Life Cycle Impacts of Heating with Wood in Scenarios Ranging from Home and Institutional Heating to Community Scale District Heating Systems

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Introduction

Change often introduces uncertainty, and this is certainly the case when considering changes in the source of energy used to power our homes and community. Questions about cost, reliability, safety, esthetics, and impacts to the local environment and beyond quickly arise in discussions about something as basic as energy supply.

This section of the report focuses on published studies of life cycle and at-combustion-site impacts of wood energy systems and comparisons of impacts to more traditional systems, such as those powered by natural gas, heating oil, and propane. Energy systems examined include individual home heating systems, larger systems for institutional heating, small and medium scale district heating systems, and combined heat and power (CHP) systems. Some of the studies cited herein have examined full life cycle impacts (in life-cycle lingo "cradle to grave") of various energy systems, while others were limited to evaluation of impacts linked to energy resource extraction, transportation, combustion, and disposal (if any) of ash and other combustion residues.

Findings of various studies are reported, with emphasis on energy efficiency, combustion emissions and air quality, and general environmental impacts. Information is then interpreted in the context of specific options under consideration in Cook County (Grand Marais) and Ely, Minnesota.

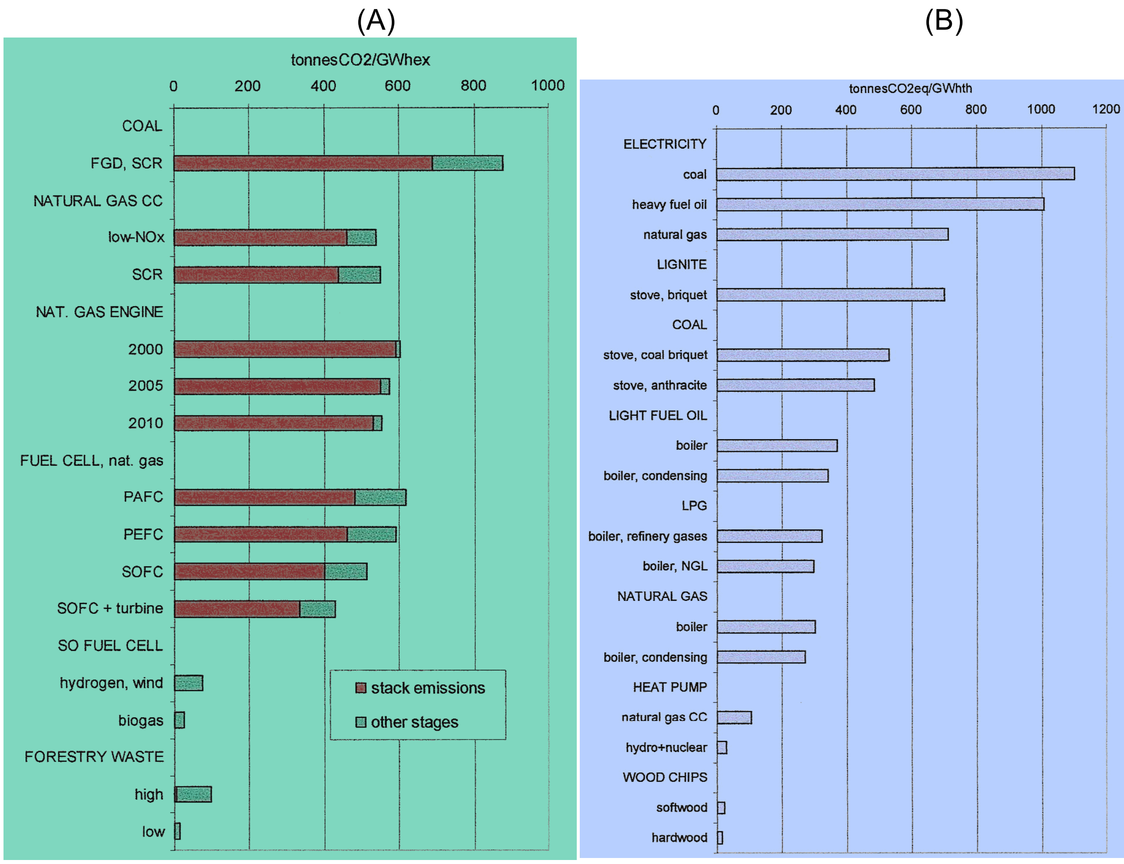
Life Cycle Impacts of Wood Energy

Full life cycle analyses consider all aspects of energy systems – including the manufacture and installation of combustion and distribution equipment, mining, extraction and transport of energy raw materials, energy production, disposal of ash, and end of life issues. Such analyses provide insights into total impacts of consumption choices that are otherwise elusive.

Wood Energy and Carbon

The World Energy Council (2004) conducted an extensive life cycle analysis of various forms of energy, including transportation fuels, electricity, and energy used for heating. All analyses considered the whole production chain, from exploration and extraction, processing and storage to transport, transformation into secondary fuels and final use, but did not consider installation of energy producing equipment. One measure of comparison was production of greenhouse gases (GHG), expressed as carbon dioxide equivalents (CO_2e). Figure 1(A) compares emissions of fuel cycle systems with combined heat and power (CHP) production. In this figure, emission values are per GWh of exergy produced, with exergy defined as a measure of how large a part of a quantity of energy can be converted into mechanical work. Figure 1 (B) is a summary of greenhouse gas emissions from alternative space heating systems, including those producing heat by stoves burning coal products and by boilers burning light fuel oil, natural gas, liquefied petroleum gas or wood chips.

Figure 1
Summary of Greenhouse Gas Emissions for Fuel Cycles with Combined Heat and Power (CHP) Production (A), and for Alternative Space Heating Systems (B)



Source: World Energy Council (2004)

In both Figures 1 (A) and (B) energy generated from wood results in very low greenhouse gas emissions compared to alternatives. For CHP systems, emissions are lowest for wood in the highest efficiency scenario, and behind only wind, hydrogen, and biogas systems in the lowest efficiency scenario. Comparing space heating systems, GHG emissions were found to be lowest for wood among all systems examined.

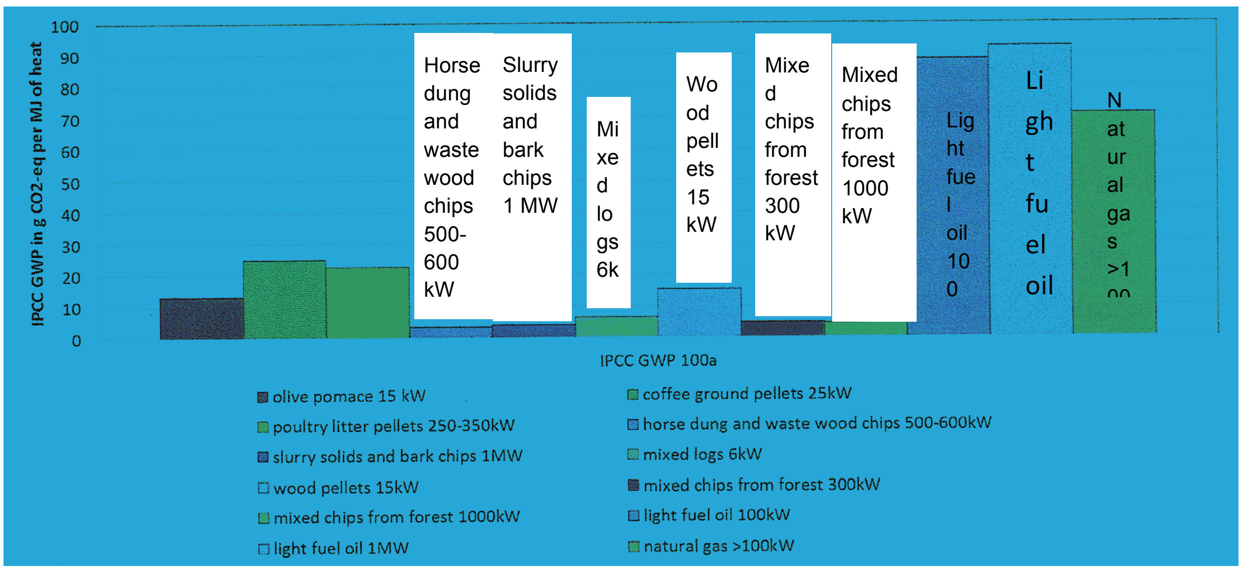
These comparisons are based on an assumption that energy production from wood is carbon neutral, an assumption based on the premise that forests from which energy wood is harvested are adding wood volume more rapidly than the rate of wood removal. [1]Wood fuels are typically sourced locally, are renewable, and their combustion releases carbon captured in the relatively recent past by plants as part of the global carbon cycle (biogenic carbon) rather than carbon that has been released from carbon stored millions of years ago (fossil carbon). When the use of fossil fuels is avoided, the geologic storage of carbon is preserved and new additions of carbon to the carbon cycle are

[1] Annual growth of all of the forest species of northern and northeastern Minnesota far exceeds annual removals, with the exception of jack pine (Minnesota DNR 2011).

prevented. For these reasons, carbon released from wood combustion is typically not considered in life cycle assessments of wood energy.

Another recent study (Itten et al. 2011) examined environmental impacts over the full life cycle for a number of biomass fuels. Global warming potential (GWP)[2] of several forms of wood fuels and other biomass fuels were compared to light fuel oil and to natural gas (Figure 2); in general, GWP for the wood fuels studied was only 5-7 percent that of fossil fuels. The GWP of wood pellet fuels was found to be considerably higher than for other forms of wood fuels, but nonetheless only 15-20 percent of the GWP of fossil fuels.

Figure 2
Global Warming Potential for the Generation of 1 MJ of Useful Heating for Various Fuels



Source: Itten et al. (2011).

Gustavsson and Karlsson (2001) found larger carbon emissions differences between wood fuels and fossil fuels. They examined emissions from various heating systems and fuel types, reporting emissions in each stage of the energy system (Table 1). They found carbon emissions from wood fuels to be only 1-6 percent of emissions from oil and 1-9 percent of emissions from natural gas. They also found CO_2 emissions from pellet fuels to be over 7 times greater than for unprocessed wood.

[2] Global warming potential (GWP) is a measure of the potential for releases to air to contribute to warming of the atmosphere through trapping of heat. A number of compounds are known to have heat trapping properties, with considerable differences in the various compounds. The compound best known for having the potential to warm the atmosphere is carbon dioxide (CO_2). Other compounds (and their heat trapping potential compared to CO_2) include methane (which has a warming potential 23X greater than CO_2), nitrous oxide (300X greater), hydrofluorocarbons (120-12,000X greater), chlorofluorocarbons (5,700-11,900X greater), and sulfur hexafluoride (22,000X greater). GWP is calculated by determining releases of these various compounds and weighting these values by their warming potential relative to carbon dioxide.

Table 1

Emissions of CO_2 (kg) From Various Stages of Energy Systems When Producing 1MW

	System				
	Wood boiler	Pellet boiler[b]		Oil boiler	Natural gas boiler
Production of fuel	0.039	4.4	(3.9)	4.2	3.7
Transport of chips/			(0.56)		
Distribution of natural gas	0.50	0.63		0.14	5.9×10^{-4}
Processing of fuel	0.0057	0.23	(0.23)	–	–
Transport of pellets	–	0.46	(0.46)	–	–
End-use conversion	0.27	0.50	(0.57)	94	69
Total	0.81	6.3	(5.7)	98	73

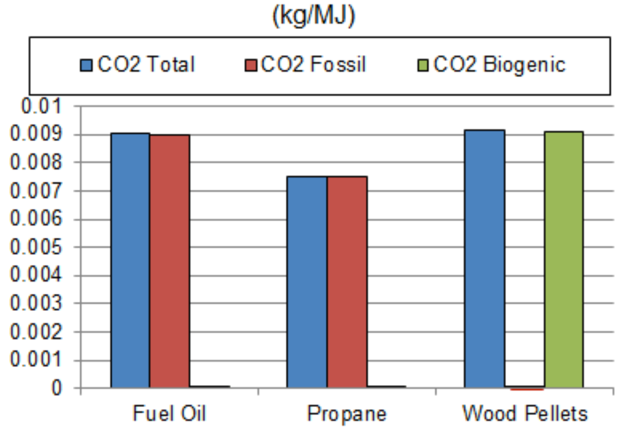
Source: Gustavsson and Karlsson (2001).

Pa (2010) used a life cycle approach to determine emission factors for various heating appliances, including upstream emissions linked to extraction/production of combustion fuels, relying in part on studies of others (Johansson et al. (2004), Swiss Centre for Life Cycle Inventories (2008), USEPA (1995). Fossil CO_2e emissions were again found to be far lower than for alternatives (fuel oil and propane), but in this study all carbon dioxide emissions were reported. Findings indicate that total CO_2 emissions to air are actually higher for wood fuels than for fuel oil or propane (Figure 3), with carbon emissions from wood combustion almost entirely biogenic (i.e. from a renewable source). As noted earlier, wood combustion in energy production is considered to be carbon neutral when forests from which energy wood is harvested are adding wood volume more rapidly than the rate of wood removal.

