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A LIFECYCLE EMISSIONS ANALYSIS: URBAN AIR POLLUTANTS AND GREENHOUSE-GASES FROM PETROLEUM, NATURAL GAS, LPG, AND OTHER FUELS FOR HIGHWAY VEHICLES, FORKLIFTS, AND HOUSEHOLD HEATING IN THE U.S.

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SUMMARY

This paper presents a detailed lifecycle analysis of emissions of greenhouse gases and urban air pollutants from a number of alternative fuel and feedstock combinations for highway vehicles, forklifts, and residential and commercial heating. I find that among the major near-term energy sources, natural gas and LPG have relatively low lifecycle emissions of urban air pollutants, and relatively low lifecycle emissions of greenhouse gases. Ultimately, using natural gas instead of oil as a primary resource will reduce greenhouse-gas emissions if the lower carbon/GJ content of NG is not offset by higher fuelcycle energy requirements or higher fuelcycle emissions of methane. It is important to look beyond end-use emissions and consider the entire lifecycle, because emissions from "upstream" fuelcycle activities, and from the lifecycle of materials, can be significant relative to end-use emissions. Findings for one sector, such as highway vehicles, do not necessarily apply to other sectors, such as offroad engines or residential heating, on account of differences in end-use energy efficiency and emissions.

1 INTRODUCTION

For over a decade, policy makers in the U.S., Europe, Japan, and elsewhere have been searching for clean alternatives to petroleum fuels, which are a major source of greenhouse gases (GHGs) and urban air pollutants. To properly evaluate these alternatives, one must consider the environmental impacts of the entire lifecycle of the fuels. This paper presents the results of a detailed lifecycle analysis of emissions of GHGs and urban air pollutants from a number of alternative fuel and feedstock combinations for highway vehicles, forklifts, and household heating. This comparative analysis focuses on natural gas and LPG because they are perhaps the most immediately and widely available of the near-term alternatives to petroleum, in all three end uses examined.

The first section describes the lifecycle model used in the analyses. Subsequent sections describe the application of this model to each of the three end uses: highway vehicles, forklifts, and home heating. The "upstream" portions of the fuelcycle are substantially the same (or the same) for all three end uses, but end-use emission factors and energy use can differ substantially. Thus, each section on a particular end use discusses the key end-use emissions and energy-use parameters, and presents the main results of the analysis for the years 2000 and 2020 in the U.S.

2 THE LIFECYCLE ENERGY USE AND EMISSIONS MODEL

2.1 A Tool for Evaluating the Environmental Impact of Alternative Fuels

The task of developing and evaluating strategies to reduce emissions of urban air pollutants and GHGs is complicated. There are many ways to produce and use energy, many sources of emissions in an energy-production-and-use pathway, and several kinds of pollutants (or GHGs) emitted at each source. An evaluation of strategies to reduce emissions of GHGs must be broad, detailed, and systematic. It must encompass the full "lifecycle" of a particular technology or policy, and include all of the relevant pollutants and their effects. Towards this end, I have developed a detailed, comprehensive model of lifecycle emissions of urban air pollutants and greenhouse-gases in the U.S. Although there are other models of the lifecycle environmental impacts of alternative-fuel vehicles (Maclean and Lave, 2000; Wang, 1999; Kreucher, 1998), there is to my knowledge no model of comparable detail that estimates fuelcycle emissions of a wide range of pollutants (including CO_2-equivalent impacts from *all* pollutants), from a comprehensive set of emissions sources, for a wide range of alternative fuels, in several end-uses[1].

The lifecycle emissions model (LEM) estimates emissions of GHGs and urban air pollutants, and the use of energy, for the lifecycle of fuels and vehicles for a variety of combinations of energy feedstocks, fuels, and end-use technologies. In this model, the lifecycle comprises all activities associated with developing and using fuels, vehicles, and electricity:

- *End use* : the use of a finished fuel product, such as gasoline, electricity, or heating oil, by consumers.
- *Dispensing of fuels* : pumping of liquid fuels, and compression or liquefaction of gaseous fuels.

- *Fuel distribution* : the transport of a finished fuel product to end users; for example, the shipment of gasoline by truck to a service station. Includes operation of bulk-service facilities.
- *Fuel production* : the transformation of a primary resource, such as crude oil or coal, to a finished fuel product or energy carrier, such as gasoline or electricity. Includes a detailed model of emissions and energy use at petroleum refineries.
- *Feedstock transport* : the transport of a primary resource to a fuel production facility; for example, the transport of crude oil from the wellhead to a petroleum refinery. Includes a complete country-by-country accounting of imports of crude oil and petroleum products by country.
- *Feedstock production* : the production of a primary resource, such as crude oil, coal, or biomass. Based on primary survey data at energy-mining and recovery operations, or survey or estimated data for agricultural operations.
- Assembly and transport of motor vehicles.
- *Materials* : the complete lifecycle of raw and finished materials used in motor vehicles.
- *Vehicle servicing* : the operation of maintenance and repair facilities for motor vehicles (not used in the comparison of alternative fuels, on the assumption that associated emissions are the same for all fuels).
- *Secondary support infrastructure for transport modes* : building, servicing, and providing administrative support for transport and distribution modes such as large crude-carrying tankers or unit coal trains.

GHGs and criteria pollutants are emitted from:

- the combustion of fuels that provide process energy (for example, the burning of bunker fuel in the boiler of a super-tanker, or the combustion of refinery gas in a petroleum refinery);
- the evaporation or leakage of energy feedstocks and finished fuels (for example, from the evaporation of hydrocarbons from gasoline storage terminals);
- the venting, leaking, or flaring of gas mixtures that contain GHGs (for example, the venting of coalbed gas from coal mines);
- chemical transformations that are not associated with burning process fuels (for example, the curing of cement, which produces CO_2, or the denitrification of nitrogenous fertilizers, which produces N_2O, or the scrubbing of sulfur oxides (SO_x) from the flue gas of coal-fired power plants, which can produce CO_2); and
- changes in the carbon content of soils or biomass, or emissions of non-CO_2 greenhouse from soils, due to changes in land use.

The model estimates emissions of the following pollutants, with CO_2-equivalency factors (explained briefly below) shown in brackets:

- carbon dioxide (CO_2) [1.0] ;
- methane (CH_4) [20] ;
- nitrous oxide (N_2O) [355] ;
- carbon monoxide (CO) [4.1] ;
- nitrogen oxides (NO_x) [-2.4] ;
- nonmethane organic compounds (NMOCs),weighted by their ozone-forming potential [~7] ;
- sulfur dioxide (SO_2) [-14] ;
- particulate matter less than 10 microns diameter (PM_{10}) [-5.2] ;
- chlorofluorocarbons (CFC-12) [7435] ; and
- hydrofluorocarbons (HFC-134a) [2000] .

Ozone (O_3) is not included in this list because it is not emitted directly from any source in a fuelcycle, but rather is formed as a result of a complex series of chemical reactions involving CO, NO_x, and NMOCs. Note that in the LEM, NMOC emissions are weighted by their relative ozone-forming potential.

The LEM estimates emissions of each pollutant individually, and also converts all of the pollutants into CO_2-equivalent greenhouse-gas emissions. The CO_2 equivalent of a pollutant other than CO_2 is equal to the mass emission of the pollutant multiplied by its CO_2 equivalency factor. The CO_2 equivalency factor for a pollutant is the mass emission of the pollutant that has the same effect on global climate (or on some measure of the impact of climate change) as has the emission of one mass unit of CO_2. The Intergovernmental Panel on Climate Change (IPCC, 1996a) estimates CO_2-equivalency factors called "Global Warming Potentials," which equilibrate emissions on the basis of degree-years of warming integrated over some time period (e.g., 100 years). Other analysts, including economists, estimate CO_2-equivalency factors that equilibrate emissions on the basis of the economic impact of the change in climate (Hammit et al., 1996; Kandlikar, 1996; Tol, 1999). However, neither the IPCC nor the other researchers have published comprehensive CO_2 equivalency factors for NO_x, SO_x, and PM, and hence one must estimate the factors for these pollutants by analyzing their specific impacts on global climate. The CO_2-equivalency factors used here are from Delucchi (2000a), who reviews and analyzes the literature referenced above, and other sources, and makes original, albeit crude, estimates of equivalency factors for NO_x, SO_x, and PM.

