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CALCULATING BUILDINGS' GREENHOUSE GAS EMISSIONS

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Summary

Increased concern about climate change has led many building designers throughout the world to focus on reducing energy use in buildings. It is often assumed that energy use is more or predictive of greenhouse gas GHG) emissions However, there are numerous time-dependent variations in building energy use and electric grid operation that result in important differences between the quantity of energy used and the related GHG emissions. These differences are not generally considered or even recognized by most designers or even regulators and others who are now striving to develop a carbon neutral economy. Efforts have begun to recognize the important factors that determine a building's GHG emissions based on its energy use, but these efforts are still in the preliminary stages. This paper identifies some of the important factors that affect the estimation of GHG emissions based on energy use data from simulations during design or from actual energy meters or purchases. These differences are being considered in a new effort to develop a tool that will more accurately predict building GHG emissions based on design alternatives, thus allowing design professionals to improve the GHG emission performance of their buildings.

Keywords: Greenhouse gas, climate change, GHG emissions, energy, design

1. Introduction

Buildings are responsible for a significant fraction (~40%) of fossil fuel consumption and related greenhouse gas (GHG) emissions globally. In the United States, buildings are responsible for 70% of total electricity use. While these factors vary from country to country and even among regions within countries, the numbers reflect the relative magnitude of building energy consumption in most of the developed world. In the developing world, the percentages are different with a shift toward combustion of biomass and less electricity use. However, the human contribution to GHG emissions is still significant and growing as developing countries gain access to modern energy-consuming technology, electricity, and a more mobile life style.

Growing concern about climate change and the human contribution to it through emissions of greenhouse gases (GHG) has led to increasing focus on reduction of GHG usually referred to as carbon dioxide equivalents (CO_2eq) using United Nations Framework Convention on Climate Change factors for global warming potentials of various atmospheric emissions. Efforts to reduce building's contributions to climate change focus on reduction of emissions of GHGs. Calculation of GHG emissions is usually done with simple conversion factors that translate fuel consumption and electricity use to GHG emissions. However, these conversion factors may not reliable inform design or building operational decisions due to potentially large influences of time and weather on actual GHG emissions compared with annual averages.

In the paper we describe the approach to GHG calculation commonly used today, some of the challenges facing those who are developing more reliable tools for such calculations, and some of the sources of uncertainty in any method for estimating GHG emissions from buildings.

1.1 Background: Global Greenhouse Gas Emissions

Emissions of GHGs have increased since the industrial revolution. The dramatic increase that began after World War II has resulted in an average annual increase in atmospheric CO_2 of 2 ppm to the present level of 383 ppm. The rate of increase has also increased in recent years. It is forecast that GHG emissions will increase by 50 percent by 2025. Emissions in developing countries are growing and are expected to continue to grow the fastest. To avoid dangerous climate change requires slowing this trend in the short term and eventually and reversing it over the coming decades.

While CO_2 comprises the majority of GHG emissions, at about 77 percent of the worldwide total (measured in global warming potentials). Methane (CH_4) and nitrous oxide (N_2O) are the next most important GHG, and methane's short term impact is dramatically larger than its longer term impact, the usual basis for comparison of global warming potentials (GWP) among the various GHGs. Fluorinated gases (SF_6, PFCs, and HFCs) have a small share of the remaining important GHGs.

In developing countries, the contributions of CH_4 and N_2O are significantly larger in and in some cases exceed those of energy-related CO_2 emissions.

GHG emissions come from almost every human activity. Because of their large contributions, key policy targets are electricity and heat, transport, buildings, industry, land-use change and forestry, and agriculture. In terms of future growth the electricity and transport sectors are particularly important sectors. In terms of potential for short-term and cost-effective reductions, buildings and transport both figure prominently.

Global emissions are dominated by a small number of countries producing the majority of global GHG emissions. Most of these are among the most populous countries and have the largest economies. However, the major emitters are comprised almost equally of developed and developing countries and some transition economies of the former Soviet Union.

Projection of emission by nations is highly uncertain, especially among developing country economies due to their volatility and vulnerability to external shocks.

Not surprisingly, most large current emitters are among the largest historic emitters.

Coal is the highest carbon fuel and it plays a dominant role in electric power generation throughout the world. Its future growth is expected to be significant. Many leaders in the building and environmental communities advocate reducing or eliminating emissions from coal-fired power plants either be carbon sequestration or by eliminating the plants altogether and stopping construction of new plants.

