

Air Emissions from Residential Heating: The Wood Heating Option Put into Environmental Perspective

James E. Houck and Paul E. Tiegs
OMNI Environmental Services, Inc.
Beaverton, OR

Robert C. McCrillis
Air and Energy Engineering Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC

Carter Keithley and John Crouch
Hearth Products Association
Arlington, VA

Approximately six quadrillion Btus (6.5×10^{18} Joules) of energy were consumed for space heating in 1997 in the United States, representing about \$45 billion in expenditures. There were an estimated 99 million households in the U.S. in 1997, most of which required some form of space heating. The major space heating energy options are natural gas, fuel oil, kerosene, liquefied petroleum gas (LPG), electricity, coal and wood. Each of these residential space heating options has air quality issues associated with it. To accurately compare national or global scale air quality impacts among energy options, emissions from off-site production, processing, and transportation of the energy need to be taken into consideration along with the pollutants emitted locally from individual residences.

Residential wood combustion (RWC) meets 9% of the Nation's space heating energy needs and utilizes a renewable resource. Wood is burned regularly in about 30 million homes. Residential wood combustion is often perceived as environmentally dirty due to elevated emissions of fine particles from older wood burning devices. In response to this emission problem, lower emitting new technology wood heating devices have been developed by industry and the U.S. Environmental Protection Agency requires new stoves to be certified by undergoing emission testing. Only about 11% of the RWC appliance types subject to certification and in use today are either certified or can be considered new technology devices. Other RWC devices, such as fireplaces and furnaces, are not subject to national certification requirements and many that are currently in use are older appliances due to their long usable lifetime. Therefore, most of the existing air quality impacts and the perception of the potential impacts from wood heating are still based on old technology devices.

This paper compares the national scale (rather than local) air quality impacts of the various residential space heating options. Specifically, the relative contributions of the space heating options to fine particulate emissions, greenhouse gas emissions and acid precipitation impacts are compared.

INTRODUCTION

In 1993 all but 0.9 percent (mostly located in Hawaii) of the 96.6 million households in the United States had some form of space heating^{1,2}. Significantly, energy for space heating represents about 8% of the total energy consumed for all purposes, including transportation, in the United States^{2,3}. Considerable ancillary energy beyond the 8% is also needed for the ultimate production of space heat. Notably, this includes energy for such activities as extracting, transporting, processing and distributing fossil fuels. All forms of energy consumption have associated environmental and human health impacts. These include impacts to the ambient air, water, and land media. Terms such as “total environmental costs” (TECs), “environmental externalities,” and “energy return on investment” (EROI) have been introduced to facilitate the assessment of the real environmental and societal costs of energy⁴⁻⁷.

The major energy sources for residential space heating, in descending order of end-use energy consumption, are natural gas, fuel oil, wood, electricity, liquefied petroleum gas (LPG), coal and kerosene (Table 1). Due to electric power-plant inefficiencies and transmission line losses about three times the amount of energy consumed by the residential end user for electrical space heat is needed for its production. Further, in regards to electricity’s use for space heating, it should be noted that electricity is not a primary source of power and it is in turn produced principally by fossil fuel combustion. Table 2 shows the total energy by primary source consumed for residential space heating calculated by adding energy consumed for space heating directly at residences with the energy by source type consumed to produce electricity subsequently used for space heating. Not including the ancillary energy requirements for activities such as extracting, transporting, processing and distributing fuels, about 86% of the energy consumed for residential space heating is from fossil fuels. About 8% is from wood. The remaining 6% is principally from nuclear and hydroelectric sources used to produce electricity.