2.2 Major Outputs of the LEM

Emissions per km from the use of conventional and alternative transportation fuels and vehicles. The LEM estimates CO_2-equivalent emissions per km from many combinations of end-use fuel, primary feedstock, and motor-vehicle technology (Table 1). For baseline petroleum fuels (gasoline and diesel fuel), the results are reported as grams of individual gases or CO_2-equivalent emissions from each stage of the fuelcycle, per km of travel by the vehicle. For the alternative fuel vehicles, the results are reported as grams/km, and as a percentage change relative to the petroleum-fuel gram-per-km baseline. The LEM also estimates lifecycle emissions from trains, ships, off-highway vehicles, and forklifts.

Table 1 Fuel, feedstock and vehicle combinations included in the lifecycle emissions model

Fuel ▸ ▾ Feedstock	Gasoline	Diesel	Methanol	Ethanol	CNG, LNG	LPG	H_2	Electricity
Petroleum	I, F	I				I		B
Coal			I, F					B
Natural gas		I	I, F		I	I	I, F	B
Wood or grass			I, F	I, F	I			B
Soybeans		I						
Corn				I				
Solar power							I, F	B
Nuclear power							I, F	B

A letter in a cell indicates the type of vehicle that uses the corresponding fuel and feedstock combination: I = ICEVs (internal-combustion engine vehicles), F = FCVs (fuel-cell vehicles), B = BPEVs (battery-powered electric vehicles). Fuels: CNG = compressed natural gas; LNG = liquefied natural gas; H_2 = hydrogen.

Emissions per from the use of electricity, and from end-use heating. The model calculates grams of individual gases and grams of CO_2-equivalent emission from the entire fuelcycle, per kWh of electricity delivered to end users. It analyzes coal, residual fuel oil, natural gas (boilers and turbines), methanol, nuclear, and hydro power plants, individually or in any combination. The model also estimates lifecycle emissions from the use of natural gas (NG), LPG, fuel oil, and electricity for space heating and water heating, in grams CO_2-equivalent emissions per GJ (gigaJoule = 10^9 J) of heat delivered.

The model is documented in DeLuchi (1991, 1993), Delucchi (1997, 2000a), and Delucchi and Lipman (1997).

2.3 An Important Caveat

The LEM is a engineering systems model, not an economic model. For example, it does not account for the effect of price changes, brought about by a change in demand for propane as a heating fuel, on the world market for propane. Changes in the markets for propane and propane substitutes will of course lead to changes in emissions of air pollutants and GHGs -- changes which might not be small compared to the "first" order emissions from the "initial" change in the propane market[2]. Ideally, in order to analyze the actual impacts of any specific alternative-fuel policy, one would merge an economic/price model with an engineering systems model. (My colleagues and I have started a project to investigate this.)

3 ANALYSIS OF HIGHWAY VEHICLES

3.1 The Environmental Challenges

Highway vehicles are a major source of urban air pollutants and GHGs. In most of North America and Europe, and elsewhere, light-duty gasoline vehicles are major sources of volatile organic compounds (VOCs), nitrogen oxides (NO_x), and toxic air pollutants, and the single largest source of carbon monoxide (CO). Heavy-duty diesel vehicles are significant sources of NO_x and often sulfur oxides (SO_x), and, in terms of personal exposure, often a major source of particulate matter (PM) (EPA, 1997a; World Health Organization [WHO], 1992; Delucchi and McCubbin, 1996).

These air-pollutant emissions from highway vehicles lead to serious air quality problems. Urban areas throughout the world routinely violate national ambient air quality standards and international air-quality guidelines promulgated by the WHO, especially for ambient ozone and PM (WHO, 1999; United Nations Environment Programme and WHO, 1988). Clinical and epidemiological studies have associated ambient levels of PM, O_3, and other pollutants with human morbidity and mortality (WHO, 1999; U.S. EPA, 1996a, 1996b; McCubbin and Delucchi, 1999). In response to these apparently serious health effects, the U.S. Environmental Protection Agency (EPA) has promulgated new ambient air quality standards for O_3 and PM (EPA, 1998) and the WHO (1999) has determined that for PM there is no threshold below which there are no adverse effects.

Motor vehicles also are a major source of carbon dioxide (CO_2), the most significant of the anthropogenic pollutants that can affect global climate. In the U.S., the highway-fuel lifecycle contributes about 30% of all CO_2 emitted from the use of fossil fuels (Table 2). In the OECD (Organization for Economic Cooperation and Development), the highway-fuel lifecycle contributes about one-quarter of all CO_2 emitted from the use of fossil fuels (emissions in Europe generally are below the OECD-wide average, and emissions in the U.S. above). Worldwide, the highway fuel-lifecycle contributes less than 20% of total CO_2 emissions from the use of fossil fuels, primarily because outside the OECD relatively few people own and drive cars.

Table 2 Contribution of highway fuel to total carbon emissions

Country	Year	Fuel End-Use in Transport (EJ)[a]			Fossil Fuel Use in All Sectors (EJ)[a]		
		Gasoline	**Diesel**	**LPG**	**Coal**	**Petroleum**	**NG**
U. S.	1988	14.43	2.93	0.03	19.90	36.11	19.57
W. Germany	1988	1.24	0.63	0.00	2.61	5.28	2.14
Norway	1988	0.08	0.03	0.00	0.03	0.39	0.06
Japan	1988	1.37	1.03	0.07	3.14	10.22	1.74
U. S. S. R.	1987	3.31	0.14	0.00	14.44	20.12	22.09
Poland	1988	0.17	0.08	0.00	5.22	0.77	0.50
Indonesia	1988	0.18	0.20	0.00	0.14	1.16	0.53
India	1987	0.13	0.62	0.00	3.93	2.18	0.24
Mexico	1988	0.72	0.07	0.00	0.21	3.45	0.94
Argentina	1988	0.20	0.20	0.00	0.30	1.02	0.74
Nigeria	1987	0.17	0.05	0.00	0.03	0.46	0.15
A	B	C	D	E	F	G	H

Country	Year	Total fossil C (Tg)[b]	Carbon from Fuel Use by Transportation			
			(Tg)		% of Total Fossil Fuel C	
			End use[c]	Fuel cycle[d]	End use[e]	Fuel cycle[f]
U. S.	1988	1,455	319.8	433.3	22.0%	29.8%
W. Germany	1988	195	34.5	45.9	17.7%	23.5%
Norway	1988	9	2.1	2.9	23.6%	31.6%
Japan	1988	296	45.8	60.2	15.4%	20.3%
U. S. S. R.	1987	1,050	63.2	86.8	6.0%	8.3%
Poland	1988	154	4.6	6.1	3.0%	4.0%
Indonesia	1988	33	7.0	9.1	21.3%	27.8%
India	1987	144	13.9	17.5	9.7%	12.2%
Mexico	1988	83	14.5	19.8	17.4%	23.8%
Argentina	1988	37	7.3	9.6	19.8%	25.9%
Nigeria	1987	12	4.1	5.6	35.7%	47.9%
A	B	I	J	K	L	M

[a] ExaJoules (= 10^{18} J). See DeLuchi (1991) for data sources and methods.

