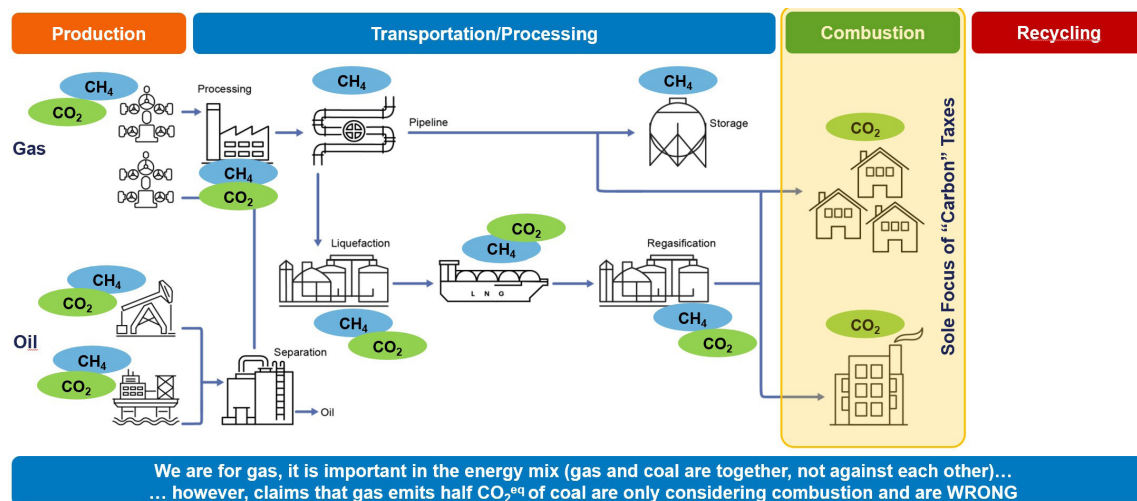
In addition, using the GWP₂₀ metric it can now be demonstrated that marginally, NG emits more CO₂^{eq} than the average coal as soon as more than about 2%⁴ of CH₄ is lost prior to gas combustion compared to coal along the value chain of production, processing, and transportation of pipeline natural gas (PNG) or LNG. For comparison, using GWP₁₀₀ coal reaches climate parity with NG at about 5% additional CH₄ loss prior combustion⁴. This figure is principally confirmed by Ladage *et al.* (2021), who estimate a break-even CH₄ leakage rate of 2,7% for the USA and 4,1% for Germany. However, Ladage *et al.* do not consider the natural CO₂ uptake as confirmed by the IPCC, and thus overestimate the break-even CH₄ leakage rate by about 50%. The exact relationship of natural gas or LNG to coal depends on the origin of the gas, the distance and efficiency of the gas logistics, as well as the technology used for refining, liquefaction, transportation, and regasification (Figure 4 and Appendix). It is relatively certain and the authors' understanding, though unproven due to lack of data, that the global LNG supply chain on average results in CH₄ leakages greater than 5% (see Appendix).

Costs and benefits of carbon dioxide and methane

The value chain for production, transport, and use of oil, PNG, and LNG is illustrated in Figure 4. Current CO₂ taxation and related policies primarily target the combustion stage (right side)

⁴The numbers vary and are assumed as follows: 375 g CO₂/kWh at partial load combined cycle PNG (48% efficiency), 825 g CO₂/kWh partial load coal (41% efficiency); Δ450 g CO₂/kWh becomes 207 g after 54% natural CO₂ uptake; 26,400 kJ/kg CH₄ and 1,47 m³/kg CH₄ translate to 200,5 m³/MWh; 1% methane loss translates to 2 m³/MWh or 1,4g CH₄ per kWh or 115 g CO₂^{eq}/kWh @GWP₂₀; therefore at 1,8% methane leakage coal and gas are on par; @GWP₁₀₀, coal and gas are on par at 5,4% methane leakage.