Avoiding dangerous climate change will require reduced coal use or geologic sequestration of coal-related emissions. Similarly, major emitting countries will need to reduce their dependence on oil, particularly in the transport sector where it has near monopoly status.

1.2 Buildings' Share of Global GHG Emissions

The proportion of total national emissions attributable to buildings ranges widely depending on the definition of building-related emissions, the accounting method used, and, of course, the level of development and energy efficiency of the national building stock. The major drivers of buildings energy demand are population growth, economic development, diffusion level of energy use equipment, size of households, square meters of buildings areas, and behavioral factors" (de la Rue du Can and Price, 2008).

In developed countries, buildings' share is relatively similar at around 25% to 35% of total national GHG emissions according to the World Resources Institute. In contrast, there is great diversity in buildings' share among developing countries ranging from around 10% (Brazil) to 40% (Poland) (Baumert et al, 2005). Where air-conditioning is common and widespread, electricity consumption will increase in non-residential buildings. In the U.S. the fraction of air conditioned homes (~70%) and commercial buildings is extremely high while in most other developed countries it is increasing in commercial buildings while in residences the penetration is strongly dependent on climate and other factors. Furthermore, the overall distribution of energy sources and the carbon intensity of the combustion fuels and electricity will be reflected in the national share of carbon emissions attributable to buildings.

"The residential sector is characterized by a striking contrast in fuel use between developed and developing countries. More than half the world's population lives in rural areas, of which more than 90% are in developing countries. The vast majority of this population is dependent upon traditional wood fuel to serve the basic need of cooking and water heating. Hence the share of biomass in the global residential final consumption represents more than 40% in 2004. In developed countries, natural gas and electricity are the most used fuel in residential buildings. While energy demand growth in residential sector was 1.4% over the period 1971–2000, growth in the commercial sector was 2.4%. Three quarters of the energy use in the commercial sector is currently consumed in developed countries. The commercial sector is characterized by a high level of electricity consumption, representing almost half of the total energy use (48%) in 2004." (de la Rue du Can and Price, 2008).

In the mid-1990s very different calculations done by the present author for buildings in the U.S. (Levin, Boerstra, and Ray, 1995) and by the World Resources Institute for buildings worldwide estimated buildings' share of total national carbon emissions at approximately 40% to 45% of total national energy consumption and a similar value for carbon emissions. Some authorities currently claim that buildings' share is even higher in the U.S. (e.g., 48% by Ed Mazria) (2008). The Levin et al estimate included building materials manufacturing, construction, operation, maintenance, renovation, and end-of-life disposal of buildings in this total. However, it should be noted that approximately 20 to 25% of building energy use is for "plug loads," that is energy used for appliances, electronics, and other devices that are not part of the building itself but that derive their energy from the same electrical source as the whole building. Therefore, their electrical consumption is measured at the electric meter and large scale data analysis and reporting often does not separate the building-related and the within-building-but-not-building-related energy uses. There remains a question as to whether devices like refrigerators, cookstoves, and plug-in lamps should be included in building-related energy uses for purposes of attribution and carbon emissions estimation

Table 1. Greenhouse gas emissions in 2004 by sector excluding land use change and forestry (source: adapted from Climate Analysis Indicators Tool (CAIT) Version 5.0. (Washington, DC: World Resources Institute, 2008).

Sector	**World** %	**United States** %	**European Union** %	**Asia** %
Energy	96.3	99.1	97.1	93.0
Electricity & Heat	45.3	45.8	39.4	46.5
Manufacturing & Construction	18.8	11.5	16.3	24.8
Transportation	19.1	30.5	23.1	10.9
Other Fuel Combustion	12.6	10.9	18.2	10.7
Fugitive Emissions	0.6	0.4	0.1	0.1
Industrial Processes	3.7	0.9	2.9	7.0
Total ($MtCO_2$)	**29,319.4%**	**5.873.8**	**4,013.1**	**9,968.1**

As can be seen in Table 1, the dominant source of human GHG emissions throughout the world is energy consumption with somewhere between 40 and 50% attributable to buildings. If construction and demolition are added to the total, buildings share is well over half. However, much of the electricity used in buildings is not to operate the building itself but is attributable to "plug loads' including appliances, electronics, etc. Nevertheless, building services uses of energy are approaching half of total energy use in developing countries.