[b] Teragrams (= 10^{12} g) of carbon derived from fossil fuel use are equal to kilograms (= 10^3 g) of carbon/GJ of fuel multiplied by EJ of fuel consumed (Columns F-H). I assumed worldwide values for carbon emission factors of 13.8 kg of carbon/GJ of NG, 25.3 kg of carbon/GJ of coal, and 18.9 kg of carbon/1GJ of petroleum.

[c] This represents the total for all road-transport fuels, which is the sum of the products obtained by multiplying EJ of each road fuel consumed (Columns C-E) by kg of carbon/GJ for each road fuel (Tables C.1 and C.3 of DeLuchi, 1993).

[d] The result from Column J, multiplied by the ratio of CO_2 emissions from the whole fuel production and use cycle (including vehicle manufacture) to CO_2 emissions from vehicles only. These ratios are 1.380:1 for gasoline (based on light-duty vehicles), 1.234:1 for diesel fuel (based on heavy-duty vehicles), and 1.272:1 for LPG (calculated from DeLuchi's [1991, 1993] lifecycle emissions model).

[e] Column J divided by Column I, multiplied by 100.

[f] Column K divided by Column I, multiplied by 100.

Many scientists now believe that an increase in the concentration of CO_2 and other "greenhouse" gases, such as methane and nitrous oxide, will increase the mean global temperature of the earth. In 1995, an international team of scientists, working as the Intergovernmental Panel on Climate Change (IPCC), concluded that "the balance of evidence suggests that there is a discernible human influence on global climate" (IPCC, 1996a, p. 5). In the long run, this global climate change might affect agriculture, coastal developments, urban infrastructure, human health, and other aspects of life on earth (IPCC, 1996b).

3.2 Interest in Alternative Transportation Fuels for Highway Vehicles

These local, regional, and global environmental concerns are influencing international, national, and sub-national transportation policy. Over the past decade, policy makers worldwide have become increasingly interested in developing alternative fuels and vehicle technologies to reduce emissions of urban air pollutants and GHGs from the transportation sector. For example, in the U.S., the "Climate Change Action Plan" proposed by President Clinton and Vice President Gore in 1993 calls on the "National Economic Council, the Office on Environmental Policy, and the Office of Science and Technology Policy to co-chair a process...to develop measures to significantly reduce greenhouse gas emissions from personal motor vehicles, including cars and light trucks" (Clinton and Gore, 1993, p. 30). There are similar initiatives in Europe, Japan, and elsewhere. (See Sperling and DeLuchi, 1993, for an evaluation of the air pollution and greenhouse gas impacts of alternative fuels in the OECD.) The so-called "Kyoto Protocol" commits the signatory nations to reduce greenhouse-gas emissions by an average of 5% from the 1990 level between the years 2008 and 2012.

Alternative-fuel vehicles are a tiny but growing fraction of the U.S. vehicle fleet. In 1999, there were 274,000 LPG (liquefied petroleum gases -- mainly propane) vehicles, 98,000 NG vehicles, 40,000 alcohol vehicles, and 6,400 electric vehicles in use in the United States (Energy Information Administration [EIA], 2000), out of a total of more than 210 million (Federal Highway Administration, 1999). Recently, General Motors announced that it will produce two new dedicated LPG vehicles, a light-duty pickup truck and a school bus. These are the first dedicated (that is, single-fuel, as opposed to bi-fuel) LPG vehicles to be offered by a major auto manufacturer (*New Fuels and Vehicles Report,* 2000).

3.3 Results of the Lifecycle Analysis: Urban Air Pollutants from Highway Vehicles

Emissions tests of alternative-fuel light-duty and heavy-duty vehicles show that, compared to gasoline and diesel fuel, some alternative fuels can reduce vehicular emissions of PM, ozone precursors, and CO. The results of these tests, reviewed in Delucchi (1997, 2000a), are the basis of the LEM results summarized in Table 3. Table 3 shows g/km emissions from baseline light-duty gasoline and heavy-duty diesel vehicles, in the year 2000, and alternative-fuel vehicle emissions *relative* to the baseline petroleum-vehicle emissions.

The relative emission factors of Table 3 indicate that CNG and LPG vehicles can offer significant reductions in emissions of urban air pollutants. Most beneficial are the reduction in PM emissions from heavy-

Table 3 In-use emissions from petroleum and alternative-fuel highway vehicles in the U.S., year 2000

Pollutant	**LDGV (g/km)**	**Emissions relative to conventional gasoline**						
		RFG	**Diesel**	**M100**	**NG**	**H_2**	**E100**	**LPG**
O_3-wtd. NMOC[a]	0.88	70%	23%	34%	7%	3%	57%	23%
CH_4 exhaust	0.04	100%	50%	50%	1500%	34%	150%	100%
CO exhaust	8.20	80%	20%	60%	60%	10%	60%	60%
N2O exhaust	0.09	100%	25%	100%	75%	0%	100%	100%
NO_x as NO_2	0.86	85%	150%	90%	90%	90%	90%	90%
SO_x as SO_2	0.06	82%	86%	30%	14%	26%	29%	21%
PM exhaust	0.03	100%	1000%	40%	20%	11%	40%	25%
CO_2 from fuel	204	101%	84%	88%	77%	2%	94%	91%
CO_2 equivalent[b]	273	98%	67%	85%	78%	2%	90%	87%

Pollutant	HDDV (g/km)	Emissions relative to low-sulfur diesel fuel						
		FTD	SD	M100	NG	H_2	E100	LPG
O_3-wtd. NMOC[a]	1.03	81%	18%	166%	186%	1%	282%	252%
CH_4 exhaust	0.06	90%	30%	100%	3023%	10%	300%	100%
CO exhaust	10.96	65%	30%	130%	10%	2%	130%	10%
N2O exhaust	0.04	100%	100%	401%	302%	95%	400%	400%
NO_x as NO_2	19.53	95%	130%	50%	50%	50%	50%	50%
SO_x as SO_2	0.29	28%	62%	29%	14%	26%	28%	21%
PM exhaust	0.79	76%	50%	20%	3%	5%	30%	3%
CO_2 from fuel	1015	96%	114%	92%	93%	2%	97%	107%
CO_2 equivalent[b]	1030	95%	108%	101%	100%	1%	107%	112%

Source: the lifecycle emissions model documented in Delucchi (1997, 2000a). The conventional-gasoline vehicle (model year 1995 in calendar year 2000) is assumed to have an in-use fuel consumption of 9.4 L/100-km (25 miles per gallon [mpg]); the baseline low-sulfur heavy-duty diesel-fuel vehicle (model-year 1996 in calendar year 2000) is assumed to have an in-use fuel consumption of 39 L/100-km (6 mpg). LDGV = light-duty gasoline vehicle; HDDV = heavy-duty diesel vehicle. Per-km emission estimates are based on the EPA's MOBILE5 model, but with accounting for so-called "off-cycle" emissions.

RFG = reformulated gasoline; FTD = Fischer-Tropsch diesel (diesel-like fuel made from natural gas); SD = soy diesel; M100 = 100% methanol; NG = natural gas; H_2 = hydrogen; E100 = 100% ethanol; LPG = liquefied petroleum gas (95% propane, 5% butane).

[a] Equal to exhaust NMOC plus evaporative NMOC emissions, weighted by their ozone-forming potential relative to that of gasoline. Evaporative emissions include resting-loss, running-loss, hot-soak, and diurnal emissions from ambient-temperature liquid fuels; boil-off of cryogenic fuels, and leakage of gaseous fuels.