Among the various categories of environmental and human health impacts, the research reported here was focused on national scale (global) air quality issues. The three topical and national scale air quality issues most relevant to residential space heating are: 1. fine particulate emissions, for their impact on visibility and human health, 2. greenhouse gases, and 3. acid precipitation. (The ozone impact is not relevant to space heating sources even though they produce significant VOC and nitrogen oxide ozone precursors since elevated ozone is primarily a summertime phenomenon.) Total impacts for each of the three national scale air quality categories for each space heating option were calculated by summing the contributions of emissions from off-site activities performed to obtain the subsequent space heating energy with emissions directly from space heating sources in residences. The base year 1993 was used for the comparisons because it was the most recent year for which the extensive data needed for the comparisons were readily available. In conducting the evaluations, special emphasis was placed on putting emissions from RWC into perspective with other options.

THE STATUS OF RESIDENTIAL WOOD COMBUSTION

There are approximately 37 million RWC appliances in the United States (Table 3). These include 9.3 million wood stoves, 27 million fireplaces and about 0.6 million other appliance types^{2,8,9}. (Other appliance types include pellet stoves, masonry heaters and wood-fired furnaces.) About seven million of the 27 million fireplaces are seldom used^{9,10}. Most of the fireplaces that are used are either used as supplemental heating sources or for minor heating or aesthetic purposes¹⁰. Only 0.4 million are used as primary heating sources; most of these are located in the Southeast². Surveys have shown that 7.1 million fireplaces have inserts of which 0.3 million are Environmental Protection Agency (EPA) certified inserts^{9,11}. Of the 9.3 million wood stoves, about one million of them are EPA certified^{9,11}.

The EPA has promulgated New Source Performance Standards (NSPS) for wood heaters which establish threshold particulate emission rates for wood heaters to be certified¹². Since 1992, only certified wood heaters can be sold in the United States. Wood stoves, cordwood fireplace inserts and some pellet stoves/inserts must pass through the EPA certification process. Fireplaces themselves are exempt from EPA certification, however, the state of Washington does have certification requirements for them.

It has been estimated that 28% of the cords of wood burned annually are burned in fireplaces and

72% are burned in wood stoves¹³. Because only about 11% of the wood stoves currently in use are EPA certified, only 4% of the fireplace inserts are EPA certified and only one state now requires new fireplaces to be certified, the majority of wood is currently burned in older technology appliances. Importantly, the perception of RWC as being an especially environmentally “dirty” heat source is based largely on the relatively high fine particulate emissions of the older technology units. Considerable improvements have been made in the environmental performance of RWC appliances in the last decade^{14,15}.

EMISSION FACTORS AND ACTIVITY LEVELS

National emissions of: 1. acid equivalents, 2. fine particles, and, 3. the mass of carbon equivalents of greenhouse gases were obtained from emission factor and activity level compilations^{2,3,16-22}. Each of these three measures of pollutant emissions were normalized by the number of quads of energy delivered nationally for residential space heating by energy source. The final units for comparisons of acid precipitation, fine particulate and greenhouse gas impacts were billion acid equivalents per quad, thousand short tons of particles per quad and million short tons of carbon equivalents of greenhouse gases per quad, respectively.

The overall in-home effectiveness of heating appliances was not taken into consideration in normalizing the air pollutant emissions per unit of energy for the various categories because its effect will be small as compared to many of the other factors evaluated. The overall effectiveness of appliance types is influenced by the inherent efficiency of the appliance type, by usage characteristics and by siting practices. Siting refers to the location of the appliance in the home, e.g., next to an exterior wall versus the center of the home. Usage characteristics refer to such factors as the unused energy waste associated with convenient and/or furnace type appliances heating an entire home, even when all or part of it is not occupied. When all these factors are considered, industry experts agree, that the overall effectiveness differences in home heating options is small.

