Basics of Building Decarbonization

An Online Continuing Education Course for Engineers

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Craig Keenan, P.E., CEM

Introduction:

Building decarbonization means reducing the use of fossil fuels in buildings. It has become more popular in recent years due to governmental, institutional, and corporate goals to reduce the amount of greenhouse gas (GHG) emissions released into the atmosphere, which are primarily carbon dioxide due to combusting hydrocarbons.

This course will assist in helping understand how to reduce building-related GHG emissions, which are primarily produced from burning fossil fuels on-site for space and water heating and indirectly from using fossil-fuel-derived electricity. It will describe the background of GHG emissions, the different kinds of emissions, and how to account for these emissions. It will also discuss benchmarking, energy efficiency, renewable energy, electrical infrastructure, and electric vehicles. It will mainly focus on reducing carbon emissions in existing buildings, since new buildings are typically covered by existing building codes and energy efficiency standards.

This course will detail important aspects of building design, particularly mechanical, electrical, and plumbing systems, and how their equipment can be decarbonized effectively and operated efficiently. Because electric vehicles are an effective way to decarbonize transport, this course will cover types of electric vehicle supply equipment (EVSE), charging and range concerns, and electric vehicle charging infrastructure.

This course will primarily focus on concepts relevant to residential and commercial buildings in the United States of America, but may be helpful for buildings in other locations as well. It will not focus in-depth on strategies to decarbonize industrial processes, but its concepts may still be relevant. Hopefully, this course will give the reader more confidence in how to account for and reduce building GHG emissions, as well as assist in the planning, design, and operation of decarbonizing buildings.

Background on GHG Emissions:

For most of human history, biomass such as wood, peat, or other materials was burned for heating. Starting in England in the 1800's, large-scale coal mining developed, and due to the higher heating value of coal, higher temperatures were able to be created. The higher heating value of coal allowed for the development of industrial processes using coal-fired steam engines and turbines, but also created higher greenhouse gas emissions because, unlike biomass, coal is a fossil fuel. As the Industrial Revolution spread to other countries, such as the United States, Germany, and Russia, coal production and emissions also increased. Later in the 1800's, petroleum started to be used as a fuel, and over time, petroleum was refined into other products such as gasoline, kerosene, diesel fuel, and fuel oil. All of these petroleum products were used in industrial processes as well as more consumer products such as automobiles, small gasoline engines, boilers, furnaces, and kerosene lamps.

After World War II, more technological advances allowed for greater use of fossil fuels and better ways to extract them. Uses for petroleum products, such as plastics and natural gas, which is a byproduct of petroleum extraction, were expanded. The United States continued to grow economically and, through the Marshall Plan, started to spread its consumer activities to other postwar economies in Europe and Japan. Also, at the same time, the Soviet Union increased its industrial base and increased fuel use. Throughout the 20th century, per-capita carbon emissions increased drastically, especially in developed countries, and by the end of the 20th century was also increasing in developing countries in Latin America, the Middle East, and throughout Asia.

Due to the oil embargo in the 1970s, Energy Efficiency started to be pursued by the US government and other institutions to reduce reliance on imported fossil fuels, as well as research into renewable energy such as solar photovoltaics. Later on, scientists started to become concerned about the amount of carbon dioxide emissions and how it was affecting the atmosphere and the global climate.

Starting in the 1990s, there was an international focus on reducing worldwide greenhouse gas emissions, with countries setting targets for themselves to reduce emissions within a certain time frame, such as the Kyoto Protocol in 1997. Also, some countries instituted a carbon tax as a way to make the price of burning fossil fuels more expensive and subsidize renewable energy and other forms of emission-free power. Over time, there has been more pressure on governments, corporations, institutions, and individuals to reduce their GHG emissions, and many goals for significant reductions and net-zero carbon emissions by the mid-21st century.

Types of GHG Emissions

GHG emissions can be categorized into different scopes: Scope 1, Scope 2, and Scope 3.

Scope 1 includes GHG emissions that are produced on-site, typically from combustion of fossil fuels. For most commercial buildings, this would be from natural gas, fuel oil, or other fuels burned for space heating or water heating. It can include gasoline or diesel fuel burned for motor vehicles.