[b] CO_2 plus the CO_2 equivalent of non-CO_2 GHGs. See the text for a brief discussion.

duty trucks, due mainly to the gaseous state and simple chemical structure of LPG and CNG, and the reduction in the ozone-forming potential of emissions from light-duty (spark-ignition) applications. These environmental benefits might make LPG or CNG an attractive choice for light and heavy-duty fleet vehicles, such as buses and taxis. Overall, the urban air-quality benefits of LPG and CNG vehicles are greater than the benefits of the alcohol-fueled vehicles

It is important also to consider emissions of urban air pollutants from the "upstream" fuelcycle, from feedstock recovery through fuel dispensing, and from the lifecycle of materials used to make motor vehicles (Tables 4 and 5). Table 4 shows emissions of urban air pollutants and CO_2-equivalent GHGs, in grams emitted per GJ of fuel delivered to vehicles, for the entire upstream fuelcycle. For perspective, part B of Table 4 expresses upstream emissions of each pollutant as a percentage of vehicular emissions of the pollutant. Table 5 shows emissions from the materials lifecycle and vehicle assembly and transport, in the "natural" units of g-pollutant/kg-vehicle, and also as a percentage of vehicular emissions.

These relative percentages are interesting in several respects. In all cases but one, upstream fuelcycle emissions of CH_4, SO_x, and PM exceed vehicular emissions, by a wide margin (the exception is upstream fuelcycle PM emissions from diesel vehicles) (Table 4). The story is similar for material and vehicle lifecycle emissions (Table 5). This is significant because CH_4 is a potent greenhouse gas, and SO_x and PM are the most damaging of all urban pollutants, per kg emitted (Delucchi, 2000b). If humans, materials, crops, and other "recipients" of pollutant damage were as exposed to upstream-fuelcycle and materials-lifecycle emissions as to vehicular emissions, then these emissions probably would be more damaging (per km of travel) than would vehicular emissions. However, in most places, people are much more exposed to vehicular emissions than to emissions from, say, petroleum refineries or automobile plants, which generally are not located in the center of metropolitan areas (Delucchi and McCubbin, 1996). The remoteness of these sources greatly diminishes the impact of their relatively high emissions of SO_x and PM, with the result that the health-damage cost per km of fuel-upstream and material-lifecycle emissions is considerably less than the damage cost per km of vehicular emissions (McCubbin and Delucchi, 1999).

Upstream and material-lifecycle emissions of CO and N_2O are relatively minor, except for the ethanol fuelcycles, which produce large amounts of N_2O from the use of fertilizers for the biofuel crops. Upstream and material-lifecycle emissions of NO_x and NMOCs generally are significant fractions of vehicular emissions, and in some fuelcycles (e.g., ethanol) exceed vehicular emissions. Upstream CO_2, NO_x, and CO_2-equivalent emissions are large in those fuelcycles in which fuel production is relatively energy intensive (ethanol, methanol, and hydrogen from natural

Table 4 Pollutant emissions from the transportation-fuel lifecycle, from feedstock production through fuel dispensing

A. Year 2000 (grams/GJ-fuel dispensed)

Pollutant	Fuel (in bold) and Feedstock (in italics)									
	Ethanol *cellulose*	**LPG** *NG*	**LPG** *oil&NG*	**LPG** *oil*	**Diesel** *oil*	**CNG** *NG*	**RFG** *oil*	**MeOH** *NG*	**CH2** *NG*	**EtOH** *corn*
CO_2	(1,592)	4,739	7,263	10,548	11,544	9,712	17,400	33,101	80,978	69,209
NMOCs	43.3	10.4	18.3	28.5	18.3	6.6	60.2	30.8	9.2	228.1
CH_4	94.3	111.2	114.9	119.7	124.2	296.9	141.9	368.2	359.4	204.0
CO	215.1	22.8	27.4	33.4	41.0	30.3	38.2	64.2	50.2	200.5
N_2O	23.3	0.1	0.3	0.4	0.7	0.3	0.5	1.1	1.3	55.7
NO_x	350.8	46.3	51.9	59.0	60.7	76.5	72.8	179.2	153.2	467.2
SO_x	46.3	10.2	29.8	55.1	56.8	26.2	55.3	44.6	95.2	200.2
PM	71.5	2.6	10.0	19.8	21.1	4.6	21.1	13.3	11.9	265.7
CO2eq	7,756	6,883	9,241	12,309	13,449	15,344	19,728	40,142	87,107	89,424

B. Year 2000 (emissions relative to end-use vehicular emissions)[a]

Pollutant	Fuel (in bold) and Feedstock (in italics)									
	Ethanol *cellulose*	**LPG** *NG*	**LPG** *oil&NG*	**LPG** *oil*	**Diesel** *oil*	**CNG** *NG*	**RFG** *oil*	**MeOH** *NG*	**CH2** *NG*	**EtOH** *corn*
CO_2	-3%	8%	13%	19%	17%	20%	28%	57%	7009%	113%
NMOCs	27%	17%	30%	46%	23%	37%	32%	25%	101%	138%
CH_4	543%	1006%	1040%	1084%	1767%	181%	1282%	5123%	8654%	1227%
CO	14%	2%	2%	2%	6%	2%	2%	4%	19%	12%
N_2O	83%	1%	1%	1%	8%	1%	2%	4%	-	197%
NO_x	143%	20%	22%	25%	12%	33%	33%	74%	60%	191%
SO_x	835%	263%	761%	1410%	282%	1026%	368%	544%	1793%	2885%
PM	1679%	101%	397%	781%	16%	225%	208%	229%	954%	5214%
CO2eq	10%	9%	13%	17%	19%	24%	24%	54%	5030%	114%

gas). My findings with regards to "upstream" fuelcycle emissions (Table 4) are broadly similar to those of Wang (1999) and, to a lesser extent, those of Kreucher (1998), and my findings with regards to emissions from the lifecycle of materials used in vehicles (Table 5) appear consistent with the lifecycle energy-use findings of Maclean and Lave (1998). My estimates of g/km emissions of PM, SO_2, NO_x, and CO_2 from the materials lifecycle (Table 5) are similar to those from a detailed, industry-sponsored lifecycle analysis of a generic U.S. family sedan (Sullivan et al., 1998).

3.4 Results of the Lifecycle Analysis: GHG Emissions from Highway Vehicles

Table 6 shows the results of the greenhouse-gas lifecycle emissions analysis for the years 2000 and 2020. On the basis of this analysis, we can conclude that LPG, CNG, LNG, and hydrogen made from NG will

Table 4 (Cont'd)
C. Year 2020 (grams/GJ-fuel dispensed)

Pollutant	Fuel (in bold) and Feedstock (in italics)									
	Ethanol	**LPG**	**LPG**	**LPG**	**Diesel**	**CNG**	**RFG**	**MeOH**	**CH2**	**EtOH**
	cellulose	*NG*	*oil&NG*	*oil*	*oil*	*NG*	*oil*	*NG*	*NG*	*corn*
CO_2	(10,880)	4,577	6,976	10,099	11,253	9,468	16,550	25,953	77,497	63,209
NMOCs	22.4	5.9	10.4	16.2	11.3	5.5	29.4	20.5	7.5	213.2
CH_4	35.3	93.9	90.9	87.0	90.3	243.2	105.6	286.6	287.8	156.3
CO	134.1	21.7	26.3	32.1	37.2	29.6	36.9	59.1	47.3	171.8
N_2O	14.8	0.1	0.3	0.4	0.7	0.3	0.4	1.0	1.3	47.7
NO_x	165.5	27.0	31.7	37.6	39.2	45.0	45.6	117.9	96.8	327.3
SO_x	(8.9)	7.5	22.5	42.1	43.9	16.7	38.2	35.9	57.3	61.3
PM	22.8	1.3	7.2	14.8	15.9	2.6	15.1	3.9	6.1	25.2
CO2eq	(4,671)	6,444	8,602	11,411	12,695	14,236	18,356	31,586	82,873	83,031

Source: the lifecycle emissions model documented in Delucchi (1997, 2000a).
Fuel = fuel used by vehicles; feed = feedstock used to make fuel; LPG = liquefied petroleum gases; CNG = compressed natural gas; RFG = reformulated gasoline; MeOH = methanol; EtOH = ethanol; CH_2 = compressed hydrogen; cellulose = a mixture of wood and grass; CO2eq. = CO_2 equivalent emissions (CO_2 + the CO_2-equivalent impact of all of the other gases listed in the table plus the impact of HFC-134a and CFC-12, which are not shown).