Figure 3

CO_2 Emissions from Home Heating Using Various Devices

(kg/MJ)

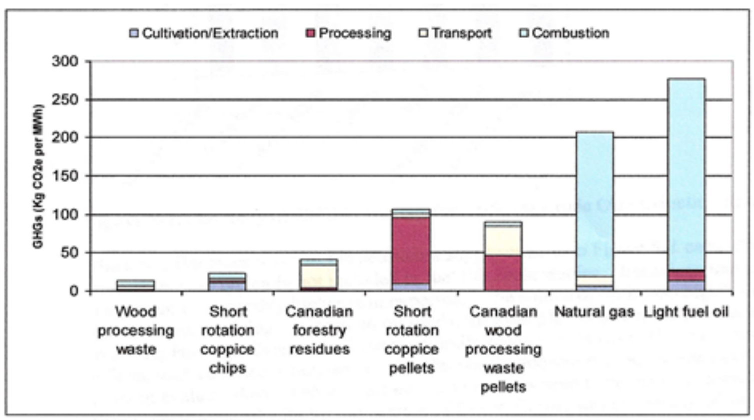


Source: Pa (2010), USEPA (1995).

A study in the UK examined emissions from home heating using various fuels. Emissions differences over the full fuel life cycle, between home heating using wood processing wastes, chips and pellets from dedicated short rotation woody energy crops, natural gas, and light fuel oil are shown in Figure 4. They study included consideration of imported Canadian wood. The large differences shown in Figure 4 in GHG emissions between the two fossil fuels – natural gas and fuel oil – and the various wood fuels is consistent with the previous discussion. It is interesting to note that processing emissions for short rotation wood pellets account for the greatest GHG impact of that fuel type.

The fact that something other than combustion emissions account for the greatest GHG impact is unusual. Most studies show the vast majority of environmental impacts to be linked to combustion emissions. Impacts linked to equipment manufacture are relatively greater with small scale systems than with systems of larger scale and in systems that are intermittently operated. An example of this was provided by a study done in the UK by McManus (2010) who investigated impacts of wood-fueled district heating systems in three case studies:

Figure 4
GHG Life Cycle Emissions from Production and Consumption of Various Fuels



Source: Bates and Henry (2009).

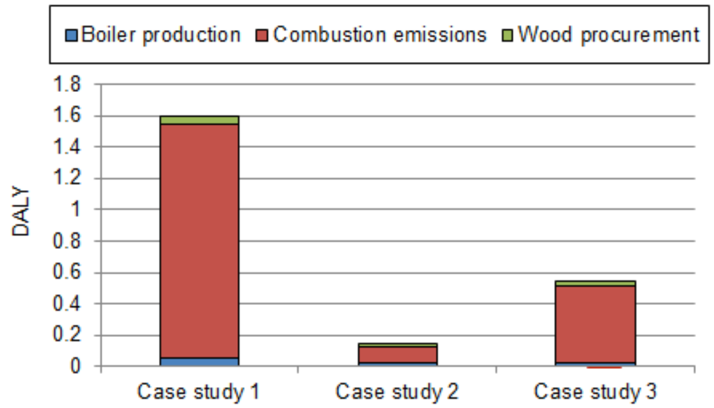
Case study one – 1.2-1.7 mm Btu/hour (350-500 kW or 1256-1800 MJ)

Case study two – 0.26-0.50 mm Btu/hour (76-149 kW or 274-538 MJ); this system was run only occasionally.

Case study three – 0.61-0.68 mm Btu/hour (180-200 kW or 644-717 MJ)

Included within the scope of the investigation were energy use in manufacturing boilers and the heat distribution systems, energy use in wood collection and transportation, and environmental impacts linked to production of energy. As shown in Figure 5, environmental impacts were found to be heavily defined by emissions of respiratory inorganics resulting from biomass combustion; impacts are expressed as “Disability Adjusted Life Years” (DALY), a commonly used metric in the European Union for impacts to human health of emissions to air.

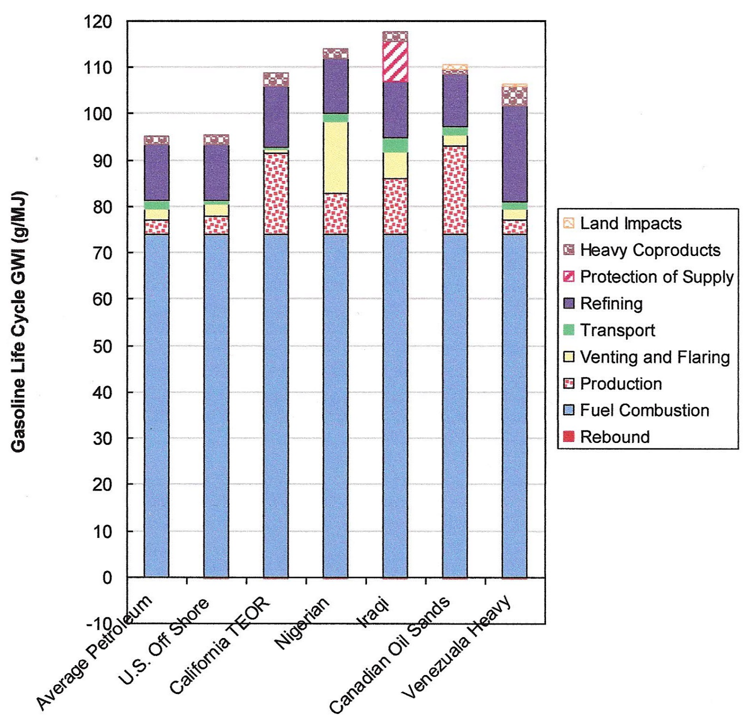
Figure 5
Impacts of Life Cycle Emissions for Three District Heating Systems



Source: McManus (2010).

Combustion emissions likewise dominate life cycle emissions associated with fossil fuels, although in comparison to biomass fuels, a greater proportion of emissions occur "upstream" of combustion. Unnasch et al. (2009), in examining petroleum used in the U.S. and obtained from various sources, found 23-35% of greenhouse gas (GHG) emissions to be linked to activities other than energy generation (Figure 6).

Figure 6
Summary of GHG Emissions for Different Crude Oil Production Scenarios

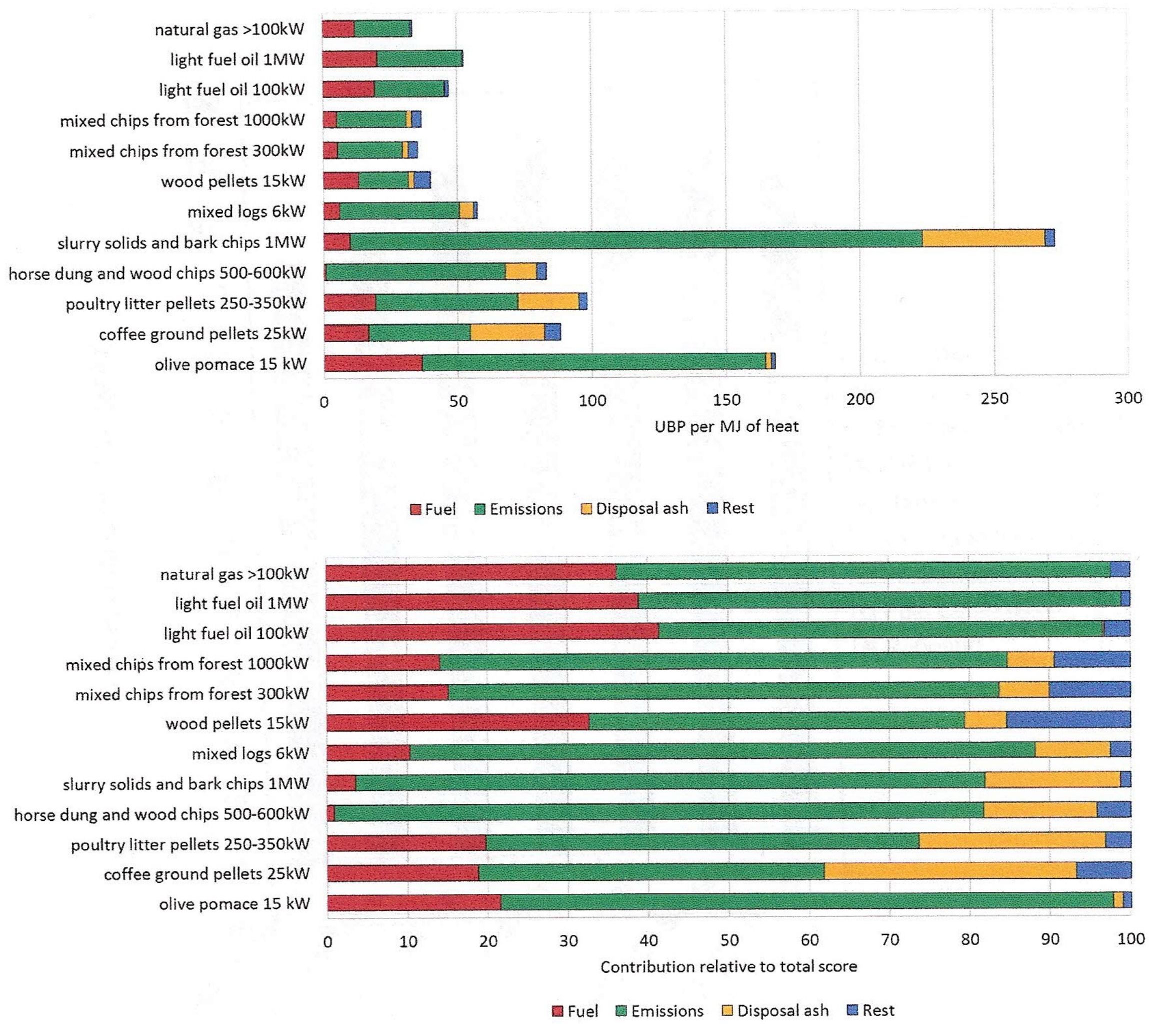


Source: Unnasch (2009).

Upstream emissions of GHG in electricity production from natural gas have been found to approximate 18% of total emissions (Meier 2002), while non-combustion emissions of SO_x and NO_x have been determined to be as high as 25 to 45 percent for natural gas (Jaramillo 2007).

Itten et al. (2011) documented emissions for different fuels, reporting releases in fuel production, combustion, ash disposal, and other activities. Combustion emissions were found to be dominant for all fuels (Figure 7).

Figure 7
Emissions by Stage of Fuel Cycle per MJ of Heat Generated Using the Ecological Scarcity (UBP) Method
(Top graphic shows emissions by fuel. Bottom graphic shows percentage of emissions attributable to each stage in the fuel cycle for each fuel)



Source: Itten et al. (2011).

Because emissions are mostly associated with combustion, the majority of life cycle impacts occur in the local area where fuels are converted to heat or other form of energy. However, those fuels that generate considerable emissions in the course of collection/ extraction, processing, or transport – such as short rotation pellets depicted in Figure 7 – local impacts are moderated by the fact that a significant portion of emissions occur elsewhere in the supply chain.

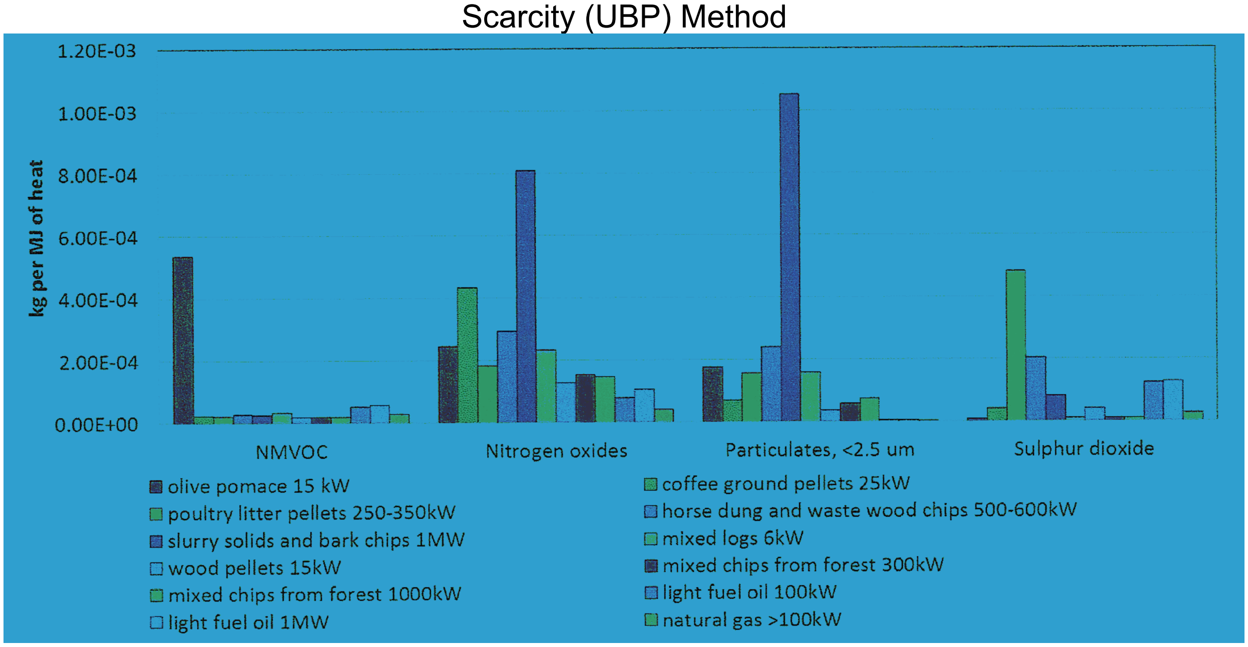
Overall Environmental Impacts

<u>Comparisons of Fuel Types</u>

Wood combustion yields a variety of compounds. In addition to carbon dioxide and nitrous oxide, primary emissions of wood combustion include carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x), methane (CH_4), non-methane volatile organic compounds (NMVOC), ammonia (NH_2), particulate matter (PM), and trace elements of heavy metals, and dioxins and furans (Van Loo and Koppegan 2008). Wood combustion also releases polyacrylic aromatic hydrocarbons (PAH).