Of course there are many ways of classifying the users of energy and of doing the accounting. According to the World Resources Institute (see Table 1), buildings account for only 15% of global GHGs. Of that amount, 65% is residential, 35% commercial. Within the residential sector, public electricity is 43%, District heat is 12%, and direct fuel combustion is 45%. In the commercial building sector, 65% is electricity, 4% is district heat, and 31% is direct fuel combustion. It is not clear whether the

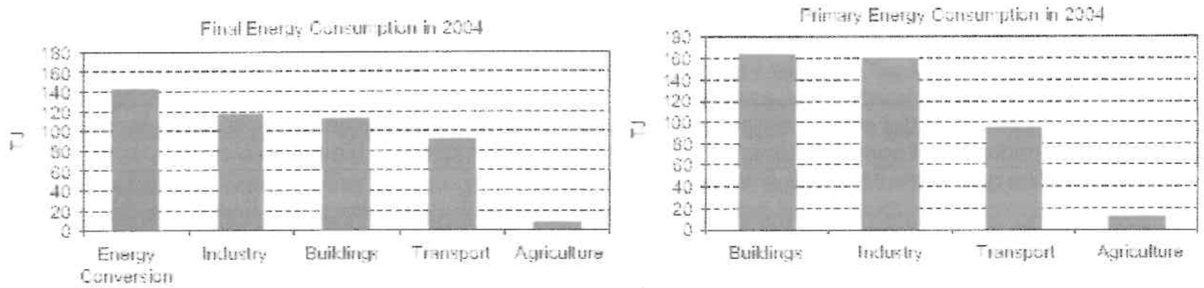

Figure 1. Final and Primary Energy Consumption by Sector in 2004 (source: de la Rue du Can and Price, 2008).

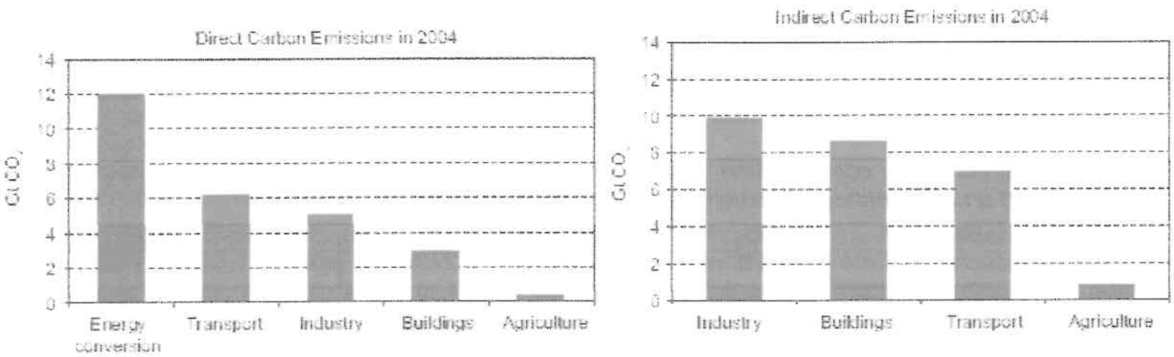

Figure 2. Direct and Indirect Carbon Dioxide Emissions in 2004 (source: de la Rue du Can and Price, 2008).

Regardless of the precise quantity of its share of global GHG emissions, it is clear that buildings are important sources of GHG emissions. It is also important to note that the range of building energy efficiencies and of potential sources of energy for buildings major consumption categories suggest that buildings can be far more energy efficient and emit far less GHGs. It may also be true that careful selection of energy efficiency measures can ensure optimization of both energy conservation goals as well as GHG emission reduction goals. However, since there is not a one-to-one relationship between energy use and GHG emissions, it is important to understand the GHG emissions implications of various alternative technologies to reduce energy use. For example, electricity from coal-fired power plants is associated with roughly twice the GHG emissions as that from natural gas-fired plants. Hydroelectric and wind electric energy plants are responsible for far less GHG emissions, although their construction, operation, and ultimate disposal do have GHG emission implications as does the transmission of electricity from any plant to the site where it is used. Large-scale concentrating solar electricity generation is viewed as one of the potentially viable renewable sources of future electricity, but it too has GHG emissions associated with its construction, operation, and electricity distribution. On site photovoltaic electric generation eliminates the transmission losses but does have a several-year payback for the energy required to manufacture and install the system. Even passive solar heating and cooling where high performance glass, shading, thermal storage, and other components are included in order to improve system performance still must be accounted for in total GHG emissions required to install and "operate" for their entire life cycles.