[a] Equal to g/GJ (part A of this table) multiplied by the GJ/km fuel consumption of the vehicle, divided by end use vehicular emissions. The fuel consumption is estimated on the basis of a 9.4 L/100-km (25 mpg) gasoline vehicle. The CO_2 "credit" for carbon fixation by biomass used to make biofuels (ethanol, in this table) is not included in the vehicular emissions portion of the calculated percentages.

Table 5 Emissions from the manufacture and assembly of materials and vehicles, year 2000, U.S.

Pollutant	Emissions (g/kg)[a]		Emissions (g/km)[b]		Emissions (% of end-use)[c]	
	LDGVs	**HDDVs**	**LDGVs**	**HDDVs**	**LDGVs**	**HDDVs**
CO_2	7,151	6,381	45	65	22%	6%
NMOCs	0.95	0.82	0.01	0.01	1%	1%
CH_4	18.79	15.83	0.12	0.16	329%	257%
CO	6.20	5.51	0.04	0.06	0%	1%
N_2O	0.20	0.20	0.00	0.00	1%	5%
NO_2	24.63	22.84	0.16	0.23	18%	1%
SO_2	25.18	23.84	0.16	0.24	266%	85%
PM	27.17	27.47	0.17	0.28	519%	35%
CO_2-eq.	7,071	6,253	45	63	16%	6%

Source: the LEM documented in Delucchi (1997, 2000a). LDGV = light-duty gasoline vehicle; HDDV = heavy-duty gasoline vehicle; CO_2-eq. = CO_2-equivalent emissions (CO_2 + plus the CO_2-equivalent of non-CO_2 GHGs).

[a] Emissions from the complete lifecycle of materials used in LDGVs and HDDVs, and from vehicle assembly and transport, as estimated by the LEM (grams-pollutant/kg-vehicle).

[b] Equal to g/kg emissions multiplied by the calculated weight of the vehicle, and divided by its assumed average lifetime mileage. The weight of the vehicle is a function of the fuel economy, which is assumed to be 9.4 L/100-km (25 mpg) for the LDGV, and 39 L/100-km (6 mpg) for the HDDV.

[c] Equal to g/mi emissions from materials+assembly+transport, divided by end-use emissions from the LDGV and HDDV (Table 3).

provide slight-to-moderate reductions in GHG emissions when used in light–duty vehicles. Alcohol (methanol and ethanol) and electricity (in battery EVs) provide less of a benefit. Wang (1999) reaches broadly similar conclusions, except that he estimates greater benefits for EVs and corn ethanol.

Table 6 Projected changes in fuelcycle CO_2-equivalent GHG emissions, relative to gasoline in light-duty vehicles

A. Year 2000

	Lifecycle emissions	
Fuel type	**fuel only**[a]	**fuel+vehicle**[b]
Baseline: Conventional gasoline (CO2-equivalent g/km)	*337.0*	*388.2*
Reformulated gasoline	-1.6%	-1.4%
Low-sulfur diesel fuel	-35.2%	-32.1%
Methanol (M85) made from natural gas	4.5%	3.9%
Compressed natural gas	-22.0%	-18.7%
Compressed hydrogen made from NG	-21.1%	-17.8%
LPG made from natural gas	-22.4%	-19.4%
LPG made from 57% natural gas and 43% crude oil	-20.1%	-17.4%
Ethanol (E90) from corn (NG and coal fuel input)	-3.4%	-2.9%
Ethanol (E90) made from 50% wood, 50% grass	-69.3%	-60.1%
EVs (electricity mix: 64% coal, 20% oil, 15% NG)	-12.4%	-1.4%

B. Year 2020

	Lifecycle emissions	
Fuel type	**fuel only**[a]	**fuel+vehicle**[b]
Baseline: Conventional gasoline(CO2-equivalent g/km)	*323.9*	*396.7*
Reformulated gasoline	-1.0%	-0.9%
Low-sulfur diesel fuel	-33.2%	-30.6%
Methanol (M85) made from natural gas	-3.6%	-3.1%
Compressed natural gas	-26.9%	-23.3%
Compressed hydrogen made from NG	-27.5%	-23.7%
LPG made from natural gas	-25.2%	-22.1%
LPG made from 57% natural gas and 43% crude oil	-23.2%	-20.4%
Ethanol (E90) from corn (NG input)	-15.8%	-13.8%
Ethanol (E90) made from corn (NG and coal input)	-11.0%	-9.6%
Ethanol (E90) made from 50% wood, 50% grass	-80.7%	-70.6%
EVs (generated from 64% coal, 20% oil, 15% NG)	-23.7%	-21.0%

Source: the LEM documented Delucchi (1997, 2000a). The baseline gasoline vehicle has a fuel consumption of 9.4 L/100-km (25 mpg).

[a] The lifecycle of the fuels, as outlined in the text.

[b] Includes CO_2-equivalent from the lifecycle of materials for vehicles, and from vehicle assembly and transport, in addition to the lifecycle of fuels.

In heavy-duty vehicular applications (results not shown here), CNG and LNG cause a 5-10% increase in emissions of GHGs (compared with diesel fuel), primarily because of the much lower thermal efficiency of NG HDVs (compared with diesel HDVs) and the lower energy requirements of diesel production (compared with gasoline production). On the other hand, the use of LPG in HDVs actually decreases greenhouse-gas emissions (compared with diesel fuel).

Ultimately, using natural gas instead of oil as a primary resource will reduce greenhouse-gas emissions if the lower carbon/GJ content of NG (about 13.8 kg-C/GJ vs. about 18.5 for gasoline or diesel [higher heating values]) is *not* offset by higher fuelcycle energy requirements or higher fuelcycle emissions of methane.

There is, naturally, a good deal of technical uncertainty in the analysis. Lifecycle CO_2-equivalent emissions from LPG and CNG vehicles can range from at least 30% less than those from gasoline vehicles, to about the same as those for gasoline vehicles, depending on the thermal efficiency of the NG engine relative to the gasoline engine, the magnitude of tailpipe CH_4 emissions, the CO_2-equivalency factor for CH_4, the amount of energy required to produce LPG, the source of LPG (refineries emit more GHGs than do NGL plants), the rate of loss of CH_4 from the NG system, and other factors. LPG is comparable to CNG, in spite of its higher carbon/GJ content, because of its lower fuelcycle emissions of CH_4, and lower fuelcycle energy requirements. Also, LPG tanks are lighter than CNG tanks and hence take less energy to make and are less of a drag on fuel economy.

4 ANALYSIS OF FORKLIFTS

4.1 Background

There are about half a million industrial forklifts in the U.S. About 80% of them use LPG; the rest use gasoline or diesel fuel (Stout, 1999a; Federal Register, 1999). In the category of "large spark-ignition nonroad mobile engines," forklifts appear to be the major source of emissions (Delucchi, 2000c). Because forklifts often operate indoors, where worker exposure to pollution is regulated by the Occupational Safety and Health Administration, emission levels, particularly of carbon monoxide (CO), are an important criterion in the choice between gasoline, diesel, LPG, CNG, and battery-electric forklifts. More recent concerns with the impacts of fuel choices on global climate have made emissions of GHGs another important criterion in the choice of fuel.