The sequence of linked activities which connect the supply of a specific energy resource with a specific end use has been referred to as the energy trajectory. For example, for coal, the energy trajectory to the residential space heating end use consists of: 1. extraction (surface or underground mining), 2. transportation from the mine to the processing plant (trucking, conveyor or mine rail), processing (cleaning, sulfur removal, crushing, sizing and drying), storage (above- and underground piles, silos or bins) and distribution (unit train, mixed train, river barge, pipeline slurry, trucking and/or conveyors) to a coal-fired power plant or to a residential heating unit. If the coal is delivered to a coal-fired power plant for power generation two additional components of the energy trajectory are the actual power generation process and the transmission of the power produced to the electric home heater. Not only do emission factors and activity levels for each pollutant need to be determined for each step and finally summed to obtain an overall emission value, but the efficiency of each step must also be estimated since most emission factors are based on a mass of pollutant emitted per unit of energy or quantity of fuel at that step in the trajectory. Successive efficiency losses with each step of the trajectory have the effect of causing more energy or energy equivalents to pass through the initial stages of the trajectory with a commensurate increase in the total air emissions.

Natural gas and petroleum have similar trajectories as coal (i.e., extraction, transportation to processing facilities, processing, and transportation to a power plant or residential heating unit). The petroleum trajectory is complex since production and processing of LPG, kerosene, distillate oil and residual oil are interrelated.

The energy trajectory for wood to residential home heating is quite different and simpler than for fossil fuels. Emissions from the actual home heating combustion step dominate the overall emission values for its energy trajectory. The energy return on investment (EROI) for a commercial wood chipping operation was determined to be 27.6 to 1 (i.e., one unit of fossil fuel was required to produce 27.6 units of energy from wood)⁶. The largest fraction of this was the fossil fuel needed for a 240 km round trip for fuel pick-up. In the same study it was concluded that the typical EROI for cordwood harvesting and transport would be even higher.

GREENHOUSE GASES

Carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) are the principal greenhouse gases from energy sources. The capacity of methane and nitrous oxide to trap heat and their lifetime in the atmosphere produce a global warming potential (GWP) of 21 and 310, respectively, as compared to carbon dioxide which has a GWP of 1¹⁹. The standard convention for reporting total greenhouse gas effects is to multiply the emissions of methane and nitrous oxide by 21 and 310, respectively, then add these values to the carbon dioxide value. The effective carbon dioxide value produced by summing the contributions of the various greenhouse gases adjusted to carbon dioxide by the GWP is then converted to a carbon equivalent. This simply means that the value is multiplied by the ratio of 12/44 which converts the mass of greenhouse gas to the mass of carbon that would be in the greenhouse gases if they were all carbon dioxide.

In reviewing the relative contributions of carbon dioxide, methane and nitrous oxide to the greenhouse effect, it was discovered that carbon dioxide from combustion dominates the impact for all energy sources used for home heating. Among the energy sources, the relative greenhouse contribution of methane is the highest for natural gas for which it represents 11% of its total greenhouse effect. This is reasonable when the facts that natural gas is composed primarily of methane and that considerable natural gas losses occur in the extraction, transport and processing of natural gas are taken into consideration. For both electricity and direct coal heating, methane accounts for about 4% of the greenhouse impact. The contribution of methane to the greenhouse impact is less than a percent for all other home heating energy sources. The contribution of nitrous oxide to the greenhouse impact is less than a percent for all energy sources used for home heating. The emissions of carbon monoxide (CO), nitrogen oxides (NO_x) and nonmethane volatile organic compounds (NMVOCs) were reviewed since they can indirectly impact concentrations of greenhouse gases. It was concluded, based on their emission factors and their atmospheric fate, that their contributions would be small.

The total carbon dioxide emissions from RWC were reduced by 40% in the final tabulations because the harvesting of more mature trees for cordwood permits rapid carbon fixation in younger replacement trees. While carefully managed wood fuel plantations could achieve a nearly “greenhouse gas neutral” condition, a reasonable estimate of the steady state condition produced by standard wood harvesting practices is that 40% of the carbon emitted by RWC is in the form of fixed carbon^{6,23}.