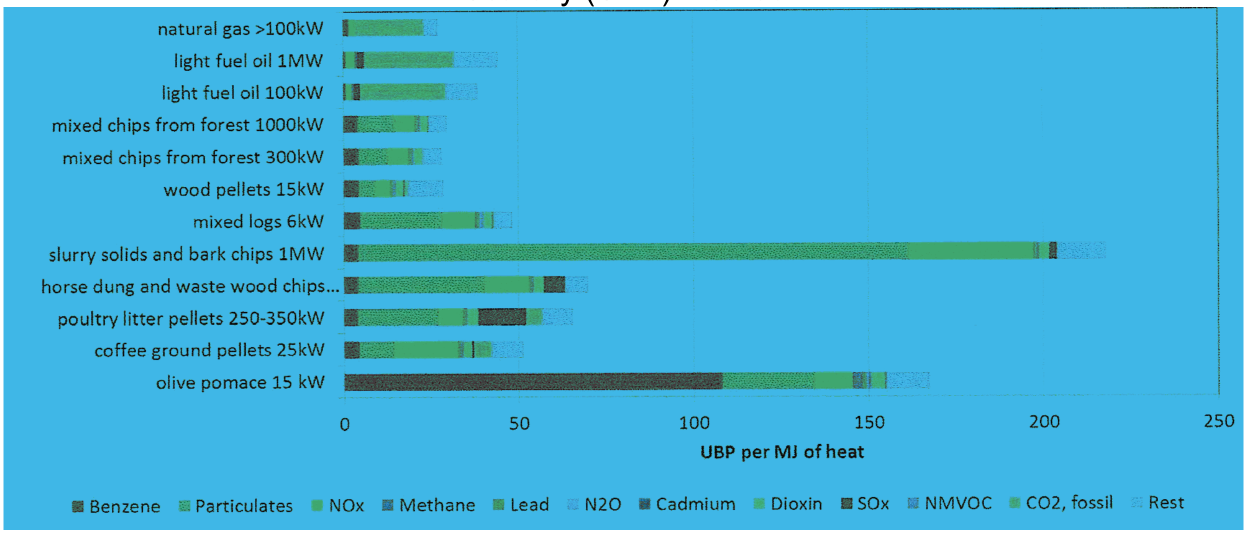
The Itten team (2011) documented releases of such compounds for the fuels referenced earlier (Figures 8 and 9). Results show wood fuels to be associated with somewhat higher emissions of NO_x, and much higher emissions of particulates (PM) than fossil fuels. PM emissions are a particular problem for woody fuels, with emissions far greater than for traditional fuels (Figures 8-10). It is this reality that underlies the observation by Ghafghazi et al. (2011b) that concerns with wood combustion for community energy generation in populated areas are mostly related to particulates found in the flue gas. Carbon monoxide emissions also tend to be higher in combustion of wood fuels than for fossil fuels as do emissions of NMVOC, polychlorinated dibenzodioxins/dibenzofurans (PCDD/F), benzene and PAH (Minnesota EPA 2009).

Figure 8
Emissions of Selected Compounds per MJ of Heat Generated Using the Ecological Scarcity (UBP) Method



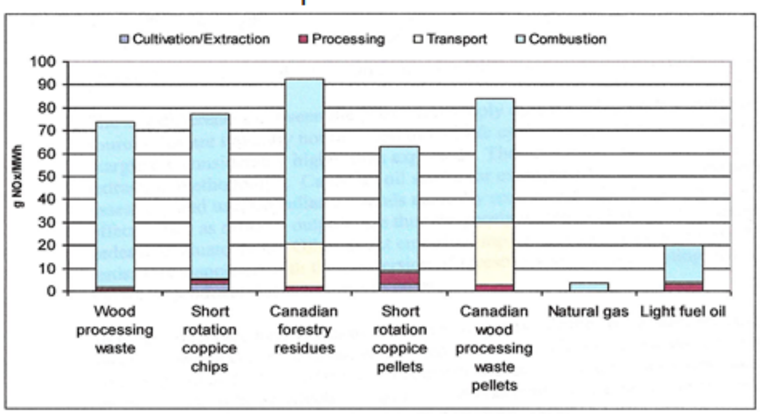
Source: Itten et al. (2011).

Figure 9
Emissions of Various Compounds per MJ of Heat Generated Using the Ecological Scarcity (UBP) Method



Source: Itten et al. (2011).

Figure 10
PM_{10} Life Cycle Emissions from Production and Consumption of Various Fuels



Source: Bates and Henry (2009).

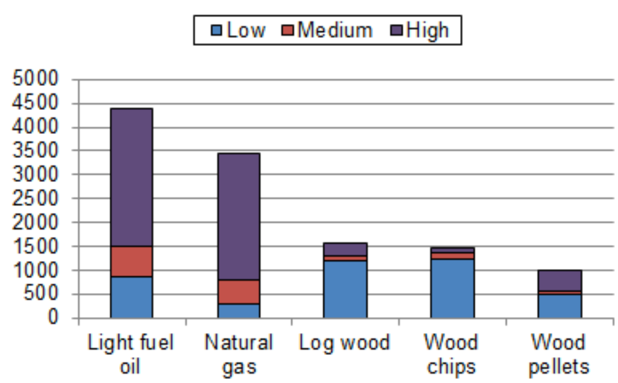
A summary of some of the environmental tradeoffs associated with replacing fossil fuels with wood fuels was developed by the government of Scotland (2006). As shown in Table 2, wood always fares better than coal, but represents the high impact option in quite a few categories.

Table 2
General Effects of Replacing Fossil Fuel by Modern Biomass Combustion Technologies

Pollutant	Advantage '+' or disadvantage '-' from change to modern biomass technology (wood) from fossil fuel		
	Gas	Oil	Coal
SO_2	--	++	+++
NO_X	-	-	+
$PM/PM_{10}/PM_{2.5}$	---	--	+
CO	-	-	+
nmVOC	-	-	+
Trace elements	--	+	+
PAH	--	-	+
PCDD/F	--	-	+

Attempting to sort out the overall impact of a given fuel can be challenging given the myriad of measures arising from thorough assessment. For instance, the fact that wood as an energy source has a substantial advantage over other sources of energy with regard to carbon emissions, but disadvantages in a number of other areas, led Kessler (2000) and Nussbaumer (2008) to the conclusion that the high environmental value of wood as an alternative fuel depends upon assignment of high importance on the greenhouse effect and global warming potential; in their view, placement of low importance on GWP would result in much lower life cycle environmental impact for fuels such as light fuel oil and natural gas (expressed as environmental impact points, where lower totals equal lower impact) (Figure 11).

Figure 11
Environmental Impact Points (EIP) for Different Valuations of the Greenhouse Effect



Source: Nussbaumer (2008).

Maraver et al. (2010) took assessment of environmental impacts of various fuels a step further than many, using several four different European life cycle evaluation methodologies to obtain weighted results for a wide range of measures in an evaluation of fuel pellets made of pine, brassica (an energy crop), coal, diesel, and natural gas. Weighted results in all categories (Tables 3-6) show the lowest impacts to be associated with wood pellets.

Table 3
LCA Final Results Using the Ecological Scarcity Method (2006) for 1) Pine Pellets, 2) Brassica Pellets, 3) Coal, 4) Diesel, and 5) Natural Gas

Impact Category	1)	2)	3)	4)	5)
Emission into air	22470	38573	79306	55006	36728
Emission into surface water	2070	3257	1540	8404	4632
Emission into ground water	3	4	4	1	1
Emission into top soil	451	586	24	28	9
Energy resources	575	945	9772	9327	14923
Natural resources	249	353	628	188	78
Deposited waste	454	749	1227	1314	536
TOTAL	26272	44466	92500	74269	56907

Source: Maraver (2010).

Table 4
LCA Final Results Using the EDIP Method (2003) for 1) Pine Pellets, 2) Brassica Pellets, 3) Coal, 4) Diesel, and 5) Natural Gas

Impact Category	1)	2)	3)	4)	5)
Global warming 100a	2.23	6.01	16.69	13.24	11.94
Ozone depletion	3.12	2.96	0.59	15.04	10.29
Ozone formation (Vegetation)	3.60	5.47	12.88	3.86	3.52
Ozone formation (Human)	3.41	5.20	12.52	3.77	3.68
Acidification	1.32	2.52	4.59	3.40	0.86
Terrestrial eutrophication	3.20	4.88	10.09	2.86	1.42
Aquatic eutrophication EP(N)	2.46	3.70	7.64	2.22	1.10
Aquatic eutrophication EP(P)	0.51	0.73	0.26	0.48	0.37
Human toxicity air	2.67	2.91	3.06	18.93	13.88
Human toxicity water	3.62	5.17	3.40	5.16	4.06
Human toxicity soil	20.55	12.30	19.76	51.96	17.62
Ecotoxicity water chronic	0.00	0.00	0.00	0.00	0.00
Ecotoxicity water acute	0.00	0.00	0.00	0.00	0.00
Ecotoxicity soil chronic	0.00	0.00	0.00	0.00	0.00
Hazardous waste	0.02	0.11	0.03	0.12	0.17
Slags/ashes	0.12	0.05	0.01	0.04	0.04
Bulk waste	0.42	1.26	0.15	0.37	0.50
Radioactive waste	6.20	9.07	18.15	15.45	5.44
Resources (all)	0.00	0.00	0.00	0.00	0.00
TOTAL	53.46	62.34	109.81	136.91	74.88

Source: Maraver (2010).

Table 5
LCA Final Results Using the EPS Method (2000) for 1) Pine Pellets, 2) Brassica Pellets, 3) Coal, 4) Diesel, and 5) Natural Gas

Impact Category	1)	2)	3)	4)	5)
Life expectancy	4.14	7.19	20.30	9.40	6.90
Severe morbidity	0.37	1.47	3.63	3.38	3.25
Morbidity	0.13	0.34	1.02	0.73	0.63
Severe nuisance	0.04	0.06	0.02	0.03	0.01
Nuisance	0.10	0.18	0.93	0.27	0.06
Crop growth capacity	0.03	0.04	0.09	0.04	0.03
Wood growth capacity	-0.05	-0.10	-0.26	-0.19	-0.14
Fish and meat production	-0.01	-0.01	-0.02	-0.01	0.00
Soil acidification	0.00	0.01	0.02	0.01	0.00
Prod. cap. irrigation Water	0.00	0.00	0.00	0.00	0.00
Prod. cap. drinking water	0.00	0.00	0.00	0.00	0.00
Depletion of reserves	4.47	21.13	13.80	38.16	90.04
Species extinction	0.03	0.08	0.23	0.15	0.14
TOTAL	9.26	30.38	39.75	51.97	100.90

Source: Maraver (2010).

Table 6
LCA Final Results Using the IMPACT Method (2002+) for 1) Pine Pellets, 2) Brassica Pellets, 3) Coal, 4) Diesel, and 5) Natural Gas

Impact Category	1)	2)	3)	4)	5)
Carcinogens	0.005	0.039	0.004	0.112	0.388
Non-carcinogens	0.299	0.445	0.159	0.180	0.865
Respiratory inorganics	7.094	8.869	22.408	6.214	1.843
Ionizing radiation	0.026	0.034	0.021	0.018	0.011
Ozone layer depletion	0.001	0.001	0.000	0.004	0.002
Respiratory organics	0.002	0.006	0.002	0.013	0.003
Aquatic ecotoxicity	0.082	0.102	0.053	0.051	0.074
Terrestrial ecotoxicity	0.685	0.866	1.251	0.937	0.297
Terrestrial acid/nutri	0.095	0.147	0.371	0.107	0.044
Land occupation	0.055	0.044	0.090	0.020	0.009
Aquatic acidification	0.000	0.000	0.000	0.000	0.000
Aquatic eutrophication	0.000	0.000	0.000	0.000	0.000
Global warming	1.659	4.314	12.102	10.349	8.522
Non-renewable energy	1.679	4.456	19.316	18.917	30.058
Mineral extraction	-0.003	0.000	-0.003	-0.001	-0.001
TOTAL	11.680	19.323	55.774	36.923	42.116

Source: Maraver (2010).