Climate impacts of fossil fuels in today's electricity systems



Source: Schernikau (2021), own Illustration

Figure 4—Illustration of GHG emissions from production, transportation/processing and combustions of gas

only. Based on annual global CH₄ emissions of approximately 590 Mt and total anthropogenic emissions of about 360 Mt, anthropogenic CO₂^{eq} emissions from CH₄ are about four times higher than CO₂ emissions from coal alone, at GWP₂₀ (see Table I). LNG and shale gas production, processing, and/or transportation increase fugitive CH₄ emissions per unit of energy produced and make the situation even less favourable for gas.

This conclusion is a surprise and one that was not anticipated by the authors. When we factored in the GWP₂₀ value from the IPCC AR5 and AR6 reports, the GWP for CH₄ – from all sources – dominates the equation. CH₄, until combusted, is a far more potent greenhouse gas (for calculations see footnote⁴ on page 139) than CO₂, and it lacks the beneficial role of CO₂ in photosynthesis which compensates at least part of other possible effects of CO₂ on the climate.

As discussed earlier, both CO₂ and CH₄ are GHGs that contribute to global warming. For this reason, both the costs and the benefits of CO₂ and CH₄ should be considered in any cost and benefit analysis of each hydrocarbon (coal, natural gas, and oil) compared to renewable sources of power. Readers are invited to consider the general practice in Western Europe to couple intermittent wind or solar with natural gas (see new gas fired-power plants in Germany or the EU's plan to put gas on the 'green' list (Abnett and Jessop, 2022; Independent, 2021).

Disregarding any benefits from CO₂, Nobel Prize winner Professor William Nordhaus (2018) calculated a GDP cost of 2,8% in 2100 from global warming, assuming his optimal scenario with 4,1°C warming. For comparison, the UN announced (UNFCCC, 2021) that their current climate trajectory is in line with about 2,7°C warming from pre-industrial times (1850-1900) until the end of century, of which 1,1°C to 1,2°C has already occurred.

Based on his work, Nordhaus earned the Nobel Prize for 'Climate Economics' in 2018. He estimates the GDP cost of global warming under different scenarios using his DICE model (the merits of using the GDP metric will not be elaborated in this paper). Suffice to say that Nordhaus makes the following important statements confirming that reduced use of fossil fuels will lead to reduced growth and therefore wealth:

- '... the revised DICE model shows more rapid growth of output in the baseline or "no-[climate]-policy" path compared to earlier DICE versions and most other models.'

- '... the international target for climate change with a limit of 2°C appears to be infeasible with reasonably accessible technologies even with very ambitious abatement strategies. This is so because of the inertia of the climate system, of rapid projected economic growth in the near term, and of revisions in several elements of the model.'
- 'A target of 2,5°C is technically feasible but would require extreme and virtually universal global policy measures in the near future.'

Professor Nordhaus' optimal DICE scenario corresponds to a peak in CO₂ emissions (not airborne CO₂^{eq}) around 2050 at approximately 40 Gt and a global warming of 4,1°C using the implausible IPCC RCP8,5 climate scenario. For comparison, it is predicted that covid-19 will cause up to a 10% drop in GDP by 2050; in line with the 10% drop in GDP after 3 years during the Great Depression (IEEJ, 2020). Lomborg (2020) and Kahn *et al.* (2021) principally confirm Nordhaus' calculations.

The potential effects of climate changes may be considerable and should not be discounted. However, the benefits of increased CO₂ concentrations in the atmosphere because of their undisputed fertilization effects on plants are confirmed by numerous peer-reviewed studies, a selection of which is listed by Idso (2021). In addition to adjusting for CO₂ fertilization, the modelled economic impact of global warming – to be fair and complete – should be compared to the costs and impacts of prematurely forcing energy systems away from conventional fuels prior to having a truly sustainable energy solution.

Carbon, oxygen, hydrogen, and nitrogen are the four most important elements for life. CO₂ is a key building block for all life on Earth as all plant life depends on CO₂, water, and solar radiation for photosynthesis. In fact, atmospheric CO₂ is the sole source of carbon contained in plants, and therefore in human and animal bodies.

