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Is the direct release of heat due to combustion of fossil fuels negligible relative to the indirect effect of heat trapped by greenhouse gases?

written by Roger Sathre on March 26th, 2011

During Director Alivisatos' presentation on Monday, January 31st, 2011, a member of the audience asked, "Is the direct input of heat due to combustion of hydrocarbons negligible relative to the indirect effect of greenhouse gas?" Director Alivisatos correctly answered that it is indeed negligible. In this paper we will elaborate on this issue, both qualitatively and quantitatively.

The relation between direct and indirect heat of fossil fuel combustion is time–dependent. While the indirect heat continues to accumulate over time, the direct heat of combustion is released immediately when the fuel is burned. Although some of the direct heat may be temporarily stored in the thermal mass of other materials (e.g. water that is boiled by the fuel), and some of the heat energy may be converted to other forms of energy (e.g. electricity), virtually all of the energy in the fuel will soon be released as heat into the environment.

When the fuel is burned, greenhouse gases (GHGs) are formed and are released into the environment. The most important GHG is carbon dioxide (CO_2), but significant emissions of methane (CH_4) and nitrous oxide (N_2O) may also occur depending on the combustion conditions. These GHGs mix uniformly throughout the atmosphere and begin to trap heat through the process of radiative forcing. Radiative forcing is an imbalance in the earth system between incoming and outgoing radiation. GHGs allow shortwave light radiation to enter the earth's atmosphere but restrict the exit of longwave heat radiation, resulting in an accumulation of energy that leads to climate change. GHGs vary in their radiative efficiency, which determines their ability to accumulate heat. Per unit of mass, N_2O traps the most heat, followed by CH_4 and then CO_2.

A GHG will continue to cause radiative forcing and trap heat in the earth system as long as it remains in the atmosphere. GHGs are removed from the atmosphere by natural processes, at time rates that vary with the GHG. The decay over time of unit mass emissions of CO_2, N_2O and CH_4 is shown in Figure 1.

Roger Sathre

Roger Sathre is a Research Scientist with the Environmental Energy Technologies Division at the Lawrence Berkeley National Laboratory (LBNL).

His primary research interests include:

- life-cycle environmental analysis of energy, industrial, and forestry systems;
- temporally-explicit modeling and optimization of climate change mitigation strategies;
- energy and climate implications of forest management and forest product use; and
- life-cycle assessment of carbon capture and

FIGURE 1
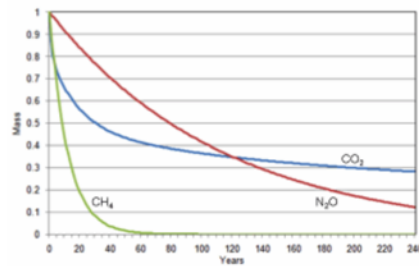
Atmospheric decay of unit pulses of CO_2, N_2O and CH_4.

Figure 2 shows the ratio of the indirect energy accumulated by GHGs released by the combustion of coal, oil, and natural gas, compared to the direct heat energy released by the combustion. The ratio is not fixed, but continues to increase over time as additional heat is accumulated for as long as GHG remains in the atmosphere. The rate of increase is not linear but becomes less steep over time, as the atmospheric concentrations of the GHGs gradually decrease. Twenty years after burning a unit of fuel, the GHG emissions from coal will have trapped about 40 units of indirect heat, while emissions from oil and natural gas will have trapped about 31 and 24 units of heat, respectively. After 100 years, the values are about 130, 100, and 80 units for coal, oil, and gas, respectively. After 200 years, one unit of coal will have accumulated about 220 units of indirect heat, while oil and natural gas will have accumulated about 175 and 130 units, respectively.

FIGURE 2
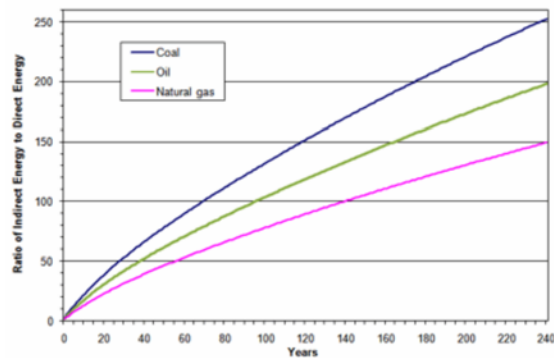
Ratio of the indirect energy accumulated by GHGs emitted by the combustion of coal, oil, or natural gas, compared to the direct heat energy released by the combustion.

The amount of indirect heat depends on the amount of GHG emitted, thus the ratio of coal is higher than that of oil and natural gas because coal produces more CO_2 per unit of heat than do oil and natural gas. For all the fuels, the amount of CO_2 emitted is much greater than the amounts of N_2O and CH_4 emitted. Therefore, CO_2 is responsible for about 99% of the indirect heat, with N_2O and CH_4 being responsible for the remainder.

In summary, the direct release of heat due to combustion of fossil fuels is very minor in relation to the indirect effect of heat trapped by greenhouse gases emitted during the combustion. The indirect effect continues to increase in significance over time, as additional energy is accumulated in the earth system as long as the GHGs remain in the atmosphere.

Appendix

In this analysis, GHG emission factors for the combustion of bituminous coal, diesel oil, and natural gas are based on default values for stationary combustion in the energy industries, provided by IPCC (2006). These factors are shown in Table 1.