A number of other studies have examined emissions differences linked to different types of wood fuels, including particulate emissions (Table 7). In these studies pellets have generally been found to have lower environmental impact than other forms of wood fuels. In addition, dry, clean (dirt-free), uniformly sized fuels are known to provide greater heating value, more uniform burning, lower emissions, and lesser needs for boiler maintenance than wet, dirty, non-uniform fuels (Miles 2011, Wierzbicka 2005). Thus, clean mill chips represent the highest fuel quality, followed by chipped bole wood, whole tree chips, and hogged forest residues.

Table 7
Pellet and Wood Combustion Emission Factors as Reported in the Literature

Source	Johansson et al. (2004)		USEPA (2005)		Swiss Centre for Life Cycle Inventories (2008)	
Fuel	Mixed wood	Pellet	Wet wood		Mixed wood chip from forest	Pellet
Emission Control			None	Multi cyclone		
Type of equipment	Median emissions for wood boilers	Median emissions for pellet boiler			Furnace 50kW	
Pollutant	Kg/MJ input					
CO_2, biogenic			9.17E-02	9.17E-02	1.03E-01	9.65E-02
CH_4, biogenic	4.35E-05	1.77E-06	9.03E-06	9.03E-06	7.00E-07	3.00E-07
N_2O			5.59E-06	5.59E-06	3.00E-06	2.50E-06
CO, biogenic	4.10E-03	3.20E-04	2.85E-04	2.85E-04	1.18E-04	6.50E-05
NMVOC	2.85E-05	2.50E-06	7.31E-06	7.31E-06	9.00E-07	1.50E-06
NOx	7.20E-05	6.70E-05	9.46E-05	9.46E-05	1.10E-04	7.40E-05
SOx			1.07E-05	1.07E-05	2.50E-06	2.50E-06
$PM_{2.5}$					3.40E-05	2.00E-05
PM	8.80E-05	1.90E-05	1.42E-04	9.46E-05	4.30E-05	2.37E-05

Source: Reported by Pa (2010)

Ghafghazi et al. (2011a) conducted a life cycle impact assessment of thermal energy production from wood pellets in comparison to natural gas in a district heating system (Table 8). Life cycle steps considered in the LCA model included fuel production, fuel transmission/transportation, construction, operation, and demolition of the district heating system. Shaded cells in Table 8 indicate greater environmental impact; results show environmental impacts of heat production from pellets to be environmentally better than heat produced from natural gas in 10 of 13 categories.

Table 8
Midpoint Categories of Various Heat Source Options per MWh Thermal Energy Produced in a District Heating Center

Midpoint category	Unit	Natural Gas	Wood Pellets
Carcinogens (HH)	kg_{eq} C_2H_3Cl	0.384	0.0288
Non-carcinogens (HH)	kg_{eq} C_2H_3Cl	5.76	0.359
Respiratory inorganics	kg_{eq} $PM_{2.5}$	0.256	0.0222
Respiratory organics	kg_{eq} ethylene	0.0345	0.000102
Ozone layer depletion	kg_{eq} CFC-11	1.25E-08	0.00183
Aquatic ecotoxicity	kg_{eq} TEG* water	36,000	2,390
Terrestrial ecotoxicity	kg_{eq} TEG* soil	7.45	24.8
Terrestrial acidification/ nutrification	$kg_{eq}SO_2$	4.68	0.59
Aquatic acidification	$kg_{eq}SO_2$	2.72	0.201
Aquatic eutrophication	$kg_{eq}PO_4^{3-}$	0.00258	0.000227
Global warming potential	$kg_{eq}CO_2$	240	24.6
Non-renewable energy	MJ primary	4,390	29.8
Mineral extraction	kg_{eq} iron	0.0271	0.0528

* Tri-ethylene glycol

Source: Ghafghazi et al. (2011a)

Findings reported thus far strongly suggest that wood pellet fuels are environmentally superior to forest residues. However, there are several important caveats to be considered, including distance of transport for wood pellets and other fuels, and full accounting of impacts linked to wood fuels production. With respect to the former, Nussbaumer and Oscar (2004) analyzed fuel efficiencies as a function of transport distance for energy resources and energy produced. What they found (Table 9) are large differences in energy yield and efficiency of non-renewable fuels use depending upon the transport distance for woody fuels, the fuel used in drying of wood in the pellet manufacturing process, the distance that heat is conveyed, and the concentration of users in a district heating system. Pellets manufactured in processes that employ bioenergy for drying of wood have considerably lower environmental impacts than those made in processes that use fossil fuels in drying.

Nussbaumer/Baumer described energy yield coefficients for non-renewable energy as acceptable if 2.0 or greater, but ideal if above 5.0. For all fuels the higher the EYC, the better. In this regard, Nussbaumer and Oser identified a stand-alone, latest technology wood stove as providing the greatest energy yield, especially when fuel transport distances are great and heating density in a district heating system is low.

Table 9
Energy Yield Coefficients Associated with Residential Heating

Heating fuel	Heating System	Max. fuel transportation distance (miles)	Capacity of heating system expressed as energy input		Energy Yield Coefficient (all fuels)	Energy Yield Coefficient (non-renewable fuels)
			kW	mmBtu		
Pellets with district heat, 1.5 MWh $a^{-1}m^{-1}$	DH	30	1,000		0.580	2.81
Pellets w/o dh	Stove	3,000	15		0.419	0.88
Pellets w/o dh	Stove	300	15		0.613	2.63
Pellets w/o dh	Stove	30	15		0.643	3.27
Pellets w/o dh	Stove	10	15		0.645	3.34
Eco-pellets* w/o dh	Stove	30	15		0.647	8.30
Wood chips with district heat, 0.6 MWh $a^{-1}m^{-1}$	DH	10	1,000		0.583	7.89
Wood chips with district heat, 1.5 MWh $a^{-1}m^{-1}$	DH	10	1,000		0.658	8.96
Wood chips with district heat, 3 MWh $a^{-1}m^{-1}$	DH	10	1,000		0.687	9.37
Wood chips w/o dh	Stove	10	1,000		0.732	13.00

* Eco-pellets are distinguished by the fact that pellets are dried with biomass heat.

Source: Nussbaumer and Oser (2004)

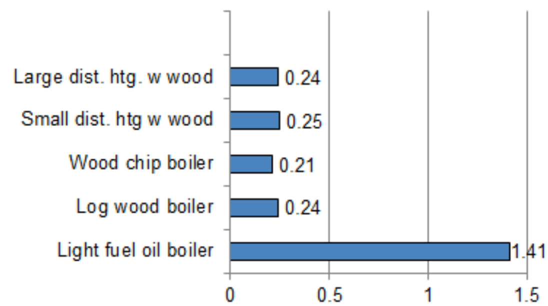
Pa (2010) found the same thing based on a full life cycle assessment of wood-based district heating text in which pollution control devices were considered. In the author's words "In all aspects an uncontrolled wood pellet scenario performs better than an uncontrolled wood waste scenario. But when emission controls are installed, wood waste performs better than wood pellets in terms of external costs, ecosystem quality and human health impact over the entire life cycle. This is due to the fact that wood waste requires little upstream processing and has high stack emission while the opposite is true for wood pellets. Since the emission controls are only effective for controlling the end stage emission, the overall impact of the controlled wood waste scenario is lower than pellets. However, the main concern for biomass utilization in district heating systems is its impact on human health for residents in the proximity of the heating facility. By comparing human health impact linked directly to end usage alone, it is observed that controlled wood pellet gasification would result in only a 12% increase in health impact while controlled wood waste has a much greater increase at 133% from the natural gas base case." While Pa's findings were expressed in the context of the environment of a large metropolitan area (Vancouver, Canada), the bottom line is that use of pellet fuels minimize local environmental impacts while resulting in greater environmental impacts overall.

Comparisons of Energy Generation and Distribution Systems

Home and Institutional Heating

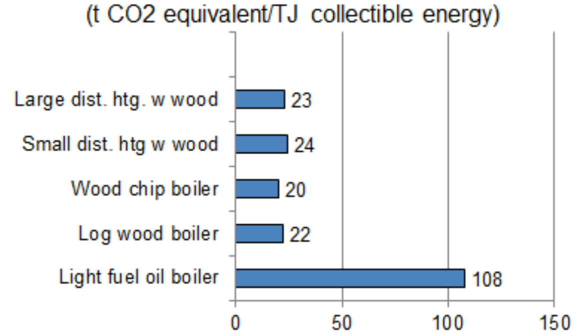
The observation by Nussbaumer and Oser (2004), stated above, is worth repeating: a stand-alone, latest technology wood stove provides the greatest energy yield, especially when fuel transport distances are great and heating density in a district heating system is low. They based that statement on a study that compared consumption of primary energy and greenhouse gas emissions for heating of single family homes throughout the full fuel life cycle. Examined were small boiler systems fueled by light fuel oil, firewood, and wood chips, and small and large wood-based district heating systems. A life cycle approach was used that considered energy consumed in collection/production of energy resources, transportation, the source of heat used in drying in pellet production, combustion, and heat distribution in a district heating system. For both primary energy consumption and GHG emissions, they found about the same impacts for both individual boilers and district heating systems. Significant advantages in comparison to light fuel oil were found in all cases (Figures 12 and 13).

Figure 12
Comparison of Different Systems for Heating and Hot Water Supply for Single Family Home with 18 kW Heat Demand
(TJ Primary Energy/TJ Collectible Energy)



Source: Nussbaumer and Oser (2004).

Figure 13
Comparison of Different Systems for Heating and Hot Water Supply for Single Family Home with 18 kW Heat Demand
(t CO2 equivalent/TJ collectible energy)



Source: Nussbaumer and Oser (2004).

Pehnt (2006) looked at the same question using a life cycle approach, comparing individual residential heating (central heating) to heating provided via a district heating system (wood heating plant), both fueled with forest residues. His findings point to environmental benefits of heating multiple buildings from a single energy generating plant (Table 10); superior environmental performance is indicated by cells shaded in light green.

Table 10
Selected Inventory and Impact Assessment Results of Two Wood Heating Systems

Product: 1MJth			
Resources	Unit	Forest Wood Heating Plant (District Heating)	Forest Wood Central Heating (Individual Home)
Cumulative energy demand	kJ	61	60
Iron Ore	mg	108	178
Bauxite	mg	3	4
Emissions to air			
CO_2	g	4.2	4.1
CH_4	mg	8	17
N_2O	mg	5	5
SO_2	mg	10	19
CO	mg	62	75
NOx	mg	124	119
NMHC	mg	9	36
Particles/dust	mg	6	28
HCl	mg	4	7
NH_3	mg	0.03	0.03
Benzene	mg	0.8	3.8
Benzo(*a*)-pyrene	Ng	25	210
Impact Assessment			
GWP	g	6	10
Acidification	mg	100	169
Eutrophication	mg	16	21

Source: Pehnt (2006).

A study done by the Government of Scotland (2006) which only considered impacts at the combustion site also found environmental advantages of boilers in comparison to wood stoves, and of automatically fed boilers in comparison to manually fed boilers (discussed further on page 29).

District Heating

Homes, individual businesses and institutions, communities, and even large cities can be heated and cooled via district heating systems using a wide range of energy options. One option is wood in the form of forest biomass, mill residues, or wood pellets. Wood-based district energy systems are relatively rare in the United States, but at the same time rather common in northern Europe. For example, as reported by Bratkovich et al. (2009) Denmark commissioned its first CHP plant over 100 years ago using household waste to generate electricity with the surplus heat used for district heating, and today has 430 citywide (public) district heating systems with 300 CHP units and 130 heat-only boilers. In addition, 60% of all houses and residential units in Denmark are supplied with district heating of which 25% (or more than 600,000 houses) are heated by biomass based district heating. Finland, on the other hand, is reportedly number one in the world in bioenergy use, and Sweden has over 400 wood-fired district heating plants that in 2007 supplied 29% of the energy delivered to the residential and service sectors; wood contributed nearly one-half of the feedstock nationwide for district heating.