The CO₂ concentration in the atmosphere increased by a little more than 0,01% or 100 ppm (by over 30%) in the past 100 years, apparently due mainly to combustion of carbon-rich oil, coal, and NG. The release of this additional CO₂ has contributed to warming and to noticeable greening of our planet. NASA and the World Economic Forum confirm that elevated CO₂, slight warming, and precipitation increases contribute to the overall net greening of the Earth over the past decades (NASA Earth Observatory, 2019, Dunne, 2019). The increase in the Leaf Area Index (LIA) and

Climate impacts of fossil fuels in today's electricity systems

Vegetation Index due to CO₂ fertilization has been confirmed by several researchers, *e.g.*, Zaichun *et al.* (2016) and Wang *et al.* (2020). This greening is crucial in providing sufficient food to the growing population and its benefits have not been properly calculated. Zhu *et al.* (2016) point out that vegetation increased by about 14% from 1981 to 2014, about 70% of which is due to CO₂ fertilization. The growth equals an area twice as large as the USA. Deforestation counteracts CO₂ fertilization and needs to be further reduced; however, at a global scale, more biomass is added than is lost by deforestation.

Atmospheric CH₄, in contrast, has no benefit to the environment but only costs. CH₄ needs to be captured to have value for energy generation. CH₄ that ends up in the atmosphere, according to the IPCC, is a far more potent GHG causing global warming (see footnote⁴, p.139). Additionally, it is understood that CH₄ does not only have climate impacts but also affects air quality because it is an ingredient in the formation of ground-level ozone, a dangerous air pollutant.

In summary, higher CO₂ emissions such as those from fossil fuel combustion are more beneficial for plant life relative to lower CO₂ emissions (the emphasis is on *plant life*). Higher CH₄ emissions have no benefit to the environment, are a potential health hazard, and have a larger GHG effect. These undisputed facts also need to be considered in energy policy.

Conclusions

This paper has sought to raise awareness that oil, coal, and natural gas account for approximately 80% of global PE and 95% of measured-human-energy CO₂ emissions, but a smaller portion of total anthropogenic airborne CO₂^{eq} (about 55% at GWP₂₀ to 70% at GWP₁₀₀). The benefits of these energy sources as well as their related costs are not all incorporated in current energy policy discussions. Anthropogenic CO₂ emissions account only for about 35% of total anthropogenic airborne CO₂^{eq} at GWP₂₀ (60% at GWP₁₀₀) after accounting for CH₄.

It is evident that global GHG policies at least need to include documented changes in anthropogenic measured airborne CO₂^{eq} to avoid spending large amounts of public funds on ineffective or sub-optimal policies. Nowadays many governments, most global funds, international banks, conglomerates, and insurers have publicly announced they will abandon coal but will continue to support LNG and PNG projects, which are required to power human life.

The authors recommend that energy policies be reviewed taking all available information into account. Policies that focus only on combustion but leave out the true and full life-cycle emissions of all types from mining, processing, transportation, and utilization will lead to environmental surprises and potentially very large economic costs. The authors strongly support the fact that energy from all sources, including natural gas, oil, coal, nuclear, and renewables, is required to eradicate poverty. Increased wealth translates to increased resilience against illness and natural disasters.

Applying the IPCC's 20-year global warming potential GWP₂₀, measured CH₄ emissions significantly outstrip global anthropogenic airborne energy-related CO₂, or coal's total CO₂^{eq} emissions (see Tables I and II). Moreover, the dominant CH₄ emissions are not from human energy-related sources, which contribute only about 20%, but they arise from natural wetlands, agriculture, and waste handling. Elimination of those CH₄ sources would mean eliminating biologically productive areas, food resources, and the waste products of billions of people (Figure 3).