This section presents a total fuelcycle analysis of emissions of air pollutants and GHGs from LPG, CNG, gasoline, diesel, and battery-powered forklifts. Because I lack data on the weight and material composition of forklifts, I do not estimate emissions associated with the assembly of forklifts or with the lifecycle of materials used to make forklifts.

4.2 Applying the LEM to Forklifts

In the LEM, the upstream fuelcycle for forklift fuels -- that is, every stage or activity *except* vehicle end use and manufacture -- is the same as the upstream fuelcycle for transportation fuels. Of course, the energy use and emissions of forklifts are different from the energy use and emissions of highway vehicles. I estimate forklift emission factors, in grams of pollutant per horse-power-hour of brake work (g/bhp-hr), and, in order to convert the upstream emission factors from grams/GJ-fuel to grams/bhp-hr-work, estimate the thermal efficiency of forklift engines.

The EPA has developed a national nonroad emissions model, "NONROAD," which predicts emissions of urban air pollutants for five general fuel categories: diesel (2-stroke and 4-stroke combined), gasoline 2-stroke, gasoline 4-stroke, CNG (2-stroke and 4-stroke combined), and LPG

Table 7 In-use emission factors and fuel consumption for forklifts

Fuel	Model	Thermal	Emission factors (g/brake-kWh)[c]						
	year[a]	effic.[b]	*CH_4*	*Exh.*	*Evap.*	*CO*	*NO_x*	*PM*	*N_2O*
diesel	pre-1988[f]	0.268	0.08	2.35	~0	8.13	18.77	2.15	0.030
	1988-1997	0.268	0.11	2.80	~0	10.81	11.47	1.97	0.030
	1998-2003 [1]	0.274	0.08	1.97	~0	3.10	9.53	1.97	0.030
	2004-2007 [2]	0.280	0.07	1.11	~0	3.10	7.19	0.40	0.030
	2008+ [3]	0.285	0.05	0.54	~0	3.10	4.56	0.13	0.030
gasoline	pre-2002	0.254	0.40	13.41	4.39	375	8.05	0.13	0.032
	2002+	0.267	0.09	1.34	0.66	54	2.68	0.07	0.118
LPG	pre-2002	0.254	0.40	4.02	0.1%	80	16.09	0.03	0.032
	2002+	0.280	0.09	0.67	0.1%	32	2.41	0.02	0.118
CNG	pre-2002	0.254	4.02	2.01	0.1%	80	16.09	0.03	0.032
	2002+	0.280	1.14	0.34	0.1%	32	2.41	0.01	0.089

Source: see the brief discussion in the text here, and, for details, see Delucchi (2000c). Shaded rows indicate the emission factors used in the two model runs here. SO_x emission factors are not shown because they are calculated on the basis of the sulfur content o the fuel. Exh. = exhaust NMOC emissions; Evap. = evaporative NMOC emissions.

[a] The numbers in brackets refer to the emissions-level "Tier" in the EPA standards (EPA, 1997b, Federal Register, 1998).

[b] The thermal efficiency of the engine (the ratio of kWh of brake-work to kWh of fuel input [higher heating value]). I calculate the efficiency of pre-1988 diesel forklifts from data in Beardsley and Lindhjem (1998) and the efficiency of pre-2002 gasoline forklifts from data in EPA (1991). Then, I assume that the efficiency of diesel forklifts increases 2% at each Tier, and that post-2002 gasoline engines are 5% more efficient than pre-2002 engines. On the basis of data on automotive engines, I assume that pre-2002 LPG and CNG forklift engines have the same efficiency as their gasoline counterparts, but that post-2002 LPG and CNG forklift engines are 5% more efficient than their gasoline counterparts.

[c] Except evaporative emissions for CNG and LPG, given in % loss.

(2-stroke and 4-stroke combined) (Lindhjem, 1998; Pollack and Lindhjem, 1997). I base my emission factors (shown in Table 7) partly on the estimates from NONROAD, partly on recently promulgated or anticipated emissions standards for forklifts (EPA, 1999b, 1997b; Federal Register, 1999, 1998; Stout, 1999b), partly on other EPA emissions data (EPA, 1991), and partly on emissions data from CNG and LPG highway vehicles (Delucchi, 2000a, 2000c).

4.3 Energy Use of Forklifts

Emissions of criteria pollutants and GHGs should be estimated per unit of service provided, so that alternative fuels and technologies can be compared holding the major "benefit" -- the service provided -- constant. In the case of highway vehicles, the service is km of travel, and hence the ultimate emission measure of interest is grams emitted per km of travel. Unfortunately, the case of forklifts is more complicated, because forklift engines provide two different services: lifting other things (measured, say, in feet of lift) and propelling themselves (measured, say in km of travel).

The problem, ultimately, is that inherent differences in the weight of forklifts, due to differences in fuel storage and drivetrain systems, affect the self-propelling service, but not the lifting service. (CNG and battery forklifts need extra energy to move themselves, because of their heavy tanks, but not to lift things.) I use my judgment to combine the lifting and the moving service in an integrated measure: I assume that about 1/3 of the engine output of a forklift goes to lifting, and 2/3 goes to propelling the forklift, and calculated a weighted engine output accordingly.

Electric forklifts. The energy use of the electric forklift is calculated as the product of the energy consumption of the gasoline forklift and the ratio of the efficiency of the gasoline driveline to the efficiency of the electric driveline. I assume that the electric driveline does not have regenerative braking. The resultant gasoline/EV efficiency ratio is in the range of 20-25%. (See Delucchi [1999] for analyses of electric drivetrains in automobiles.)

4.4 Results of the Evaluation: Indoor and Urban Air Pollutants and GHGs from Forklifts

I analyze 1997 model-year forklifts in calendar-year 2000, and 2017 model-year forklifts in calendar-year 2020. (Forklifts have a life of 6-7 years [Lindhjem and Beardsley, 1998; Stout, 1999a], and hence will be at the midpoint of their life in the calendar years of this analysis.) The 1997 model year generally is not be subject to stringent controls, whereas the 2017 model year will be (EPA, 1997b; Federal Register, 1998, 1999). As we shall see, this difference actually affects CO_2-equivalent GHG emissions significantly.

As indicated by the emission factors of Table 7, CNG and LPG forklifts can offer significant reductions in emissions of indoor and urban air pollutants. Most beneficial are the reduction in PM emissions compared to diesel, due mainly to the gaseous state and simple chemical structure of LPG fuel, and the reduction in the CO emissions compared to gasoline.

Emissions of urban air pollutants from the upstream stages of the transportation-fuel lifecycle are the same as in the analysis for highway vehicles, and are discussed in that section and shown in Table 4.

Table 8 shows changes in fuelcycle CO_2-equivalent GHG emissions when using gasoline, CNG, LPG, and battery power, compared to using diesel fuel, in forklifts. In the near-term (year 2000, model-year 1997) analysis, emissions of regulated pollutants, such as CO, contribute significantly to CO_2-equivalent fuelcycle emissions. Indeed, the very high CO emissions from

Table 8 Fuelcycle CO_2-equivalent GHG emissions from forklifts

A. Calendar year 2000 (model year 1997)

Forklift fuel	g-CO_2-eq. /b-kWh[a]	% change vs. diesel
Diesel fuel	1,067	--
Gasoline	2,202	106%[b]
LPG (95% propane) from 57% NGLs and 43% LRGs	976	-9%
LPG (95%) from 100% NGLs	943	-12%
LPG (95%) from 100% LRGs	1,019	-5%
Compressed natural gas	1,014	-5%
Electricity (generated from 55% coal, 13% NG, 3% oil)	646	-39%
Electricity (generated from 100% natural gas)	629	-41%
Electricity (generated from 100% fuel oil)	890	-17%
Electricity (generated from 100% coal)	974	-9%

B. Calendar year 2020 (model year 2017)

Forklift fuel	g-CO_2-eq. /b-kWh[a]	% change vs. diesel
Diesel fuel	1,033	--
Gasoline	1,285	24%
LPG (95% propane) from 57% NGLs and 43% LRGs	894	-13%
LPG (95%) from 100% NGLs	869	-16%
LPG (95%) from 100% LRGs	929	-10%
Compressed natural gas	878	-15%
Electricity (generated from 55% coal, 13% NG, 3% oil)	656	-37%
Electricity (generated from 100% natural gas)	453	-56%
Electricity (generated from 100% fuel oil)	852	-18%
Electricity (generated from 100% coal)	1,004	-3%

Source: the LEM documented in DeLuchi (1991,1993) and Delucchi (1997, 2000a). NGLs = natural gas liquids; LRG = liquefied refinery gases; NG = natural gas; CO_2-eq. = CO_2 equivalent.