The results of the greenhouse gas analysis are illustrated in Figure 1. Residential wood combustion has the lowest effective greenhouse impact per unit of energy delivered followed by natural gas. Electricity has the highest greenhouse impact, with the direct use of coal and petroleum being intermediate in impacts. It is reasonable that electricity has a higher impact than either coal or petroleum burned directly in home heating appliances since 1.22 quads of energy were consumed by electric power generating units in 1993 to produce only 0.41 quads delivered to residences for home heating and since coal and petroleum together account for 64% of the electrical energy generated.

FINE PARTICLES

Atmospheric fine particles originate from two processes, i.e., from the direct emissions of particles (primary particles) and from the transformation of emitted gases once they are in the atmosphere (secondary particles). The principal sources of secondary particles are the formation of ammonium sulfate from sulfur dioxide (SO₂) gas and the formation of ammonium nitrate from nitrogen oxide (NO_x) gases. Consequently, the emissions of primary particles as well as sulfur dioxide and nitrogen oxides were evaluated to estimate the effective fine particulate impacts of the various home heating options.

Sulfur dioxide gas is produced by combustion and is directly related to the sulfur content of the fuel. Sulfur dioxide is also released in the energy trajectory of fossil fuels during desulfurization steps. Nitrogen oxide gases are produced by combustion, both from nitrogen contained in the fuels and from the oxidation of atmospheric nitrogen at high temperatures. It is estimated that about 30% of sulfur dioxide gas is converted to secondary particles²⁴. The fraction of nitrogen oxide gases converted to ammonium nitrate can be estimated by comparing national emission inventories and typical national particulate nitrate

concentrations^{18,25}. The value for the conversion of nitrogen oxide gases to ammonium nitrate particles is about 7.4%.

Besides secondary particles produced from SO₂ and NO_x gases, secondary particles can also be formed from nonmethane volatile organic compounds (NMVOC); however, the effect appears to be small relative to secondary particles formed from SO₂ and NO_x gases²⁶. Further, for sources such as RWC, that have particles composed of a high percentage of organic compounds, there appears to be a net loss of organic material from particles due to volatilization²⁷.

PM₁₀ emission inventories were used to estimate primary fine (PM_{2.5}) particulate emissions since the majority of PM₁₀ particles formed from combustion are also PM_{2.5} particles. (The fugitive PM_{2.5} emissions from coal mining were estimated to make up 10% of the PM₁₀ emissions.) Secondary particles are overwhelmingly PM_{2.5} particles and secondary particulate contributions were added directly to the primary particulate values to obtain an effective fine particulate impact per unit of heat delivered for residential heating. Before addition, sulfur dioxide and nitrogen oxides emissions (as nitrogen dioxide) were multiplied by 0.30 and 0.074, respectively, to obtain an estimate of the amount of secondary particles that they would produce.

For all sources, except RWC, secondary particles make up the majority of the total effective fine particulate values. Except for natural gas, secondary ammonium sulfate alone makes up between 65% to 90% of the values of these sources. In the case of natural gas, secondary ammonium nitrate accounts for 72% of the effective fine particulate value and secondary ammonium sulfate accounts for 22%. Primary particles formed by combustion make up 98% of the effective particulate value for RWC.

The results of the fine particulate analysis are illustrated in Figure 2. As can be seen, natural gas has the lowest effective fine particulate emissions per unit of heat delivered for residential heating, followed by LPG. Residential wood combustion has the highest value. The direct use of coal and electricity also show high values with fuel oil and kerosene intermediate in values. It should be noted that the emission factors for RWC used in this analysis primarily reflected old technology wood heaters and that a 50% reduction in the value shown in Figure 2 is reasonably achievable with new technology devices^{14,15}. It should also be noted that a reduction in particulate emissions by 50% or more makes RWC comparable to electricity in terms of effective fine particulate emissions. The projected fine particulate emissions from using new technology wood burning appliances are shown in Figure 2 above the caption "new wood". This projection includes the weighted effect of replacing both old technology wood stoves and using advanced fireplaces designs and/or using manufactured fuels in fireplaces. As with wood stoves, new technology coal stoves should reduce particulate emissions below that shown in Figure 2 since many coal appliances in use are older units. However, there are no data to estimate the magnitude of this expected reduction in emissions for coal-fired heaters. Also, in regards to residential coal use, higher quality fuel, i.e., anthracite, will reduce particulate and acid gas emissions if utilized more widely in home heating units.