Scope 2 refers to GHG emissions from energy used on-site but produced off-site. One common example is electricity, because electricity is used on-site but is produced off-site and delivered via the electrical grid. Oftentimes, the electricity produced in the electrical grid comes from many different power plants, including coal, natural gas, nuclear, hydropower, wind, or solar. Depending on where you are in the United States or in different countries, Scope 2 emissions can differ quite widely due to the power plants on the grid. Other examples of Scope 2 emissions are from district steam or chilled water systems, which exist in campuses or in downtown utility systems.

Scope 3 refers to the embedded GHG emissions in different processes or systems. For example, if someone buys office supplies, there are GHG emissions that were produced in order to manufacture the product and deliver the product, as well as to dispose of the product. One way to look at Scope 3 emissions is that they are other people's Scope 1 and Scope 2 emissions. Scope 3 emissions can be difficult to calculate, particularly for large users. Oftentimes, when people are focused on GHG emission reduction, they are referring to Scope 1 and Scope 2 emissions, since they are easier to quantify, and that will be the focus of this course.

Hydrocarbons and Combustion:

A greenhouse gas is a term for a gas that, once it is in the atmosphere, increases the greenhouse effect. These include carbon dioxide, methane (natural gas), refrigerants, and other chemicals. Although carbon dioxide is not the strongest greenhouse gas, it is the most prevalent due to the combustion of fossil fuels. Most fossil fuels were created hundreds of millions of years ago through the decomposition of carbon-based plants, so they are primarily made of hydrocarbons.

Not all hydrocarbons are fossil fuels. Renewable resources such as wood and biomass are organic materials that do not contribute to an overall increase in greenhouse gas emissions, since if they biodegraded, they would also produce emissions. Similarly, renewable natural gas (RNG) or digester gas from wastewater or agricultural waste is a hydrocarbon but not a fossil fuel.

Combustion is a chemical reaction that takes place when hydrocarbons (H_xC_x) are exposed to oxygen (O_2) in the air at a certain temperature. In this reaction, the hydrocarbon's chemical bonds are broken, and water vapor (H_2O) and carbon dioxide (CO_2) are produced, as well as a net increase in heat energy.

$$H_xC_x + O_2 = H_2O + CO_2 + Heat$$

The main byproducts of this reaction are water vapor and carbon dioxide. However, there are other potential byproducts, including carbon monoxide, nitrous oxides, sulfur dioxide, and other products, depending on the makeup of the hydrocarbon. Simpler hydrocarbons, such as natural gas and propane, create fewer pollutants, such as sulfur dioxide (the primary component in acid rain) and nitrogen oxides (NO_x). MSW, petroleum products, and coal can produce particulate matter, which is hazardous to human health and is regulated by laws such as the Clean Air Act. However, regardless of whether byproducts are produced, all of these combustion reactions produce carbon dioxide (CO_2) gas.

Although carbon dioxide is the main contributor to GHG emissions, it is not the only one. Methane, the chemical term for natural gas (CH_4), is emitted from petroleum drilling, refining, and distribution, and is also produced in anaerobic digestion in landfills, wastewater treatment, and agricultural waste. When it is combusted, and carbon dioxide is produced, the overall GHG emissions are reduced.

Nitrous oxide (N_2O) and other gases are also greenhouse gases. Many refrigerants, such as R410A (Puron) and R134a, are powerful greenhouse gases and are being phased out in favor of other refrigerants that are less harmful. Care must be taken when working on refrigerant lines so that they are emptied, so the refrigerant is collected and not vented to the atmosphere.

Carbon Intensity and Heating Value:

Different fossil fuels have different carbon intensities. Carbon intensity is the measure of the amount of carbon dioxide emissions per unit of heat energy provided. Also, different fossil fuels have different heating values. The heating value is the amount of heat energy released in combustion per unit of weight or volume. In general, cheaper and dirtier fuels tend to have lower heating value and, as a result, have a higher carbon intensity. These include wood, biomass, coal, petroleum, and petroleum byproducts like fuel oil and gasoline. Natural gas and propane have a low carbon intensity and a higher heating value.