[a] Grams of CO_2-equivalent emissions per brake-kWh of output. Here, the brake-kWh output is adjusted for the effect of weight on energy consumption, as discussed in the text. (The emission factors of Table 7 are not adjusted.)

[b] This is not a typographical error. The extremely high CO emissions (see Table 7), multiplied by the CO_2-equivalency factor for CO, result in a doubling of fuelcycle emissions for gasoline compared to diesel.

unregulated gasoline forklifts (see Table 7) have a greater CO_2-equivalent impact than emissions of CO_2 itself! Put another way, the EPA emission factors used here imply that most of the fuel used by gasoline forklifts is only partially burned[3], with the result that most of the fuel carbon ends up as CO, not CO_2. This seems a bit implausible, but such are the EPA emission factors.

As a result, for the year 2000, CNG and LPG, which have lower emissions of criteria pollutants than does gasoline, have *much* lower fuelcycle CO_2-equivalent emissions than does gasoline. However, they have slightly higher emissions than does diesel, on account of the greater efficiency and lower criteria pollutant emissions of diesel engines in the year 2000. Battery-powered forklifts, with their highly efficient electric drivetrains, have the lowest fuelcycle emissions of all.

For the longer-term scenario (calendar year 2020, model-year 2017), the picture changes somewhat, because criteria pollutants from spark-ignition engines are greatly reduced by controls assumed to be introduced with the 2002 model year. These controls, combined with assumed efficiency increases, actually bring fuelcycle CO_2-equivalent emissions from CNG and LPG forklifts to below those from diesel forklifts (Table 8). Battery-powered forklifts realize an even greater benefit, on account of increased drivetrain efficiency, and the assumed shifting of the electricity generation mix towards natural gas.

5 ANALYSIS OF SPACE HEATING AND WATER HEATING

5.1 Background

In the U.S., households and commercial buildings account for about 36% of total energy end-use, and 36% of total fossil-fuel CO_2 emissions (EIA, 1998a; EPA, 1999a). Space heating and water heating alone account for 10-15% of total energy end-use and fossil-fuel CO_2 emissions.

Table 9 disaggregates total residential and commercial energy consumption by end-use and energy source. Most households and buildings heat with natural gas, but a significant number use fuel oil, electricity, and even propane. As we shall see, there are large differences in fuelcycle CO_2-equivalent emissions among these energy sources, and as a result, changes in the energy mix for space heating and water heating can have an appreciable effect on emissions of greenhouse gases.

Although households and commercial buildings are major consumers of energy, they are comparatively minor sources of urban air pollutants: they account for only about 5% of NO_x and SO_x emissions, and less than 1% of PM, CO, and VOC emissions (EPA, 1997a). This discrepancy between energy use and emissions of urban air pollutants is attributable to the relatively low g/GJ emission factors for residential and commercial fuel combustion (Table 10).

5.2 Applying the LEM to Space Heating and Water Heating

In this section, I apply the LEM to estimate lifecycle emissions from LPG, natural gas, fuel oil, and electricity for space heating and water heating.

The LEM has separate lifecycles for heating fuels. In the model, the "upstream" lifecycle of a fuel used for space heating and water heating is the same as the upstream lifecycle of the same kind of fuel used in transportation, except for obvious differences in fuel distribution and dispensing. For example, the upstream NG-to-heating fuelcycle is the same as the upstream NG-to-CNG fuelcycle, except that in the former there is no final high-pressure compression stage. Generally, I assume that the distribution of LPG or fuel oil to residential or commercial users is the same as the distribution of LPG or diesel fuel to motor-vehicle service stations. I also assume that the refinery processes that produce No. 2 distillate fuel oil for heating are the same as those that produce No. 2 distillate diesel fuel for highway trucks.

Table 9 Distribution of energy used by households and commercial buildings

A. Households, 1997

End use	NG	electricity	fuel oil	LPG	*Total*
space heating	35.3%	3.9%	8.9%	2.5%	50.6%
water heating	12.6%	3.8%	1.6%	0.8%	18.8%
air conditioning	0.0%	4.1%	0.0%	0.0%	4.1%
refrigerators	0.0%	4.5%	0.0%	0.0%	4.5%
lights, appliances	3.6%	18.3%	0.0%	0.2%	22.1%
Total	51.5%	34.6%	10.4%	3.5%	100.0%

B. Commercial Buildings, 1995

End use	NG	electricity	fuel oil	district heat	*Total*
space heating	20.5%	2.1%	2.6%	6.8%	32.0%
water heating	9.8%	0.9%	1.3%	3.3%	15.2%
air conditioning	0.2%	6.4%	0.0%	0.0%	6.6%
refrigerators	0.0%	3.4%	0.0%	0.0%	3.4%
lights, appliances	6.1%	36.2%	0.5%	0.0%	42.7%
Total	36.6%	49.0%	4.4%	10.0%	100.0%

Source: EIA (1999, 1998d). Electricity is on-site consumption. Commercial buildings probably consumed an additional 0.1 EJ of LPG (EIA, 1998a).

The EPA (1990, 1995) provides emission factors for residential and commercial fuel combustion, for most pollutants. Table 10 shows the emission factors assumed in this analysis. I assume that the emission factors, which nominally are for space heating, apply to water heating as well.

5.3 Energy Efficiency of Residential and Commercial Fuel Combustion

As mentioned above, emissions of criteria pollutants and GHGs should be estimated per unit of service provided, so that fuels and technologies can be compared holding at least the major "benefit" -- the service provided -- constant. In the case of space heating and water heating, the service is useful heat: heat transferred from the heater to the air or surface. This is calculated by dividing an intermediate result, grams per GJ of fuel or electricity, by the thermal efficiency of the heat source. The thermal efficiency, discussed next, is defined as the ratio GJ of useful heat provided to GJ of fuel or electrical energy input to the heating device.

Table 10 Emission factors assumed in this analysis (G/GJ)

Pollutant	Natural gas	LPG	Fuel oil
CH_4	1.1	1.6	5.6
N_2O	0.9	0.9	0.9
Total NMOCs	2.2	2.4	2.2
CO	8.2	9.2	15.5
NO_x (NO_2)	41.1	35.3	55.8
SO_x	sulfur content	sulfur content	sulfur content
PM	0.5	0.6	1.9
PM_{10}	0.5	0.6	1.0
$PM_{2.5}$	0.5	0.6	0.8

Source: NMOC, CO, and NO_x estimates are from EPA (1990). CH_4 estimates are based on EPA's *Compilation of Air Pollutant Emission Factors,* widely known as AP-42 (EPA, 1995). N_2O estimates based on Delucchi and Lipman (1997). SO_x estimated on the basis of the sulfur content of the fuel (EIA, 1998b, 1998c; Delucchi, 2000c). PM estimates based on AP-42 (EPA, 1995), and my judgment. See Delucchi (2000c) for details. The IPCC (1997) adopts emission factors from AP-42 (EPA, 1995) and from a 1990 report by Radian Corporation.