Emissions

The World Energy Council (2004) examined life cycle environmental differences of combined heat and power (CHP) systems using a variety of fuels. As with stand-alone or small district heating systems, wood-based district heat at any scale was found to compare well to heating systems that use non-wood fuel regarding CO_2, SO_2, and VOC emissions. The comparison is less favorable or unfavorable for wood fuels in regard to NOx and particulate emissions, especially if energy is produced with the benefit of emissions control systems (Table 11). As noted earlier, emissions of CO, benzene, and PAH also tend to be higher for wood than for alternative fuels.

Frölling et al (2006) investigated different heating options for a 20MWh/year single family house in a suburban area and considered the full life cycle, including production of district heat piping systems and geothermal heat pumps, but not considering production of pellet stoves. They concluded that district heat in suburban areas with low heat density can compete with heat pumps using coal power down to a linear heat density of around 0.3 MWh/m, but that to compete with heat pumps using electricity from natural gas combined heat and power, district heat needs to be produced from biofuels or waste heat, with a well-insulated distribution system and a linear heat density of 0.5MWh/m or above. They further noted that district heat cannot compete with local furnaces using pelleted biofuels in regard to GWP, acidification, or fossil fuel use; the team found measures regarding a pellet furnace to be consistently low, whereas impacts of district heating were found to increase sharply with decreases in heating density.

Table 11
Combined Production of Electricity and District Heat (CHP)
(per 1 GWh of exergy)
Source: World Energy Council (2004)

Performance data as shown in Table 10 are consistent with the findings of Pa et al. (2011) who reported that emission control devices would clearly be needed in order to stay below local air emissions limits if wood waste or pellet gasification systems for heating metropolitan Vancouver were to be employed. Shown in Table 12 are estimated emissions under three wood-based district heating scenarios. The numbers show that both NO_x and PM emissions would need to be reduced by 37 and 66%, respectively, for wood pellets and 44 and 87% for wood waste gasification. They note that required reductions can be easily achieved using available technologies for controlling stack emissions.

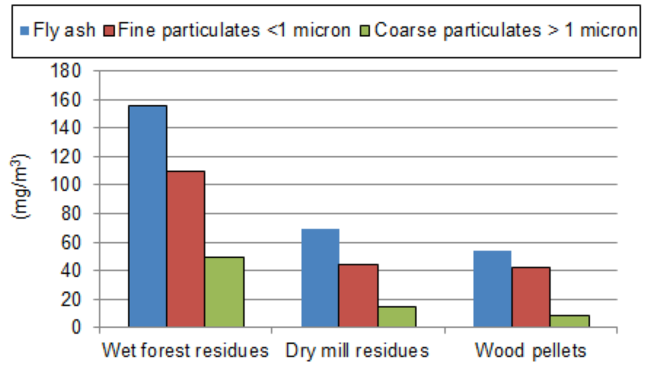
Table 12
Estimated Wood Waste and Wood Pellet Gasification Emissions and Emissions Limits for Biomass Boilers in Vancouver, Canada

Pollutant	Wood waste gasification emission factors (kg/MJ)	Estimated pellet gasification emission factors based on ratio 1 (kg/MJ)	Estimated pellet gasification emission factors based on ratio 2 (kg/MJ)	Average estimated pellet gasification emission factors (kg/MJ)	Vancouver air emission limit for biomass boilers (kg/MJ)
Biogenic CO_2	9.17E−02	8.50E−02	8.22E−02	8.36E−02	
Biogenic CH_4	9.03E−06	3.00E−07	3.00E−07	3.00E−07	
N_2O	5.59E−06	2.50E−06	2.50E−06	2.50E−06	
Biogenic CO	1.46E−05	1.26E−06	1.14E−06	1.20E−06	1.59E−04
NMVOC	4.30E−06	3.77E−07	3.02E−07	3.39E−07	
NO_X	7.31E−05	6.80E−05	6.33E−05	6.56E−05	4.10E−05
PM	4.00E−05	1.92E−05	1.14E−05	1.53E−05	5.13E−06

Source: Pa et al. (2011)

Ghafghazi et al. (2011b) examined flue gas emissions for small as well as medium-sized wood-based district heating systems. As illustrated in Figure 14, they found large differences in uncontrolled particulate emissions depending upon the type and moisture content of wood fuel, with clean, dry fuels much less prone to generation of particulates. They reported that utilization of high quality wood fuel, such as wood pellets produced from natural, uncontaminated stem wood, would generate the least PM emissions compared to other wood fuel types.

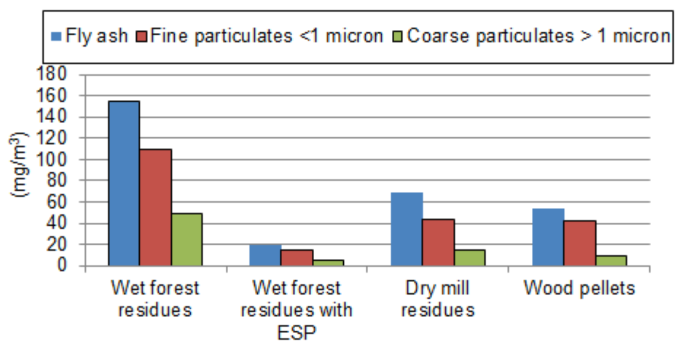
Figure 14
Particulate Emission Levels in the Flue Gas of Small and Medium Sized Wood-Based District Heating Systems



Source: Ghafghazi et al. (2011).

They also observed that emissions control devices were quite effective in reducing particulate emissions. In Figure 15, results obtained from use of an electrostatic precipitator on emissions from combustion of wet forest residues are shown; note that the effect was to reduce particulate emissions to just 13 percent of uncontrolled emissions, and to levels significantly below the other wood fuels. Similar devices used in conjunction with dry fuels can likewise substantially reduce particulate emissions.

Figure 15
Particulates in the Flue Gas of Small and Medium Sized Wood-Based District Heating Systems – Effect of Electrostatic Precipitator



Source: Ghafghazi et al. (2011).

Scale of District Heating Systems

Following energy production, distribution impacts can also be significant. Guest et al. (2011) found that environmental impacts attributable to energy distribution ranged from less than 1% to 89% of total impacts, with micro and smaller-scale systems associated with the least distribution impacts across all environmental impact measures.

Therefore, if biomass is locally abundant and sufficient to meet the energy requirements of a given CHP system, the micro to small-scale systems will likely have lower potential globalized impacts, but will still be faced with higher localized impact potential.

With regard to scale, important *localized* impact categories in this system include acidification potential (ADP), eutrophication potential (ETP), fresh water aquatic toxicity potential (FWTP), marine aquatic toxicity potential (MTP), and photochemical oxidation potential (PCOP), because the majority of environmental impact stems from a single point source (i.e. stressors from air and ash directly from the CHP plant), whereas the important *globalized* impacts are GWP, abiotic depletion potential (ABP), and ozone layer depletion potential (ODP). Because the smallest CHP plant emitted more emissions/ash per energy unit, it caused more impact in these localized categories. Conversely, the larger scale CHP plant caused more impact in the *globalized* categories, and this was largely attributed to longer biomass procurement distance.

Guest et al. also found that large scale did not necessarily translate to environmental advantage. On the one hand, micro-scale (0.2MW heating capacity) and small-scale (2.3MW heating capacity) district heating systems were reported to contribute 86 and 87% of the overall impact of a medium-scale facility (67MW), suggesting significant advantages of larger scale. On the other hand, energy consumption attributed to biomass transportation, and to energy losses in distribution from plant to end user, are typically appreciably less for micro- and small-scale facilities than for plants of larger scale, since larger facilities typically have to source fuel resources from longer distances. Transportation of biomass from forest to energy plant was reported to account for as much as 30% of GWP for a medium scale facility as compared to 7.9% and 7.2% for small- and micro-scale facilities. When all factors were considered in a comparison of medium-, small-, and micro-scale facilities, a district heating plant of small-scale was found to have the lowest CO_2e emissions and GWP, suggesting an optimized plant size.

<u>CHP Systems</u>

The USEPA has formed a Combined Heat and Power Partnership for the purpose of increasing awareness of Combined Heat and Power (CHP) systems and the advantages that they offer. As explained by the EPA, "there are considerable environmental benefits of CHP systems when compared with purchased electricity and onsite-generated heat. By capturing and utilizing heat that would otherwise be wasted from the production of electricity, CHP systems require **less fuel** than equivalent separate heat and power systems to produce the same amount of energy. Because less fuel is combusted, greenhouse gas emissions, such as carbon dioxide (CO_2), as well as criteria air pollutants nitrogen oxides (NO_x) and sulfur dioxide (SO_2), are reduced."

In more specific terms, the CHP Association of the UK reports that CHP provides the following direct benefits:

- minimum 10% energy savings, but typical markedly higher
- cost savings of between 15% and 40% over electricity sourced from the grid and heat generated by on-site boilers
- minimum 10% CO_2 savings for good quality natural gas CHP in comparison to conventional forms of energy generation

- high overall efficiency – up to 80% or more at the point of use
- additional guarantee of continuity in energy supplies for operator & consumer

Guest et al. (2011), who performed a life cycle assessment of biomass-based combined heat and power (CHP) plants, provided some interesting insights into the advantages of combining district heating with electrical production. For example, Table 13 illustrates the very low efficiency of electricity production from biomass (ηel), and how the capture of thermal energy (ηth) substantially boosts overall efficiency (ηtot).

Table 13

Technical Specifications of Several Scales of CHP in Central Norway

CHP scale	MW_{el_cap}	MW_{th_cap}	η_{el}	η_{th}	η_{tot}	Capacity factor	production (GWh)	Main source
Micro	0.1	0.22	0.24	0.52	0.76	0.51	1.40	Biosynergi, Öko-Institut
Small	1.0	2.31	0.30	0.56	0.86	0.51	15	Biosynergi, Öko-Institut
Medium	50	66.7	0.386	0.51	0.90	0.51	520	Öko-Institut

Note: MW_{el_cap}, = electrical capacity (in MW); MW_{th_cap} = thermal capacity (in MW); η_{el} = electrical efficiency; η_{th} = thermal efficiency; η_{tot} = overall efficiency.

This research team also examined environmental impacts linked to delivered energy (exergy), noting that for the three CHP systems described in Table 13, the exergy-based fraction of environmental impacts attributed to electricity production for the medium, small, and micro scale plants was calculated to be 78%, 72%, and 69%, respectively. What this means is that for the medium scale plant, only 22% of environmental impacts are linked to production of heat, while 78% are linked to electricity production. They also point out that the same limitations that apply to distance of heat transmission in a district heating system also apply to transmission of electricity. In their analysis, based on network distances and branches and assumed line materials and cross-sections, estimated electricity losses in transmission from generating plant to end-user for the medium, small, and micro-scale plants were 9.3%, 2.4%, and 0.68%, respectively. Thus, advantages of scale can be quickly lost if end users are widely scattered and user density is low. In this particular study it was concluded that an optimal small-scale CHP plant may be the best environmental option.

Combustion Emissions without Consideration of Life Cycle Environmental Impacts

On-site environmental impacts of various forms of energy are very similar in magnitude to life cycle impacts – perhaps not surprising in view of findings that combustion emissions dominate overall impact measures (Figures 5-7). Several published studies illustrate this point.

Valenti and Clayton (1998) looked at a wide range of wood heating systems, but narrow set of impact measures, providing comparisons to fuel oil and natural gas (Table 14). In this case, the analysis focused only on combustion emissions. As when full life cycle

Table 14
Emissions from Outdoor Wood-Burning Residential Hot Water Furnaces

Combustion Device	M5H Particulate mg/MJ input	PAHs mg/MJ input	Mutagenicity[b] krev/MJ input
Natural gas furnace			
Conventional	0.44	0.000124	0.007[c]
High Efficiency	0.43	0.000028	ND[c,d]
Oil furnace			
Retention head	3.2	—[e]	6
Conventional	15.1	—	20
Conventional wood stove	786	40	600
Certified wood stove			
Non-catalytic	383	28	100
Catalytic	425	24	—
Pellet (certified)	110	0.082	—
Pellet (exempt)	176	0.014	—
Fireplace 907 41	—		
Wood furnace			
Cordwood - Swedish lab tests			
Intermittent firing	1862	—	—
Continuous firing	182	15.3	148[f]
Chips (dry)	45.3	<0.02	0.48[f]
US EPA lab tests			
Furnace A[g]	*1048*	*15.6*	—
Furnace B	*681*	*16.1*	—

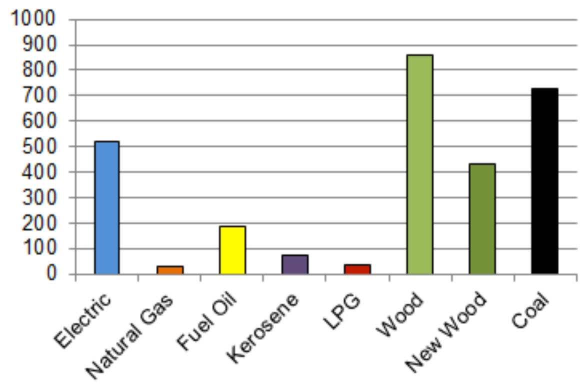
[a] All data except that in italics taken from: McCrillis, R.C., "Review and Analysis of Emissions Data for Residential Wood-Fired Central Furnaces," In Proceedings of the 88th Annual Meeting of the AWMA, Air & Waste Management Association, San Antonio, TX, June 1995, Paper No. 95-RP137.04.
[b] Microsuspension assay, TA98+S9 unless otherwise noted.
[c] Ames plate incorporation assay, TA98+S9.
[d] ND means not detected.
[e] No data available for this parameter.
[f] Ames plate incorporation assay, TA100+S9.
[g] Only includes comparison data.