Using UN-funded IPCC and IEA data sources, it can be calculated that at GWP₂₀, on a global average, surface-mined coal emits about 15% less CO₂^{eq} than natural gas. This figure increases as the use of shale gas and LNG expands. At a 100-year horizon (GWP₁₀₀) surface-mined coal still emits 25% more CO₂^{eq} than average NG. However, for LNG the situation does not look as favourable, even at GWP₁₀₀ where coal is on a par with NG at 5% additional CH₄ loss prior to combustion. Additional CO₂ releases from NG or LNG production are not measured nor accounted for. These observations make the case that investors should not favour NG over coal for electricity production but should support all energy systems in a manner that avoids an energy crisis, including variable renewable energy systems where they make sense. If CO₂ emissions need to be reduced, one of the most effective ways would be to install CCUS technology (Tramošljika *et al.*, 2021). However, the benefits of CO₂ through fertilization need to be fairly considered and evaluated.

The authors suggest that future research and development should concentrate on reducing net emissions of fossil fuel power plants and providing cost-effective and reliable conventional new power generation projects. This should be dedicated to ultra-supercritical (USC) power plants for increased efficiency, whether fossil fuel-fired or biomass-fired. The introduction of USC technologies is already growing in China and other countries and should be introduced – possibly at no cost to accelerate their deployment – to all developing countries, such as Bangladesh, Pakistan, Vietnam, Indonesia, South Africa, Kenya, Nigeria, and countries in South America. China, instead of forswearing support for coal-fired plants outside its borders, could then justify support for construction of efficient USC plants worldwide. Such advanced high-efficiency and low-emission (HELE) plants could replace less efficient existing power plants or even provide new facilities, all of which would support increasing economic activity, reduce emissions, and improve the quality of life for the growing population.

USC technology would have an immediate positive effect on nature (Tramošljika *et al.*, 2021) at a lower cost than installing grid-scale intermittent renewable energy systems with the required backup or storage. Fossil fuels, including natural gas and coal, require investment, not divestment, in the interest of our planet's health and to eradicate (energy) poverty.

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Key abbreviations

CCUS	Carbon capture utilization and storage
CO ₂ ^{eq}	CO ₂ equivalents incorporating IPCC's Global Warming Potential of CH ₄
GHG	Greenhouse gas
GWP	Global Warming Potential (specified over 20 years or 100 years)
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LNG	Liquefied natural gas
NG	Natural gas
PE	Primary energy
USC	Ultra-supercritical

Climate impacts of fossil fuels in today's electricity systems

Appendix

International studies and press releases on methane

A number of international studies and press releases, mostly funded by environmental organizations and even the gas industry itself, confirm that for 'the climate', LNG and shale gas are at best on a par with coal or will emit higher relevant GHG emissions. In the past few years there has been a shift to more focus on methane, as illustrated by IEAs Methane Tracker and various reports (Ritchie and Roser, 2020a, 2020b; IEA, 2021; Saunio *et al.* 2020; October 2021).

The studies do not typically consider the points made above, namely (1) the higher GWP₂₀ for methane compared with coal or (2) the natural CO₂ uptake of about 50%. The authors do not disagree with these studies on the comparisons made for gas *versus* coal, but their calculation shows the situation to be less favourable for natural gas than suggested, due to the fugitive methane from other identified sources. This conclusion is equally valid for GWP₁₀₀ and even for fugitive methane arising from methane produced for combustion alone.

The following references provide support for the authors' views, namely, that natural gas in various forms is likely to generate higher emissions than coal.

- Bloomberg (2021), Sarah Smith, programme director for super pollutants at Clean Air Task Force, 'World leaders are starting to recognize that curbing methane is the only clear strategy to cut warming over the next two decades'.
- CNN (2021), after the release of the IPCC AR6 Report: '... for the first time, the UN climate change report emphasized the need to control a more insidious culprit: methane, an invisible, odor-less gas with more than 80 times more warming power in the near-term than carbon dioxide'.
- Clean Energy Wire (2021): 'The advantage of natural gas in terms of climate change is disputed. It not only emits CO₂ when burned, but is mainly composed of methane, making it a powerful greenhouse gas itself'.
- IEA World Energy Outlook (2021), p. 41: 'Methane has contributed around 30% of the global rise in temperature today'.
- German Ministry for the Environment, (2020): 'LNG from shale gas does not contribute to climate goals'.