Table 1. GHG emission factors for coal, oil, and natural gas combustion (kg GHG emitted per TJ lower

heating value).

GHG	Coal	Oil	Natural gas
CO_2	94600	74100	56100
N_2O	1.5	0.6	0.1
CH_4	1	3	1

Our calculations of radiative forcing are based on the method described by Zetterberg (1993), using updated parameter values from IPCC (1997, 2001, 2007). The emissions of CO_2, N_2O and CH_4 that occur during Year 0 when the fuel is combusted are treated as pulse emissions. The atmospheric decay of the pulse emissions is then estimated using Equations 1, 2 and 3 (IPCC 1997, 2001, 2007):

(1)
$$(CO_2)_t = (CO_2)_0 \times \left[0.217 + 0.259 e^{\frac{-t}{172.9}} + 0.338 e^{\frac{-t}{18.51}} + 0.186 e^{\frac{-t}{1.186}} \right]$$

(2)
$$(N_2O)_t = (N_2O)_0 \times \left[e^{\frac{-t}{114}} \right]$$

(3)
$$(CH_4)_t = (CH_4)_0 \times \left[e^{\frac{-t}{12}} \right]$$

where t is the number of years since the pulse emission, $(GHG)_0$ is the mass of GHG emitted at Year 0, and $(GHG)_t$ is the mass of GHG remaining in the atmosphere at year t. These decay patterns are shown in Figure 1.

The time profiles of atmospheric mass of each GHG are then converted to time profiles of atmospheric concentration, based on the molecular mass of each GHG, the molecular mass of air, and the total mass of the atmosphere estimated at 5.148×10^{21} g (Trenberth and Smith 2005). Marginal changes in instantaneous radiative forcing due to the GHG concentration changes are then estimated using Equations 4, 5 and 6 (IPCC 1997, 2001, 2007):

(4)
$$F_{CO_2} = \frac{3.7}{\ln(2)} \times \ln \left\{ 1 + \frac{\Delta CO_2}{CO_{2ref}} \right\}$$

(5)
$$F_{N_2O} = 0.12 \times \left(\sqrt{\Delta N_2O + N_2O_{ref}} - \sqrt{N_2O_{ref}} \right) - f(M,N)$$

(6)
$$F_{CH_4} = 0.036 \times \left(\sqrt{\Delta CH_4 + CH_{4ref}} - \sqrt{CH_{4ref}} \right) - f(M,N)$$

where F_{ghg} is instantaneous radiative forcing in W/m^2 for each GHG, ΔGHG is the change in atmospheric concentration of the GHG (in units of ppmv for CO_2, and ppbv for N_2O and CH_4), CO_{2ref} = 383ppmv, N_2O_{ref} = 319ppbv, CH_{4ref} = 1774ppbv, and f(M,N) is a function to compensate for the spectral absorption overlap between N_2O and CH_4 (IPCC 1997, 2001, 2007). In this analysis we assume minor marginal changes in GHG concentrations.

We then estimate the cumulative radiative forcing occurring each year in units of $W \cdot s/m^2$ (or J/m^2), by multiplying the instantaneous radiative forcing of each year by the number of seconds in a year. This operation converts the energy flow per unit of time of the radiative imbalance caused by GHGs into units of energy accumulated in the earth system per m^2 per year.

The total accumulated indirect energy (J) is then estimated by integrating the cumulative radiative forcing per m^2 over the surface area of the earth, based on a mean radius of 6,371,000 m. The accumulated indirect energy (J) for each year is then divided by the direct heat of combustion (J) to yield the ratios shown in Figure 2.

Although generally robust, this analysis is subject to some uncertainties. In our calculations of radiative forcing we have assumed relatively minor marginal changes in atmospheric GHG concentrations, such that radiative efficiencies and atmospheric decay patterns of the gases remain constant. However, significant increases in the atmospheric concentration of CO_2 can be expected during the coming decades and centuries. Increased atmospheric CO_2 concentration will decrease the marginal radiative efficiency of CO_2, but will also decrease the marginal atmospheric decay rate of CO_2. These will have opposite and therefore offsetting effects on radiative forcing, thus we expect this uncertainty to be

minor. Nevertheless, taking into account the expected future trajectories of GHG concentrations would reduce this uncertainty.

We have estimated cumulative radiative forcing by integrating instantaneous radiative forcing over time. This is a simplification, as we ignore the feedback effect that the accumulated energy will have on future outgoing radiation. Radiative forcing is a measure of the radiative imbalance given that atmospheric temperatures remain unchanged. In fact, the radiative forcing calculated here will increase the heat energy accumulated in the earth system, leading to more outgoing longwave radiation and an eventual restoration of radiative balance. Since instantaneous radiative forcing does not account for this feedback effect, our results may therefore slightly overestimate the amount of accumulated heat.

We have considered GHGs produced only from the combustion of the fuels. Additional GHGs will be emitted during the upstream extraction and processing of the fuels. These emissions are due to the production and operation of infrastructure and equipment used in the mining and transportation of the fuels, as well as methane emissions from coal fields and natural gas leaks. These additional GHG emissions, which may be significant, will increase the amount of indirect heat accumulated by the fuels. Finally, the direct heat energy is here taken to be the lower heating value (LHV) of the fuels, i.e. not including the latent heat of vaporization of water released by the combustion. If the higher heating value (HHV) of the fuels were used instead, the ratios would be slightly lower.

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