Conversion of building energy use data to GHG emissions

Following are definitions of some basic terms and some background information on greenhouse gases that are useful for those calculating greenhouse gas emissions.

Carbon sequestration: The fixation of atmospheric carbon dioxide in a carbon sink through biological or physical processes.

Carbon sink: A reservoir that absorbs or takes up released carbon from another part of the carbon cycle. The four sinks, which are regions of the Earth within which carbon behaves in a systematic manner, are the atmosphere, terrestrial biosphere (usually including freshwater systems), oceans, and sediments (including fossil fuels).

Global warming potential (GWP): An index used to compare the relative radiative forcing of different gases without directly calculating the changes in atmospheric concentrations. GWPs are calculated as the ratio of the radiative forcing that would result from the emission of one kilogram of a greenhouse gas to that from the emission of one kilogram of carbon dioxide over a fixed period of time, such as 100 years.

Greenhouse gases: Those gases, such as water vapor, carbon dioxide, nitrous oxide, methane, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride, that are transparent to solar (short-wave) radiation but opaque to long-wave (infrared) radiation, thus preventing long-wave radiant energy from leaving the Earth's atmosphere. The net effect is a trapping of absorbed radiation and a tendency to warm the planet's surface.

Greenhouse effect: The result of water vapor, carbon dioxide, and other atmospheric gases trapping radiant (infrared) energy, thereby keeping the earth's surface warmer than it would otherwise be. Greenhouse gases within the lower levels of the atmosphere trap this radiation, which would otherwise escape into space, and subsequent re-radiation of some of this energy back to the Earth maintains higher surface temperatures than would occur if the gases were absent. See Greenhouse gases.

Radiative forcing: a measure of how the energy balance of the Earth-atmosphere system is influenced when factors that affect climate are altered. The word radiative arises because these factors change the balance between incoming solar radiation and outgoing infrared radiation within the Earth's atmosphere. This radiative balance controls the Earth's surface temperature. The term forcing is used to indicate that Earth's radiative balance is being pushed away from its normal state.

The principal greenhouse gases are shown in Table 2. From the table it is possible to see the growth in concentrations between pre-industrial atmospheric concentrations and those observed in 1998. Note that the atmospheric lifetimes of these gases vary greatly and are part of the reason that the time required for stabilizing climate and eventually reversing climate change through control of the concentrations of releases of these gases.

Table 2. Global atmospheric concentration (ppm unless otherwise specified), rate of concentration change (ppb/year) and atmospheric lifetime (years) of selected greenhouse gases

Atmospheric Variable	CO_2	CH_4	N_2O	SF_6 [a]	CF_4 [a]
Pre-industrial atmospheric concentration	278	0.700	0.270	0	40
Atmospheric concentration (1998)	365	1.745	0.314	4.2	80
Rate of concentration change[b]	1.5c	0.007[c]	0.0008	0.24	1.0
Atmospheric Lifetime	50-200[d]	12[e]	114[e]	3,200	>50,000

[a] Concentrations in parts per trillion (ppt) and rate of concentration change in ppt/year.

[b] Rate is calculated over the period 1990 to 1999.

[c] Rate has fluctuated between 0.9 and 2.8 ppm per year for CO_2 and between 0 and 0.013 ppm per year for CH_4 over the period 1990 to 1999

[d] No single lifetime can be defined for CO_2 because of the different rates of uptake by different removal process removal processes.

[e] This lifetime has been defined as an "adjustment time" that takes into account the indirect effect of the gas on its own residence time.

1.2. Basics of GHG Emission Calculations

It is common practice in most developed countries to use annual average conversion factors for calculating GHG emissions based on electricity consumption. These factors may vary greatly within and among countries due to differences in the composition or inventory of electricity generating plants. There is a substantial range of emissions depending on the combustion fuel used or other source of energy to produce electricity. For example, electricity produced in coal-fired power plants result in approximately twice the CO_2 emissions compared with natural gas fired electric power plants.

A general practice is to calculate a building's greenhouse gas emissions relatively simply. This involves using readily available conversion factors for each form of energy used annually. An alternative that may be somewhat more accurate is to modify fuel use data by the efficiency of the device consuming the fuel and other factors to convert the fuel consumption to emissions of each to the mass of the greenhouse gases. Then, using global warming potentials (GWP) of each pollutant emitted, the total GWP is given in carbon dioxide equivalents (CO_2e).