ACID PRECIPITATION

Emissions of nitrogen oxides and sulfur dioxide gases forming nitric acid (HNO₃) and sulfuric acid (H₂SO₄) are the primary causes of acid precipitation. Both HNO₃ and H₂SO₄ are strong mineral acids with H₂SO₄ producing two equivalents of acid per mol e (two H⁺ ions per molecule). Weak organic acids (carboxylic acids) are also emitted into the atmosphere particularly from combustion sources such as RWC²⁸, but their impact on acid precipitation is very small²⁶. Interestingly, organic acids in the presence of strong mineral acids tends to raise the pH (lessen the acidity) due to their buffering capacity.

Acid equivalents emitted per unit of energy delivered for residential heating were calculated to compare acid impacts among the energy sources. While emissions of both NO_x and SO₂ contribute to acid impacts, it is interesting to note that the contribution from NO_x was about an order of magnitude higher than SO₂ for natural gas and the reverse was true for coal directly burned in coal heaters. For all other energy sources the contributions of NO_x and SO₂ to acid impacts were within a factor of ten of each other. Similarly, while all steps in the energy trajectory contributed to acidic impacts, the combustion step (as compared to extraction, processing and transportation steps) dominated the impact

for the electricity, wood and coal sources. For petroleum and natural gas sources the combustion step contributions were within the same order of magnitude as the combined preparatory steps.

The results of the acid impact analysis are illustrated in Figure 3. Wood combustion has the lowest acid impact per unit of energy, followed by natural gas and LPG. Coal has the highest value and electricity the second highest. (Coal combustion accounts for about 56% of the energy consumed in electric power generation.) The acidic impacts per unit of heat delivered from fuel oil and kerosene are intermediate with kerosene being lower than fuel oil primarily due the fact that there is less sulfur in kerosene than in number 2 distillate fuel oil.

CONCLUSIONS

- When the contributions of all the components of energy production for residential space heating and the atmospheric fate of pollutants are taken into consideration, wood combustion has the lowest greenhouse gas and acid precipitation impacts per unit of heat delivered among the energy options. Its fine particulate impact based on existing wood burning appliances was the highest among the options.
- The direct in-home use of natural gas has the lowest fine particulate impact per unit of heat delivered. While not as low as RWC, natural gas also has low greenhouse gas and acid precipitation impacts.
- Average reductions in fine particulate values greater than 50% can be achieved with new wood burning appliances.
- In regards to national or global scale air quality impacts, residential wood heating with new technology appliances and the direct use of natural gas are the most sound environmental options.

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Table 1. Energy consumed by source for residential space heating in the United States

	electricity	natural gas	fuel oil	kerosene	LPG ¹	wood	coal
households (x 10 ⁶) ²	37.1	52.6	10.7	3.6	5.6	20.4	0.2
total energy consumed	119 billion KWH	3570 billion cubic feet	6.51 billion gallons	0.34 billion gallons	3.25 billion gallons	27.4 million cords	3 million short tons
total energy consumed in quads ³	0.41 (1.22) ⁴	3.67	0.90	0.05	0.30	0.55	0.06
percent of total	6.9	61.8	15.1	0.8	5.1	9.2	1.0

1. LPG is the abbreviation for liquefied petroleum gas.

2. Many households have more than one source of heat therefore the sum of households by heat source exceeds the total number of U.S. households (96.6 million in 1993).

3. One quad is one quadrillion Btu (Btu x 10¹⁵).

4. The 1.22 quad value in parenthesis is the energy consumed by power plants to produce the 0.41 quads of electricity consumed in residences for space heating.