Source: Valenti and Clayton (1998)

impacts are considered, particulate emissions linked to wood fuels combustion were found to be substantially higher than for fuel oil and natural gas, with differences between wood and fuel oil greater than those identified by Pa (2010). Large differences in particulate emissions were found as well between conventional and certified wood stoves and between stoves burning firewood and pellets, and between continuously and intermittently operated boilers.

Yet another study (Houck 1999) examined on-site fine particle emissions (those most associated with respiratory problems) for a variety of fuels and combustion devices, including old and new model wood stoves. Study findings (Figure 16) illustrate a central problem with wood as a heating fuel, and especially in those cases where combustion devices are inefficient and emissions uncontrolled.

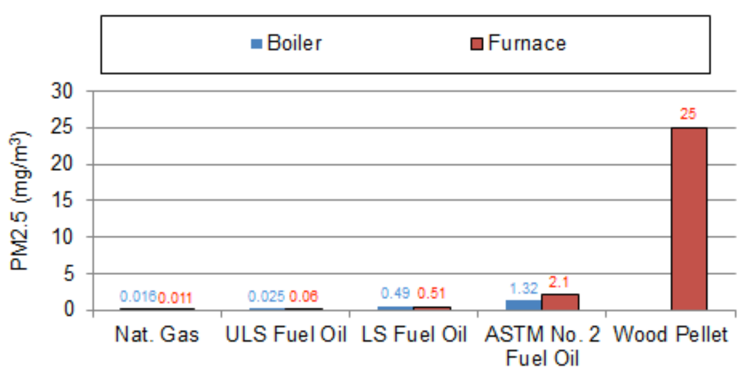
Figure 16
Fine Particle Emissions per Quad of Heat Delivered



Source: Houck (1999).

Another recent study (McDonald 2009) examined natural gas, heating oil, and wood pellet fueled residential heating system emissions, with particular emphasis on fine particulate emissions. As explained by McDonald, "Natural gas use results in very low levels of PM 2.5 emissions but substantial levels of carbon dioxide. ASTM No. 2 fuel oil fired heating appliances produce PM 2.5 levels that are about 130 times higher than natural gas and higher emission levels of carbon dioxide. Wood pellet fired heating appliances made in the United States produce PM 2.5 levels that are approximately 15 times higher than ASTM No. 2 fuel oil and from about 590 to 1850 times the levels possible with either utility gas or ultra-low sulfur oil fueled appliances." These differences are illustrated in Figure 17, where combustion emissions from natural gas, ultra-low and low sulfur fuel oil, ASTM #2 fuel oil, and premium (low ash) pellets are compared.

Figure 17
Comparison of Average PM2.5 Emissions for Five Heating Fuel Types for Hydronic Boilers and Warm Air Furnaces



Source: McDonald (2009).

On-site emissions data were also developed by the Biomass Energy Resources Center for the Massachusetts Division of Energy Resources (2007). Data shown in Table 15 and Figure 18 are based on tests of various types of boilers and boiler fuels.

Table 15
Emission Rates from Wood and Fossil Fuels[1/] (lbs/MM Btu)

	PM10	CO	NO_x	SO_x
Wood pellet boiler (test report)[2/]	n/a	0.51	0.272	n/a
Woodchip boiler[3/]	0.1	0.73	0.165	0.0082
Oil boiler	0.014	0.035	0.143	0.5
Propane boiler	0.004	0.021	0.154	0.016
Natural gas boiler	0.007	0.08	0.09	0.0005

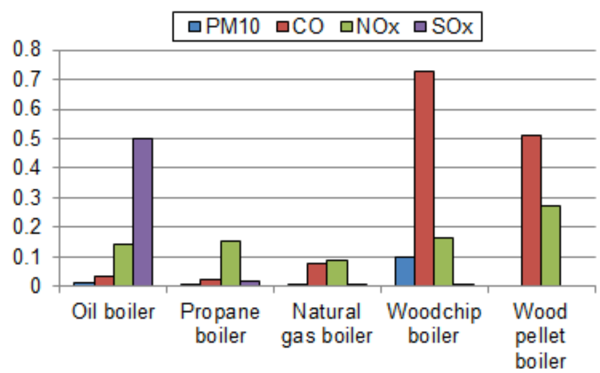
[1/] Without emission control equipment with the exception of PM10. Emissions given on a heat basis.

[2/] Emissions rates, given in pounds of pollutant per million Btu, were provided by the Danish Technological Institute and performed on a Danish pellet boiler. PM10 and SO_2 were not tested.

[3/] Emission rates, given in pounds of pollutant per million Btu, were provided by the Resource Systems Group in a report titled Air Pollution Control Technologies for Small Wood-Fired Boilers (2001). These emissions rates characterize wood fuel in general, with a specific focus on woodchips. The emissions from wood pellets may differ from the emissions rates given here.

Source: Biomass Energy Resources Center / Massachusetts Division of Energy Resources (2007).

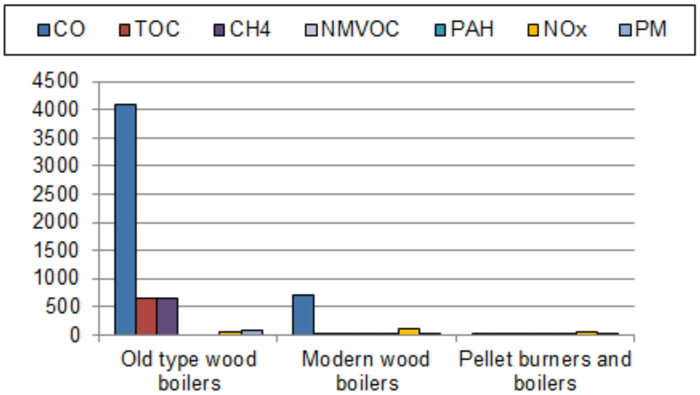
Figure 18
Combustion Emissions from Wood and Fossil Fuels
(lbs/MM Btu)



Source: Biomass Energy Resources Center / Massachusetts Division of Energy Resources (2007).

It is important to recognize that the magnitude of emissions is highly dependent upon the level of technology reflected in the combustion device. Dinca et al. (2009) showed that on-site emissions of important pollutants is only one-sixth or less in modern wood boilers as compared to older ones, and far less than that in pellet burners and boilers (Figure 19). Johansson et al. (2004) obtained the same results in extensive testing of wood combustion equipment in Sweden, concluding that emissions of non-methane volatile organics (NMVOC), total organic carbon (TOC), and particulate matter (PM) can be over 100 times higher from old low-efficiency residential wood stoves than from modern wood boilers and pellet burners.

Figure 19
Emissions from Various Types of Wood-Fueled Boilers
(mg/MJ)



Source: Dinca et al. (2009).

Perhaps the most comprehensive emissions database for various fuels is that of the European Environment Agency (EEA). The most recent edition of the EEA air pollutant emission inventory guidebook (commonly referred to in Europe as Corinair) contains detailed emissions information for wood stoves and boilers; an excerpt of this information is contained in Table 16. Presented are emissions that occur in the process

Table 16
Summary of Corinair Default Emissions Factors for Advanced Wood Combustion Technologies

Pollutants	Emission factors, g GJ^{-1}				
	Advanced stove	Pellet stove	Manual boiler	Automatic boiler	Aggregate factor
SO_2	30	30	30	30	30
NO_X (as NO_2)	150	150	150	150	150
PM	450	130	250	80	122
PM_{10}	400	120	230	70	108
$PM_{2.5}$	400	120	230	70	108
CO	3000	500	3000	300	590
nmVOC	250	20	250	20	43
	mg GJ^{-1}				
As	0.5	0.5	1	0.5	0.5
Cd	1	0.5	0.3	0.5	0.55
Cr	8	3	2	4	4.3
Cu	2	1	3	2	1.9
Hg	0.5	0.5	1	0.5	0.5
Ni	2	2	200	2	2
Pb	30	20	10	20	21
Se	0.5	-	-	-	0.05
Zn	80	80	5	80	80
PAH	400	50	150	40	77

Source: European Environment Agency (2009).

of combustion. Large differences in on-site emissions between pellet and wood stoves are shown, as are substantial emissions differences between manually and automatically fed boiler systems. Both the fuel and the equipment used clearly have an effect on emissions and overall environmental impact.

Summary of Research Findings

General observations based on research reviewed for this report are the following:

- Energy production from wood results in significantly lower emissions of fossil carbon and GHG than fossil fuels.
- Combustion of wood is considered to be carbon neutral as long as the forests from which the wood is obtained are growing at a greater rate than the rate of wood removals.
- For a given quantity of energy generated, emissions of from wood combustion are in some cases lower than fossil fuels, and in some cases higher.
- Consideration of environmental impacts over the full life cycle of energy systems and fuel types shows that in most situations, impacts are dominantly linked to fuel combustion.
- The proportion of emissions are overall environmental impacts attributable to resource extraction, processing, and transportation tend to be higher for fossil fuels than for wood fuels.
- Life cycle emissions of some air pollutants are higher per unit of energy generated from wood fuels than for some commonly used fossil fuels, while emissions of other compounds are lower.
- Overall environmental impacts, including human health impacts, linked to wood fuels have been found to be significantly lower than the impacts linked to use of fossil fuels.
- Current technology emissions control equipment can largely eliminate PM emissions from wood combustion.
- Biomass-based district heating offers an attractive alternative energy option to communities located in or near forested areas.
- Based on total environmental impacts over a full life cycle that includes resource extraction, fuel processing, transportation, and combustion, modern wood stoves that burn wood from the local area result in the lowest overall environmental impact per unit of heat produced.
- In general, clean, dry wood fuels are environmentally better than dirty, wet fuels, while also delivering superior energy efficiency.
- Wood pellet fuels tend to have higher overall environmental impact per unit of heat produced than other forms of wood fuels, but lower impact at the combustion site.
- Wood pellet stoves have substantially lower environmental impact at the local level than traditional wood stoves.
- District heating is an attractive option for many communities, offering efficiencies in combustion and economic opportunities for emissions control.
- Care must be exercised in development of district heating systems since heat losses in heat transmission increase sharply with transport distance and decreasing density of energy users.
- Balancing all factors, the largest scale does not necessarily translate to lowest environmental impact; rather, systems engineered to optimize energy use density and energy transport distance have been found to have the lowest overall impact.
- CHP operations maximize the quantity of energy gleaned from a given fuel. The same limitations of scale apply to CHP operations as to district heating systems.

Evaluating Northern Minnesota District Heating Project Options

Cook County

Single-family residence (S-1)

In this option, the impact of 500 homes with 35mm Btu free standing stoves (each consuming 3.6 odt cordwood or 2.30 odt pellets) is evaluated. On site (local area) impacts are examined first, followed by consideration of life cycle impacts over the full fuel cycle.

Local Impacts

Estimated emissions associated with this option are shown in Table 17. Comparisons to traditional fuels are provided.

Table 17
An Estimate of Combined On-Site Emissions from 500 Wood Stoves
(short tons/year)

Emission	Wood Stove (cordwood)	Wood Stove (pellets)	Fuel Oil	Propane	Natural Gas
CO_2 fossil	--	--	1,538.63	1,345.40	1,154.30
SO_2	0.36	0.23	9.84	0.01	0.01
NO_x	2.53 (Conv.) 1.81 (EPA)	1.81	1.23	1.42	0.90
PM_{10}	28.13 (Conv.) 13.59 (EPA)	5.22 (Ex) 2.49 (Cert.)	0.03	0.02	0.02
CO	208.54 (Conv.) 127.29 (EPA)	30.02 (Ex) 22.66 (Cert.)	0.34	0.82	0.38
CH_4	57.60 (Conv.) 14.95 (EPA)	0.14	0.12	0.02	0.02
NMVOC	47.98	3.83	0.05	0.09	0.05
TOC	74.70	5.96	0.17	0.11	0.11
PAH PAH_{15}	0.69 0.24 (Non Cert.) 0.10 (EPA Cert.)	0.004	<0.001	<0.001	<0.001

Source: USEPA (2001), with pellet stove data derived from EEA (2009).

In addition to the emissions shown in Table 17, local impacts for those burning cordwood include fossil fuel emissions associated with harvesting and hauling wood. For this scenario, it is estimated that harvesting and hauling translates to consumption of 9,810 gallons of diesel fuel and 177 gallons of lubricants (Appendix A) which, in turn, leads to the following emissions estimates (Table 18).