Currently, building design professionals estimate the annual energy consumption (e.g. kWh) that will be required to operate the building, and then apply actual average annual carbon emission factors (e.g., tons of CO_2 per kWh or per therm) to those estimates in order to estimate the annual carbon emissions associated with the building's operation (e.g. tons of CO_2 = kWh * tons of CO_2/kWh). The carbon emission factors applied to electricity to be purchased from the grid are based upon various sources within the building design professions today. There is not standard practice for selecting and applying carbon emission factors applied to electricity whether purchased from a utility or produced on-site. Combustion on-site is more reliably converted to emissions using standard factors although inclusion of 'embodied' emissions related to use of the fuel is not common.

Limitations of current methods for estimating GHG emissions

There are at least four aspects of the current method that may lead to less than sufficiently accurate estimates of carbon emissions associated with buildings.

Limited scope

The current emission factors for the carbon emissions associated with the generation of electricity, i.e., predominantly from the emissions from combustion of a fuel to produce electricity, do not reflect the emissions associated with the extraction and transportation of the fuels used to generate that electricity. It is also possible that these factors have not been fully adjusted to reflect the energy losses on the transmission and distribution grid between the point of generation and the point of consumption, i.e., the building. Similarly, emission factors for on-site combustion do not include the so-called 'embodied' emissions associated with extraction, transportation, and storage of the fuels.

No differentiation by time period

Annual average emission factors for electricity purchased from the grid can mask significant variations in emissions by time of day, day of the week and/or season, and therefore may not produce a sufficiently accurate estimate. This is a major reason for this project. Energy consumption and GHG emissions do not map one-to-one due to the diversity of electricity generation on the grid and its geographical and temporal variations. The question then is whether the estimate of carbon emissions would be materially improved if building design professionals could evaluate the time-dependent energy consumption at the site using emission factors based upon the corresponding time-dependent output of the electric grid providing electricity to that that site.

No differentiation by weather

There are two potential concerns in this regard. The first is similar to, if not the same as, the lack of time differentiation. Annual average emission factors for electricity purchased from the grid can mask significant variations in emissions within the year due to variations in weather conditions. In other words, electricity generation emissions under extreme weather conditions such as heat waves and cold waves are different from emissions under annual average weather. The second relates to potential mismatches between the weather assumptions underlying the estimates of building energy consumption and the weather assumptions underlying the carbon emission factors. Building energy simulations are performed using average annual weather data (Typical Meteorological Year – TMY). Therefore the estimates of energy consumption produced by those simulations reflect that weather assumption. In contrast, actual carbon emission factors for grid electricity reflect actual weather in the relevant year while projected carbon emission factors reflect the weather assumptions used in the simulation of the electric grid. Thus, there is a possibility of a mismatch between the estimates of energy consumption and the carbon emission factors being applied to those estimates.

Actual versus projected emission factors

The current emission factors for electricity purchased from the grid are based upon emissions associated with actual generation of electricity in a recent year. The concern here is whether those factors provide a sufficiently accurate estimate of the emissions that will be associated with the future mix of generation over the life of the building.

In addition to evaluating the accuracy implications of each of those aspects of the current carbon estimation methodology, the accuracy of the energy use estimates to which those factors are being applied must be considered. Research indicates that the actual levels and patterns of building energy use can be very different from the estimates of use from simulation models made during the design process. These differences between estimated and actual building energy use arise because building energy simulations rely upon assumptions about key factors such as building occupancy, use, and operation. Actual occupancy, usage and operation of the building are often very different from those assumptions.

ASHRAE's Carbon Tool Development Project

The American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) has embarked on a project to development a more robust and accurate tool for estimating building's carbon emissions to enable designers, building operators, and others to make decisions that will improve the carbon emissions performance of a building and to account for the emissions that have occurred in an existing building. The tool will weigh the accuracy of the building energy use estimates when considering the value of developing more accurate estimates of carbon emissions to be applied to those energy estimates.

While the uncertainties are very large in any prospective estimate of carbon emissions based on forecasts and historical data as well as building simulations, by identifying and characterizing the sources of uncertainty and incorporating means to reflect them in an estimating tool will provide "realistic" data as an improved basis for design and operation.