- Washington Post (2020), Chris Mooney, 'Methane is a hard-hitting greenhouse gas. Now scientists say we've dramatically underestimated how much we're emitting'.
- Dan Gocher, Director: Australasian Centre for Corporate Responsibility (ACCR, 2020): 'BHP... is still betting heavily on gas — which is proven to have the same, if not worse emissions than coal once fugitive methane emissions are factored in'.
- Environmental Council, Australia (2019): '... a major international review of LNG infrastructure released in July 2019 found the threat to the climate from LNG is as large or larger than coal'.
- EnergyWatchGroup, Germany (2019 (see Figure 5): '... the switch from coal and oil to natural gas in power plants and heating systems even *increases* the greenhouse effect of energy consumption by around 40%'.
- Bill Gates, Stanford (Stanford Energy, 2018): '... forcing function is sooner on natural gas, converting coal to natural gas for the next 50 years and then shutting it down, that's a net addition [to emissions]'.
- Total Gas study (CIRAIG, 2016): 'With 95% confidence interval, US shale gas may emit more greenhouse gases than Colombian hard coal systems'.

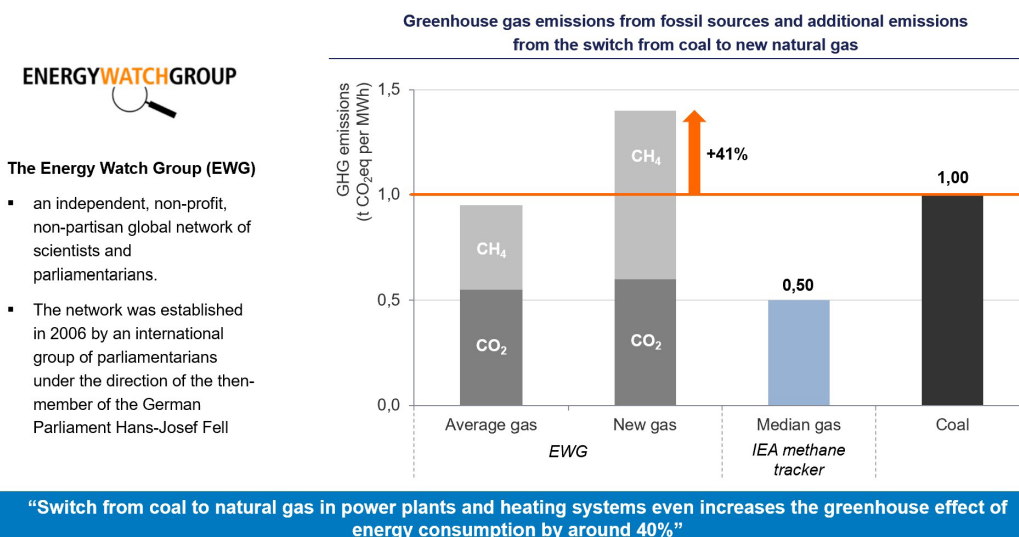
Additional resources in English and German are referenced below.

Howarth (2019) points out that 'While methane emissions are often referred to as "leaks", some of the emissions include purposeful venting, including the release of gas during the flowback period immediately following hydraulic fracturing, the rapid release of gas from blowdowns during emergencies but also for routine maintenance on pipelines and compressor stations, and the steadier but more subtle release of gas from storage tanks and compressor stations to safely maintain pressures'.

Scientific studies and reports (last accessed 25 October 2021)

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Source: Energy Watch Group Germany, 2019 (https://energywatchgroup.org/wp-content/uploads/EWG_Natural_Gas_Study_September_2019.pdf)

Figure 5—EnergyWatch - Switch from coal to gas increase GHGs

Climate impacts of fossil fuels in today's electricity systems

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