Table 18
Estimated Logging and Hauling Related
Emissions for Scenario S-1
(short tons/year)

Emission	Wood Stove (cordwood)
CO_2 fossil	111.56
SO_2	0.20
NO_x	1.72
PM_{10}	0.21
CO	0.65
CH_4	0.01
NMVOC	0.05
TOC	0.25
PAH	<0.001

A comparison of the values in Table 18 with those in Table 17 shows that with the exception of CO_2, SO_x, and NO_x emissions, logging/hauling related emissions less than 1% of those associated with wood combustion. Emissions of greenhouse gases increase by 30%. The relatively long average haul distance assumed in calculations (73 miles) is largely responsible for the relatively high CO_2, SO_x, and NO_x emissions from harvesting and transportation; reductions in average haul distance result in a proportional reduction of transportation-related emissions. Such emissions for the most part do not occur locally in the pellet fuels scenario unless pellets are manufactured within or close to Grand Marais.

While total projected emissions in every category are well within State of Minnesota emissions limits, emissions of PAH and PM could become problematic if emissions limits are tightened or should the number of people relying on wood stoves for heat increase significantly in the future. These are a particular problem when heating using individual wood stoves because of incomplete combustion, intermittent operation, and an inability to control emissions.

Polycyclic aromatic hydrocarbons (PAH) commonly result from incomplete combustion of wood, and that is why the quantities produced in wood stoves is so large compared to other forms of fuel or combustion devices (see also Figures 18-20). PAH emissions from wood stoves have been identified by the EPA as a health risk in Oregon (Meuiner

2009), a state in which significant numbers of people rely on wood for heating. PAH_{15} emissions are particularly troublesome. It is worth noting that emissions from latest technology, EPA certified or recommended stoves are significantly lower than from older technology conventional stoves. PAH emissions from pellet stoves are vastly lower.

Particulate emissions under this scenario would likewise be well within accepted limits, but again could become an issue going forward. As with PAH, the model of stove used has a large impact on the level of PM emissions, with latest technology stoves resulting in less than half of PM emissions from older models.

Pellet stoves and fuels result in far lower emissions in the local area for all categories of pollutants investigated, and in comparison to cordwood likely have lower life cycle impacts as well. Nonetheless, there are additional environmental impacts associated with pellets, with much of the environmental impact occurring in the area where pellets are manufactured.

Comparisons are given in Table 17 to heating with fuel oil, propane, and natural gas. Local emissions for these traditional fuels, other than fossil CO_2, are lower, and in most cases much lower than for wood fuels. However, as discussed on pages 12-14, when all compounds are considered and life cycle impacts of fuels compared, total environmental impacts, including human health impacts, are far greater for fossil fuels than for pelletized wood fuels.

Life Cycle Impacts

For the wood pellet and fossil fuel options significant impacts would occur outside the local area. The magnitude of these would depend upon a number of factors. For pellets, these would include hauling distance and the type of fuel used in drying wood in the pellet manufacturing process. Overall impacts may be 30-50% greater than reflected in local impact figures. When impacts of fossil fuels related to extraction, processing, and transportation are considered, the effect will also be to increase total life cycle impacts, in this case by 10-30%.

Mid-Sized Resort (Lutsen Central Buildings) (M-1)

In this option, the impact of 5,200 MMBtu Annual Heat Demand. On site (local area) impacts are examined first, followed by consideration of life cycle impacts over the full fuel cycle.

Local Impacts

Estimated emissions associated with this option are shown in Table 19. Comparisons to traditional fuels are provided.

Table 19
An Estimate of Combined On-Site Emissions from 5,200 MMBtu Annual Heat Demand from Wood Combustion and Alternative Fuels Under Scenario M-1
(short tons/year)

Emission	Manual Wood Boiler (chips)	Automatic Wood Boiler (chips)	Wood Boiler (pellets)	Fuel Oil #6	Natural Gas
CO_2 fossil	--	--	--	448.59	359.29
SO_2	0.14	0.14	0.14	3.10	<0.001
NO_x	0.87	0.87	0.58	0.93	0.40
PM_{10}	2.03	0.62	0.34	0.12	0.02
CO	21.49	2.15	1.18	0.10	0.14
CH4	1.53	0.12	0.05	0.01	0.04
NMVOC	1.15	0.09	0.02	0.01	0.04
Total VOC	2.68	0.21	0.07	0.02	0.08
PAH	0.91	0.24	0.03	<0.001	<0.001

Sources: Data for wood fuels obtained from average of Johansson et al. (2004), USEPA (2005), and the European Environment Agency (2009) (Tables 7 and 16), with supplemental data from IPCC Guidelines for National Greenhouse Gas Inventories Reference Manual. Data for fossil fuels from USEPA Aggregated Emissions Factors.

As in the previous scenario, heating with wood pellets results in lower impacts than when heating with wood, although the magnitude of difference is lower, particularly when comparing with automatic feed systems. Automatic feeding ensures uniform fuel feed rates and continuous operation, factors that have a significant impact on generation of a number of pollutants.

Note in the comparison to use of fuel oil that use of #6 fuel oil is assumed in view of cost advantages; as indicated SO_2 emissions would be substantially greater than if using #2 fuel oil (see Table 17).

In addition to the emissions shown in Table 18, local impacts of the chip- fueled boilers would include fossil fuel emissions associated with harvesting and hauling wood. Diesel fuel and lubricant consumption associated with these activities is estimated at 3,335 and 60 gallons, respectively, quantities that as in scenario S-1 increase emissions to air of most compounds by less than 1%, but of CO_2, SO_x, and NO_x by much larger percentages. Also as in scenario S-1, such emissions do not for the most part occur locally in the pellet fuels scenario unless pellets are manufactured within or close to Grand Marais.

Life Cycle Impacts

As in the first scenario considered, for the wood pellet and fossil fuel options significant impacts would occur outside the local area. The magnitude of these would depend upon a number of factors. For pellets, these would include hauling distance and the type of fuel used in drying wood in the pellet manufacturing process. Overall impacts may be 30-50% greater than reflected in local impact figures, which likely means that the overall life cycle impacts of pellet fuels are higher than those of wood chips. When impacts of fossil fuels related to extraction, processing, and transportation are considered, the effect will also be to increase total life cycle impacts, in this case by 10-30%.

Grand Marais Public Buildings (L-3)

In this option, the impact of 11,796 MMBtu Annual Heat Demand is evaluated. On site (local area) impacts are examined first, followed by consideration of life cycle impacts over the full fuel cycle.

Local Impacts

Estimated emissions associated with this option are shown in Table 20. Comparisons to traditional fuels are provided.

Table 20
An Estimate of Combined On-Site Emissions from 11,796 MMBtu Annual Heat Demand Annual Heat Demand from Wood Combustion and Alternative Fuels under Scenario L-3
(short tons/year)

Emission	Manual Wood Boiler (chips/hog fuel)	Automatic Wood Boiler (chips/hog fuel)	Wood Boiler (pellets)	Fuel Oil #6	Natural Gas
CO_2 fossil	--	--	--	1,017.60	815.04
SO_2	0.31	0.31	0.31	7.03	0.002
NO_x	1.93	1.93	1.32	2.10	0.80
PM_{10}	4.62	1.39	0.77	0.26	0.06
CO	48.52	4.85	2.67	0.22	0.32
CH_4	3.47	0.28	0.12	0.01	0.08
NMVOC	2.61	0.21	0.04	0.03	0.08
Total VOC	6.08	0.49	0.16	0.04	0.16
PAH	2.06	0.55	0.07	<0.001	<0.001

Sources: Data for wood fuels obtained from average of Johansson et al. (2004), USEPA (2005), and the European Environment Agency (2009) (Tables 7 and 16), with supplemental data from IPCC Guidelines for National Greenhouse Gas Inventories Reference Manual. Data for fossil fuels from USEPA Aggregated Emissions Factors.

As before, heating with wood pellets results in lower impacts than when heating with wood. Automatic feed systems are again shown to have advantages over manually fed systems. Use of #6 fuel oil is again assumed in view of cost.

In addition to the emissions shown in Table 20, local impacts of the chip-fueled boilers would include fossil fuel emissions associated with harvesting and hauling wood. Diesel fuel and lubricant consumption associated with these activities is estimated at 7,704 and 139 gallons, respectively, quantities that as in scenarios S-1 and M-1 increase emissions to air of most compounds by less than 1%, but of CO_2, SO_x, and NO_x by much larger percentages. Also as in scenarios S-1 and M-1, such emissions do not for the most part occur locally in the pellet fuels scenario unless pellets are manufactured within or close to Grand Marais.

Generating energy at this scale yields benefits in efficiency of energy conversion, as well as benefits that accrue from continuous operation. This kind of operation also lends itself to installation of pollution controls should that become necessary or desirable.

Life Cycle Impacts

As in the other scenarios considered, for the wood pellet and fossil fuel options significant impacts would occur outside the local area. The magnitude of these would depend upon a number of factors. Overall impacts may be 30-50% greater than reflected in local impact figures, which likely means that the overall life cycle impacts of pellet fuels are higher than those of wood chips. Overall impacts may be 30-50% greater than reflected in local impact figures. When impacts of fossil fuels related to extraction, processing, and transportation are considered, the effect will also be to increase total life cycle impacts, in this case by 10-30%.

Grand Marais District Heating Public Buildings and Business District (L-6)

In this option, the impact of 30,562 MMBtu Annual Heat Demand is evaluated. On site (local area) impacts are examined first, followed by consideration of life cycle impacts over the full fuel cycle.

Local Impacts

Estimated emissions associated with this option are shown in Table 21. Comparisons to traditional fuels are provided.

Table 21
An Estimate of Combined On-Site Emissions from 30,562MMBtu Annual Heat Demand from Wood Combustion and Alternative Fuels under Scenario L-6
(short tons/year)

Emission	Manual Wood Boiler (chips/hogfuel)	Automatic Wood Boiler (chips/hogfuel)	Wood Boiler (pellets)	Fuel Oil #6	Propane
CO_2 fossil	--	--	--	2,636.48	2456.25
SO_2	0.81	0.81	0.81	18.21	0.02
NO_x	5.10	5.10	3.42	5.45	2.55
PM_{10}	11.96	3.64	2.00	0.68	0.13
CO	125.70	12.57	6.91	0.58	1.47
CH_4	9.00	0.72	0.31	0.03	0.04
NMVOC	6.75	0.54	0.11	0.08	0.16
Total VOC	15.75	1.26	0.42	0.11	0.20
PAH	5.33	1.42	0.18	<0.001	<0.001

Sources: Data for wood fuels obtained from average of Johansson et al. (2004), USEPA (2005), and the European Environment Agency (2009) (Tables 7 and 16), with supplemental data from IPCC Guidelines for National Greenhouse Gas Inventories Reference Manual. Data for fossil fuels from USEPA Aggregated Emissions Factors.

As in previous scenarios, heating with wood pellets results in lower impacts than when heating with wood, particularly when comparing with automatic feed systems. Automatic feeding ensures uniform fuel feed rates and continuous operation, factors that have a significant impact on generation of a number of pollutants.

In this case comparisons to use of fuel oil and natural gas are provided. Use of #6 fuel oil is assumed in view of cost advantages even though SO_2 emissions are substantially greater than if using #2 fuel oil.

In addition to the emissions shown in Table 21, local impacts of the hog-fuel-supplied boilers would include fossil fuel emissions associated with harvesting and hauling wood. Diesel fuel and lubricant consumption associated with these activities is estimated at 18,528 and 334 gallons, respectively, quantities that as in scenarios S-1, M-1, and L-3 increase emissions to air of most compounds by less than 1%, but of CO_2, SO_x, and NO_x by much larger percentages (Table 22). Also as in scenarios S-1, M-1, and L-3 harvesting emissions, do not for the most part occur locally in the pellet fuels scenario unless pellets are manufactured within or close to Grand Marais; for pellets, therefore, only transportation impacts are included.

Table 22
Estimated Logging and Hauling Related
Emissions for Scenario L-6
(short tons/year)

Emission	Wood Boiler (hog fuel)	Wood Boiler (pellet fuels)
CO_2 fossil	151.84	91.11
SO_2	0.27	0.17
NO_x	2.34	1.41
PM_{10}	0.29	0.17
CO	0.89	0.53
CH_4	0.01	0.01
NMVOC	0.64	0.04
Total VOC	0.65	0.05
PAH	<0.001	<0.001

Local impacts will also be affected by heat transmission losses in this scenario, as such losses translate to a need for generation of more heat (and consumption of greater quantities of fuel) than if losses are lower. Impacts from transmission losses can be expected to increase as insulation values decline over time. Installation of high-quality, highly insulated piping can help to reduce transmission loss and degradation over time. Local impacts can also be affected by life of distribution pipes, which according to northern European experience can be expected to require replacement after about 30 years.