Discussion and Conclusion

The present inaccurate methods of estimating buildings' carbon emissions leave building design and operational professionals with inadequate information to make decisions that actually result in lower greenhouse gas emissions. The assumption that a decision resulting in less energy use is always the lower GHG emission strategy is potentially costly both to the building operator as well as to the global climate. It is important to improve on currently available estimation tools and reduce the uncertainty in decision-making around a building's carbon footprint. While the data available currently is a major constraint on the development of accurate tools, investigation and improvement of the performance of current tools can help identify the most important data needs and the value in improving data quality. ASHRAE's current efforts are unique as far as is known by the author, and they are certain to create increased awareness of the problems and means of addressing them. It is hoped that the tool itself will be a major step toward broader recognition of the most important factors related to buildings' GHG emissions and that this recognition will enable more rapid progress toward net zero GHG emission buildings.

References

Baumert, KA, Herzog, T, Pershing, J. 2005. Navigating the Numbers: Greenhouse Gas Data and International Climate Policy. Washington, DC: World Resources Institute.

de la Rue du Can, S., Price, L, 2008. Sectoral trends in global energy use and greenhouse gas emissions *Energy Policy* 36:1386–1403.

Deru, M. and P Torcellini. 2007. Source Energy and Emission Factors for Energy Use in Buildings. NREL Technical Report TP-550-38617, Revised June 2007. http://www.nrel.gov/.

IPCC, 2001. http://www.ipcc.ch/

Levin, H, A Boerstra, and S Ray, 1995. "Scoping U.S. Buildings Inventory Flows and Environmental Impacts in Life Cycle Assessment." Abstract for presentation at Second SETAC World Congress, Vancouver, BC, November 5-9, 1995.

Mazria, E. 2008. Architecture 2030. http://architecture2030.org/

UK. 2006. L2A – The Building Regulations 2000. Conservation of fuel and power in New Buildings. Office of the Deputy Minister. www.thebuildingregs.com.

Appendix

The data in this appendix are provided for more readers interested in more detailed quantification of greenhouse gases.

Table A1: Global Warming Potentials (GWP) (Relative to Carbon dioxide = 1) and Atmospheric Lifetimes (Years) IPCC 1996 values.

Gas	Atmospheric Lifetime	100-year GWPa	20-year GWP	500-year GWP
Methane (CH_4)b	12.3	21	56	6.5
Nitrous oxide (N_2O)	120	310	280	170
HFC-23	264	11,700	9,100	9,800
HFC-125	32.6	2,800	4,600	920
HFC-134a	14.6	1,300	3,400	420
HFC-143a	48.3	3,800	5,000	1,400
HFC-152a	1.5	140	460	42
HFC-227ea	36.5	2,900	4,300	950
HFC-236fa	209	6,300	5,100	4,700
HFC-4310mee	17.1	1,300	3,000	400
CF4	50,000	6,500	4,400	10,000
C2F6	10,000	9,200	6,200	14,000
C4F10	2,600	7,000	4,800	10,100
C6F14	3,200	7,400	5,000	10,700
SF6	3,200	23,900	16,300	34,900

These values were modified for the IPCC's Third Assessment Report (TAR) released in 2001 as shown in Table A2.

Table A2. Conversion Factors for Global Warming Potentials (source: 2001 IPCC GWP)

Gas	2001 IPCC GWP
Carbon Dioxide	1
Methane	23
Nitrous Oxide	296
HFC-23	12,000
HFC-125	3,400
HFC-134a	1,300
HFC-143a	4,300
HFC-152a	120
HFC-227	3,500
HFC-236	9,400
Perfluoromethane (CF_4)	5,700
Perfluoromethane (C_2F_6)	11,900
Sulfur Hexafluoride (SF_6)	22,200

Table A3 from L2, Approved document L2A emissions factors (source: UK, 2006)

Fuel	**CO_2 emission factor $kgCO_2/kWh$**
	UK
Natural gas	0.194
LPG	0.234
Biogas	0.025
Oil	0.265
Coal	0.291
Anthracite	0.317
Smokeless fuel (including coke)	0.392
Dual fuel appliances (mineral and wood)	0.187
Biomass	0.025
Grid supplied electricity	0.422
Grid displaced electricity[1]	0.568
Waste heat[2]	0.018

Notes:

1. Grid displaced electricity comprises all electricity generated in or on the building premises by, for instance, PV panels, wind-powered generators, combined heat and power (CHP), etc. The associated CO_2 emissions are deducted from the total CO_2 emissions for the building before determining the BER. CO_2 emissions arising from fuels used by the building's power generation system (.e.g., to power CHP engine) must be included in the building CO_2 emissions calculations.
2. This includes waste heat from industrial processes and power stations rated at more than 10 MWe and with a power efficiency > 35%.