Information shown in the table were calculated from data in references 2 and 3.

Table 2. Energy consumed by primary source for residential space heating in the United States¹

	coal	natural gas	petroleum ²	wood	nuclear	other ³
total energy consumed in quads	0.62	3.78	1.29	0.55	0.26	0.13
percent of total	9.5	57.0	19.4	8.3	3.9	2.0

1. The energy consumed by primary source was calculated by summing the energy in fuel burned directly in the households with the energy used by category (i.e., coal, petroleum, nuclear, etc.) to produce the 1.22 quads of energy needed to produce 0.41 quads of electricity used for residential space heating.

2. The petroleum category includes heavy and light oils (also referred to as residual and distillate oils), kerosene, LPG and petroleum coke.

3. Hydroelectricity makes up the majority of the "other" category.

Information shown in the table were calculated from data in references 2 and 3.

Table 3. Residential wood combustion appliances in the United States

appliance type	appx. number in use (millions)
wood stoves	9.3
EPA certified non-catalytic stoves	0.6
EPA certified catalytic stoves	0.4
non-certified older stoves	8.3
fireplaces¹	27
masonry (site built)	5
factory built ²	22
other appliance types	<0.6
pellet stoves ³	0.3
masonry heaters	negligible
wood-fired furnaces	<0.3

1. Owners of about 7.0 million fireplaces reported not burning wood in them in the previous 12 month period. Of the 27 million fireplaces appx. 7.1 million have inserts of which 0.5 million are EPA certified inserts.
2. Factory built fireplaces are also commonly referred to as “zero-clearance” fireplaces.
3. The pellet stove category includes both EPA certified units and those that are exempt from certification requirements.