Pellet fuels are associated with lower local impacts as in other scenarios, though as in scenarios M-1 and L-3 overall impacts may be 30-50% greater than reflected in local impact figures; this again likely means that the overall life cycle impacts of using pellet fuels would be higher than those of relying on wood chips.

As in scenario L-3, generating energy at this scale yields benefits in efficiency of energy conversion, as well as benefits that accrue from continuous operation. This kind of operation also lends itself to installation of pollution controls should that become necessary or desirable.

In Table 23, emissions under this scenario are compared to those that would result from an equivalent number of small wood stoves, generation of an equivalent amount of heat from a propane generator, and recent emissions from the Minnesota Power facility in Taconite Harbor. Note that emissions for both wood boiler options are significantly less than any of these alternatives.

Table 23
Comparisons of Emissions Associated with Several Options under Scenario L-6 (30,562 MMBtu/yr. Heat Demand) to Emissions of Existing Facilities in the Region

Emission	30,562 MMBtu Annual Heat Demand					
	Automatic Wood Boiler (chips)	Wood Boiler (pellets)	Equivalent Number of Small Wood Stoves (cordwood)		Propane Generator	Taconite Harbor Minnesota Power* Total Operations
			Worst Case	Best Case		
CO_2 fossil	151.8	91.1	227.8	227.8	2,636.5	1,752,752
SO_2	1.1	1.0	1.2	1.2	0.02	5,538
NO_x	7.4	4.8	8.1	6.7	2.6	3,373
PM_{10}	3.9	2.2	57.9	28.2	0.1	291
CO	13.5	7.4	427.1	261.2	1.5	2,875
CH_4	0.7	0.3	117.6	30.5	0.04	17.0
NMVOC	1.2	0.2	98.1	98.1	0.16	--
Total VOC	1.9	0.5	216.1	128.6	0.20	--
PAH	1.4	0.2	1.4	1.4	< 0.001	0

(Short Tons/Year)

* Emissions are averages for 2003/2004

Life Cycle Impacts

As in other scenarios considered, for the wood pellet and fossil fuel options significant impacts would occur outside the local area. The magnitude of these would depend upon a number of factors. For pellets, these would include hauling distance and the type of fuel used in drying wood in the pellet manufacturing process. Overall impacts may be 30-50% greater than reflected in local impact figures. When impacts of fossil fuels related to extraction, processing, and transportation are considered, the effect will also be to increase total life cycle impacts, in this case by 10-30%.

Ely

In this option, the impact of a 1000kw (KWe) Organic Rankine Cycle District Heating System, initially firing 13,000 tpy of biomass is evaluated. On site (local area) impacts are examined first, followed by consideration of life cycle impacts over the full fuel cycle.

Local Impacts

Estimated emissions associated with this option are shown in Table 24. Comparisons to traditional fuels are provided.

Table 24
An Estimate of Combined On-Site Emissions from a 1000kw (KWe) Organic Rankine Cycle District Heating System
(short tons/year)

	Proposed Energy System		Current Energy Supply			
Emission	Automatic Wood Boiler (hogfuel)	Wood Boiler (pellets)	Fuel Oil #2	Propane	Electricity (No local impacts)	Total
CO_2 fossil	805.7	483.0	1,992	1,127	8.2	3,127
SO_2	4.1	2.0	12.7	0.01	0.03	1.3
NO_x	46.8	22.8	1.6	1.2	0.02	2.8
PM_{10}	17.6	8.8	0.04	0.02	<0.01	0.1
CO	101.2	45.8	0.4	0.7	--	0.5
NMVOC	31.3	7.7	0.1	0.1	--	0.1
TOC	94.9	9.3	0.2	0.1	--	0.3
PAH	0.1	0.03	<0.01	<0.01	--	<0.01

Included in the emissions shown in Table 24 are local impacts associated with harvesting and hauling wood; in the case of wood pellets, only impacts related to hauling are included (assuming harvesting impacts outside the local community). In both cases a 72 average haul distance is assumed.

Local impacts will also be affected by heat transmission losses in this scenario, as such losses translate to a need for generation of more heat (and consumption of greater quantities of fuel) than if losses are lower. Impacts from transmission losses can be expected to increase as insulation values decline over time. Installation of high-quality, highly insulated piping can help to reduce transmission loss and degradation over time. Local impacts can also be affected by life of distribution pipes, which according to northern European experience can be expected to require replacement after about 30 years.

Installation of a combined heat and power facility would significantly increase the efficiency of energy fuels consumed, increasing efficiencies from district heating alone from 50-65% to 75-90%. Once energy systems are installed, increased efficiency of energy use can be obtained without increasing overall environmental impact as compared to district heating alone; at the same time, the environmental impact per unit of energy produced can be expected to be higher for electrical energy than for heat energy, largely due to impacts linked to system installation and lower efficiencies in production of electrical energy.

Following are addition evaluations of biomass energy options for Ely.

Table 25
An Estimate of Combined On-Site Emissions from 7,227 MMBtu Annual Heat Demand from Wood Combustion and Alternative Fuels Under Option 1
(short tons/year)

Emission	Manual Wood Boiler (chips)	Automatic Wood Boiler (chips)	Wood Boiler (pellets)	Fuel Oil #6	Natural Gas
CO_2 fossil	--	--	--	448.59	359.29
SO_2	0.19	0.19	0.19	3.10	<0.001
NO_x	1.20	1.20	0.81	0.93	0.40
PM_{10}	2.82	0.86	0.47	0.12	0.02
CO	29.67	2.97	1.63	0.10	0.14
CH4	2.12	0.17	0.07	0.01	0.04
NMVOC	1.59	0.13	0.03	0.01	0.04
Total VOC	3.72	0.30	0.10	0.02	0.08
PAH	1.26	0.34	0.04	<0.001	<0.001

Sources: Data for wood fuels obtained from average of Johansson et al. (2004), USEPA (2005), and the European Environment Agency (2009) (Tables 7 and 16), with supplemental data from IPCC Guidelines for National Greenhouse Gas Inventories Reference Manual. Data for fossil fuels from USEPA Aggregated Emissions Factors.

Table 26
An Estimate of Combined On-Site Emissions from 16,235 MMBtu Annual Heat Demand
Annual Heat Demand from Wood Combustion and Alternative Fuels under Option 2
(short tons/year)

Emission	Manual Wood Boiler (chips/hog fuel)	Automatic Wood Boiler (chips/hog fuel)	Wood Boiler (pellets)	Fuel Oil #6	Natural Gas
CO_2 fossil	--	--	--	1,017.60	815.04
SO_2	0.43	0.43	0.43	7.03	0.002
NO_x	2.71	2.71	1.82	2.10	0.80
PM_{10}	6.35	1.93	1.06	0.26	0.06
CO	66.75	6.67	3.67	0.22	0.32
CH_4	4.78	0.38	0.16	0.01	0.08
NMVOC	3.58	0.29	0.06	0.03	0.08
Total VOC	8.36	0.67	0.22	0.04	0.16
PAH	2.83	0.75	0.10	<0.001	<0.001

Sources: Data for wood fuels obtained from average of Johansson et al. (2004), USEPA (2005), and the European Environment Agency (2009) (Tables 7 and 16), with supplemental data from IPCC Guidelines for National Greenhouse Gas Inventories Reference Manual. Data for fossil fuels from USEPA Aggregated Emissions Factors.

Table 27
An Estimate of Combined On-Site Emissions from 21,553 Annual Heat Demand from Wood Combustion and Alternative Fuels under Option 3A
(short tons/year)

Emission	Manual Wood Boiler (chips/hogfuel)	Automatic Wood Boiler (chips/hogfuel)	Wood Boiler (pellets)	Fuel Oil #6	Propane
CO_2 fossil	--	--	--	2,636.48	2456.25
SO_2	0.57	0.57	0.57	18.21	0.02
NO_x	3.60	3.60	2.41	5.45	2.55
PM_{10}	8.43	2.57	1.41	0.68	0.13
CO	88.62	8.86	4.87	0.58	1.47
CH_4	6.35	0.51	0.22	0.03	0.04
NMVOC	4.76	0.38	0.08	0.08	0.16
Total VOC	11.10	0.89	0.30	0.11	0.20
PAH	3.76	1.00	0.13	<0.001	<0.001

Sources: Data for wood fuels obtained from average of Johansson et al. (2004), USEPA (2005), and the European Environment Agency (2009) (Tables 7 and 16), with supplemental data from IPCC Guidelines for National Greenhouse Gas Inventories Reference Manual. Data for fossil fuels from USEPA Aggregated Emissions Factors.

Table 28
Comparisons of Emissions Associated with Several Options under Option 3A
(21,553 MMBtu/yr. Heat Demand) to Emissions of Existing Facilities in the Region
(Short Tons/Year)

	21,553 MMBtu Annual Heat Demand					
			Equivalent Number of Small Wood Stoves (cordwood)			
Emission	Automatic Wood Boiler (chips)	Wood Boiler (pellets)	Worst Case	Best Case	Propane Generator	Taconite Harbor Minnesota Power* Total Operations
CO_2 fossil	107.05	64.25	160.65	160.65	1859.32	1,752,752
SO_2	0.78	0.71	0.85	0.85	0.01	5,538
NO_x	5.22	3.39	5.71	4.72	1.83	3,373
PM_{10}	2.75	1.55	40.83	19.89	0.07	291
CO	9.52	5.22	301.20	184.20	1.06	2,875
CH_4	0.49	0.21	82.93	21.51	0.03	17.0
NMVOC	0.85	0.14	69.18	69.18	0.11	--
Total VOC	1.34	0.35	152.40	90.69	0.14	--
PAH	0.99	0.14	0.99	0.99	< 0.001	0

* Emissions are averages for 2003/2004

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Appendix A

Timber Harvesting: Stump to Biomass Plant

Diesel use for felling, skidding, processing, and loading is estimated at 4.2 liters per cubic meter of biomass (L/m^3) for both softwoods and hardwoods (2.47 gallons per cord). Hauling the raw material to the biomass plant (73 miles is an average based on the LCI) raises this value to 11.1 L/m^3. (6.54 gal/cord). Similarly, average lubricant use for the same in-woods steps is estimated at 0.076 L/m^3 (stump to truck), and 0.200 L/m^3 for stump to biomass plant (Oneil, Table 3); this translates to overall lubricant consumption of 0.118 gallons/cord. The table below shows diesel and lubricant use converted to gallons of use per each scenario.

Note: The S1 scenario requires 3 cords of green wood per heating unit. If current use of wood stoves in Cook County (500 units) increases by 30%, then an additional 150 units would require 450 cords per year (150 units x 3 cords per unit).

Scenario	Diesel Use (gallons)	Lubricant Use (gallons)	Notes:
Cook Co. - S1	19.62 gallons per 3 cds.; 2943 gal. per 450 cds.	0.354 gallons per 3 cds.; 53.1 gal. per 450 cds.	3 cords of green wood per heating unit
Cook Co. - M1	3335.4 gallons	60.18 gallons	510 green cords
Cook Co. - L3	7704.12 gallons	139.00 gallons	1,178 green cords
Cook Co. - L6	18,527.82 gallons	334.29 gallons	2,833 green cords
Ely VCC	3335.4 gallons	60.18 gallons	510 gr. cords (chips)
Ely EBHC	11,046.06 gallons	199.30 gallons	1,689 gr. cords (chips)
Ely DH (Hartley)	87,452 gallons	1,577.89 gallons	13,372 gr. cords/yr (hog fuel)

Emissions to Air

Emissions values associated with diesel and lubricant consumption were collected from the Environmental Protection Agency and various other sources. Emissions reported are primary emissions, or those which pose specific hazards. These are:

> Aldehyde – any of a class of highly reactive organic compounds that are analogous to acetaldehyde and characterized by a carbonyl group attached to a hydrogen atom (Merriam Webster).

CO – Carbon Monoxide: A colorless, odorless, poisonous gas produced by incomplete fossil fuel combustion.

CO_2 – Carbon Dioxide: A naturally occurring gas, and also a by-product of burning fossil fuels and biomass, as well as land-use changes and other industrial processes.

Methane – A colorless, nonpoisonous, flammable gas created by anaerobic decomposition of organic compounds.

Non-methane VOC (NMVOC) – Organic compounds, other than methane, that participate in atmospheric photochemical reactions.

NO_x – NOx is the collective term for nitrogen compounds such as NO and NO_2. A group of gases that cause acid rain and other environmental problems.

Organic substances – of, relating to, or derived from living organisms; of, relating to, or containing carbon compounds. (Merriam Webster)

Particulates – Fine liquid or solid particles such as dust, smoke, mist, fumes, or smog, found in air or emissions.

PM_{10} - Particles with a diameter of 10 micrometers or less (0.0004 inches or one-seventh the width of a human hair).

SO_x – Oxides of sulfur.

*http://ofmpub.epa.gov/sor_internet/registry/termreg/searchandretrieve/termsandacronyms/search.do