Fuel	**Lower Heating Value (Btu/lb)**	**Carbon Intensity (lbs CO_2 per Million Btu)**
Wood	6,965	213
Anthracite Coal	14,015	228.60
Gasoline	18,659	167.79 (20.86 lb CO_2/gal)
Diesel and Fuel Oil	18,401	163.45 (22.87 lb CO_2/gal)
Natural Gas (CH_4)	20,262	116.65 (11.6 lb CO_2/therm)
Propane (C_3H_8)	19,927	138.63 (12.68 lb CO_2/gal)
Ethanol	11,479	150.5
Municipal Solid Waste (MSW)	Varies	109.98

Sources:

https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html
https://www.eia.gov/environment/emissions/co2_vol_mass.php
https://www.pfpi.net/carbon-emissions/
https://www.epa.gov/sites/default/files/2015-07/documents/emission-factors_2014.pdf

Greenhouse Gas Emissions Reduction:

In general, the simplest way to reduce GHG emissions from combustion is to switch to less carbon-intensive fuels, and the most effective way is to eliminate combustion. Switching to a fuel with lower carbon intensity can reduce emissions, often without changing equipment or operations. For example, if a building that has a direct vent fuel-oil boiler converts to a natural gas-fired boiler of the same heating capacity, for the same amount of heat, it could reduce Scope 1 carbon emissions by approximately 28.7%.

$$\textit{Emissions Reduction} = (1 - (\frac{Carbon\ Intensity\ Nat.Gas}{Carbon\ Intensity\ Fuel\ Oil}))\ x\ 100\% =$$

$$(1 - (\frac{116.65\ lbs\ CO2/MMBtu}{163.45\ lbs\ CO2/MMBtu}))\ x\ 100\% = (1 - 0.713)\ x\ 100\% = 28.7\%\ reduction$$

This premise is similar for Scope 2 Emissions. The overall carbon emissions of the United States have dropped since its peak in the early 2000's, primarily from switching from coal to natural gas as its main fuel for electricity generation. Assuming a coal and natural gas power plant has the same thermal efficiency and the same power capacity, the potential Scope 2 emissions reduction from fuel switching would be:

$$\textit{Emissions Reduction} = (1 - (\frac{Carbon\ Intensity\ Nat.Gas}{Carbon\ Intensity\ Coal}))\ x\ 100\% =$$

$$(1 - (\frac{116.65\ lbs\ CO\ \ /MMBtu}{228.6\ lbs\ CO\ \ /MMBtu}))x\ 100\% = (1 - 0.510)\ x\ 100\% = 49.0\ \%\ reduction$$

Of course, the Scope 2 emissions reduction of switching to carbon-free or renewable energy, such as solar, wind, nuclear, or hydropower, is effectively 100%.

For more information on carbon intensity for Scope 2 GHG Emissions from the North American (US and Canada) electricity from the grid, see the link here:

https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator-calculations-and-references

Concepts:

Here are some helpful concepts to review before moving forward.

Energy Efficiency:

Energy efficiency is an important concept to understand in building decarbonization. Also known as thermal efficiency, it is the measure of the amount of heat energy produced based on the amount of work energy put into the system. However, historically, energy efficiency has often been more focused on cost efficiency, due to economic concerns with increases in electricity prices and volatility in fuel commodity prices. However, the thermal efficiency of most fossil fuel equipment is low, with direct vent equipment having a maximum efficiency of around 80%. Power vent equipment is higher, typically between 90-98%, and condensing boilers can have a maximum efficiency of 96-98%. Quickly, the ability to increase efficiency is "maxed out" without switching away from fossil fuel combustion equipment.

Because the vapor compression cycle transfers heat, it is more efficient and can allow for a thermal efficiency of 300-400%. However, it is typically measured as the *Coefficient of Performance (COP)* of 3 or 4. At temperatures below freezing, heat pumps may require backup heating, either electric resistance or combustion, which can reduce efficiency, but it is still a COP of approximately 2. This is a 250% increase in efficiency from a direct vent furnace. Also, because heat pumps run on electricity, they can also be tied to renewable energy sources and have ... ed or zer ... sions.

Units:

For heat energy in t ... Thermal Unit (Btu). A Btu is a small unit ... ne pound of water by 1° Fahrenheit (de ... heat power, or rate of heat energy tr ... u/hr. The metric (SI) unit for energy is t ... ed in kWh, particularly for electric ... in working with HVAC and heating equi ...

Conversions:

Here is a list of conversio ...

1 MBH = 1,000 Btu ...

1 Boiler Horsepowe ... 33.5 MBH

1 hp = 745 W

1 kW = 1,000 W

1 therm = 100,000 Btu

1 MMBTU = 1 million Btu

1 gal fuel oil = 138,500 Btu

1 kWh = 3,412 Btu

1 kW = 3,412 Btu/hr = 3.412 MBH