Figure 1. Carbon equivalents of greenhouse gases per quad of heat delivered

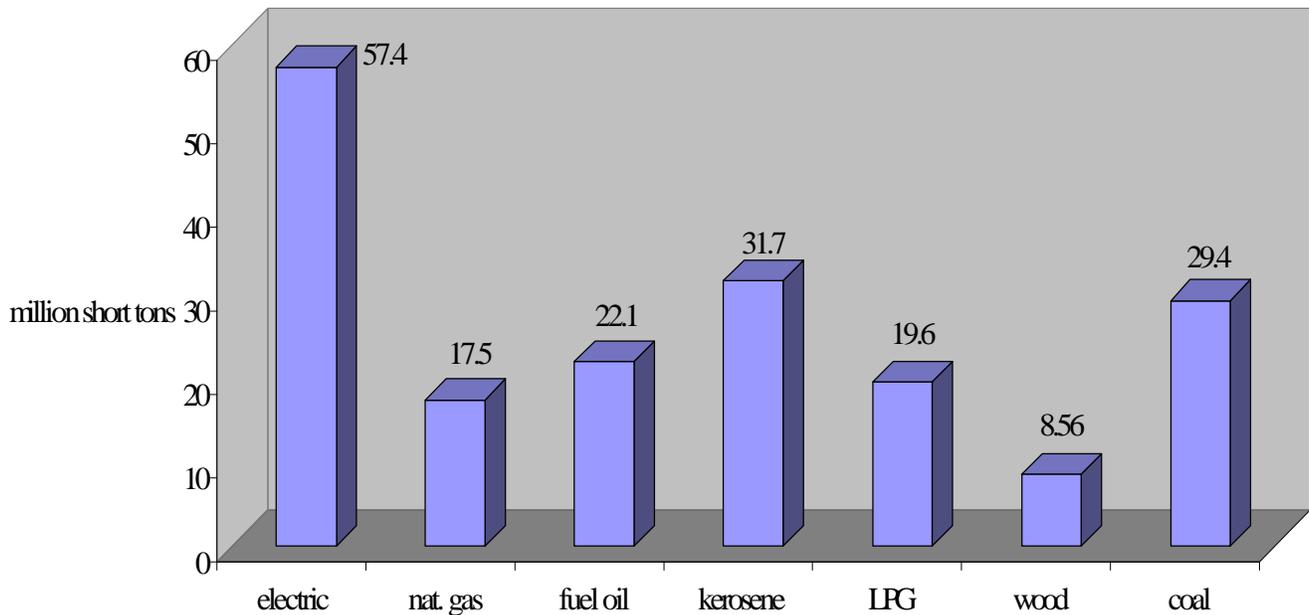


Figure 2. Effective fine particulate emissions per quad of heat delivered

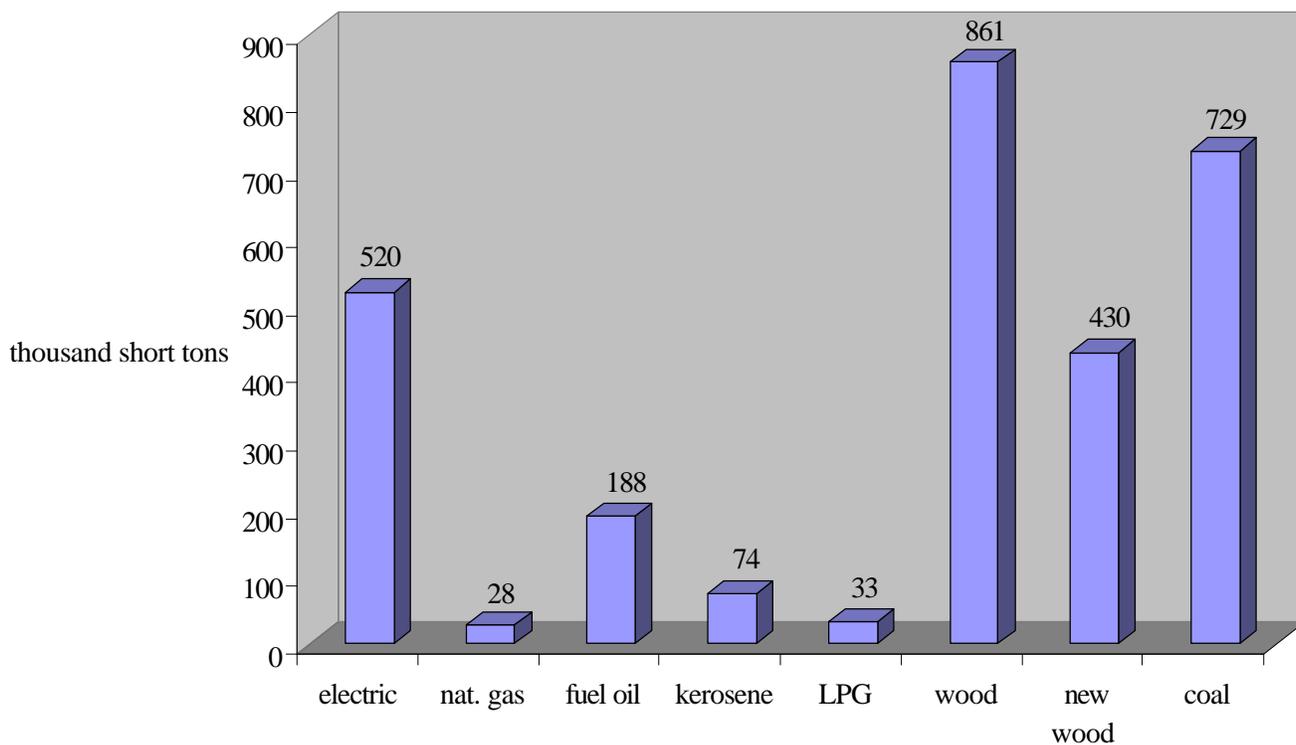


Figure 3. Acid equivalents emitted per quad of heat delivered