The thermal efficiency has two components: the efficiency of conversion of chemical or electrical energy to heat, and the efficiency of heat transfer to the air or surface. As regards conversion, fuel combustion and resistance heating are essentially 100% efficient, unless, in the case of fuel combustion, the burner is operating poorly or with insufficient air.

There is significant variability in the transfer efficiency. For electric heaters, which radiate directly into the space or onto the surface of interest, the transfer efficiency is close to 100%. However, for fuel burners, the transfer efficiency can vary from 60% to close to 100%, depending on how much heat and vapor is lost in combustion gases. Units that vent directly to the atmosphere, without dampers, are 60-70% efficient; units with dampers are about 80% efficient. Condensing or recuperative units, which capture most of the water vapor and heat that would normally be vented, are up to 97% efficient. Under U.S. federal law, all gas furnaces manufactured after January 1, 1992, must have a thermal efficiency of at least 78% (California Energy Commission, 2000).

I assume that electric heaters have a thermal efficiency of 100%, and that NG, fuel oil, and LPG heaters have an efficiency of 85%.

5.4 Results of the Analyses: Urban Air Pollutants and GHGs from Heating Fuels

Table 10 shows emission factors for residential and commercial fuel combustion. As one would expect, fuel oil generally is the most polluting fuel, with comparatively high emissions of the most damaging pollutants: NO_x, SO_x, and PM. What is most interesting in the case of heating fuels is the comparison of end-use with upstream emissions of urban air pollutants. Given that upstream emissions for heating fuels are similar to those for transportation fuels (Table 4), we see that upstream fuelcycle activities emit more of all pollutants -- including CO, NO_x, and NMOCs -- than does heating end use. This dominance of the upstream activities is more pronounced here than in the case of transportation fuels, because low-temperature external combustion for heating is much cleaner than high-temperature internal combustion in engines (a point discussed more below). On the other hand, personal exposure to emissions from residential and commercial fuel combustion undoubtedly is greater than exposure to emissions from motor vehicles. In any event, switching from fuel oil to NG or LPG will improve urban and indoor air quality.

Table 11 shows the total fuelcycle CO_2-equivalent emissions estimated by the LEM for 2000 and 2020. Natural gas has the lowest fuelcycle emissions. LPG has the next lowest, followed by fuel oil, and then electricity from various sources. The differences between the estimates for 2000 and the estimates for 2020 are not important.

There are two significant differences between the fuelcycle CO_2-equivalent results estimated here for space heating and water heating, and the results estimated for the use of transportation fuels.

First, in the case of space heating and water heating, natural gas has somewhat lower emissions than LPG, whereas in the transportation case, LPG and CNG are about the same. This difference is due mainly to end-use emissions of methane: natural gas vehicles have relatively high emissions of CH_4, but natural gas heaters have very low emissions. For example, in the case of transportation, end-use emissions of CH_4 from CNG vehicles are, by themselves, more than 10% of total fuelcycle CO_2-equivalent emissions, and also 10 times higher than CH_4 emissions from LPG vehicles. However, in the case of space heaters, CH_4 emissions from natural gas are less than 0.1% of total fuelcycle emissions. Moreover, CH_4 emissions from natural gas heaters are, according to the EPA emission factors, slightly *less* than CH_4 emissions from LPG (Table 10)[4]. Another, less important factor is that in the case of transportation, there are significant emissions associated with compressing the natural gas at the end of the pipeline, whereas in the case of heating with NG there is not.

The second significant difference between the heating results and the transportation results is the poor showing of electricity as a source of heat. In this analysis, electricity has fuelcycle emissions two to four times higher than those for NG, LPG, or fuel oil, whereas in the case of transportation, electric vehicles have somewhat lower fuelcycle emissions than do gasoline, and only slightly higher emissions than do diesel, CNG, or LPG vehicles. This is attributable to a dramatic difference in end-use efficiency. The electric vehicle is roughly four times more efficient at converting a GJ of electricity (from the wall) into a km of travel than an internal combustion engine vehicle is at converting a GJ of fuel into a km of travel, but an electric resistance heater is only 10-20% more efficient at converting a GJ of electricity into a GJ of useful heat than a fuel burner is at converting a GJ of fuel into a GJ of useful heat. Put another way, internal-combustion heat engines are much less efficient at providing work then external combustion devices are at providing heat, and hence electricity can be an efficient substitute for the former, but not the latter.

Table 11 Fuelcycle CO_2-equivalent emissions for space and water heating

A. Year 2000

Fuel (Feedstock)	g/GJ[a]	% ch. vs. NG[b]
Natural gas	72,980	--
LPG (57% NGLs, 43% LRGs)[c]	85,807	11%
LPG (100% NGLs)	82,915	8%
LPG (100% LRGs)	89,615	16%
Fuel oil (crude oil)	99,202	29%
Electricity (from 55% coal, 13% NG, 3% oil)[d]	203,280	164%
Electricity (generated from 100% natural gas)	197,828	157%
Electricity (generated from 100% fuel oil)	279,770	263%
Electricity (generated from 100% coal)	306,095	298%

B. Year 2020

Fuel (Feedstock)	g/GJ[a]	% ch. vs. NG[b]
Natural gas	71,806	--
LPG (57% NGLs, 43% LRGs)[c]	85,067	12%
LPG (100% NGLs)	82,420	9%
LPG (100% LRGs)	88,553	17%
Fuel oil (crude oil)	100,861	33%
Electricity (from 55% coal, 13% NG, 3% oil)[d]	201,519	166%
Electricity (generated from 100% natural gas)	139,365	84%
Electricity (generated from 100% fuel oil)	261,909	246%
Electricity (generated from 100% coal)	308,752	308%

NGLs = natural gas liquids; LRGs = liquefied refinery gases; LPG = liquefied petroleum gas (assume 95% propane, 5% butane).

[a] Grams of CO_2-equivalent emissions over the entire fuelcycle, per GJ of useful heat provided.

[b] The percentage change in g/GJ-useful-heat, relative to natural gas.

[c] The average feedstock mix for LPG consumed in the U.S.

[d] The projected U.S. average electricity mix in the year shown.

6 CONCLUSIONS

Among the major near-term alternative fuels for highway vehicles, LPG, especially made from natural gas, and CNG appear to have very low vehicular and upstream emissions of urban air pollutants. Ignoring potentially important economic impacts of alternative fuel policies, and considering only the "technological-systems" effects of fuel substitution, the LEM also indicates that the substitution of LPG or for gasoline would reduce fuelcycle emissions of GHGs in the near term by 20% or more.

Forklifts using LPG (especially LPG made from natural gas) or CNG can have relatively low end-use and fuelcycle emissions of urban and indoor air pollutants. The emissions model also indicates that the substitution of LPG or CNG for gasoline would substantially reduce fuelcycle emissions of GHGs. Diesel forklifts emit about as much as GHGs as do LPG and CNG forklifts; battery-powered forklifts emit less. Unregulated gasoline forklifts have very high emissions of CO -- so large, in fact, that the CO_2-equivalent of the CO emission exceeds the actual emissions of CO_2.

Natural gas and LPG for space heating and water heating have relatively low fuelcycle emissions of GHGs and criteria pollutants. Natural gas appears to have slightly lower fuelcycle emissions of GHGs than does LPG, mainly because, in the case of external combustion devices, unlike in the case of internal combustion engines, the higher carbon content of LPG is *not* offset by higher emissions of methane and higher emissions from gas compression in the natural gas fuelcycle. From the standpoint of energy efficiency and CO_2-equivalent emissions, fossil-fuel electricity is a poor choice for space heating and water heating, because electricity generation from fossil-fuel combustion wastes 60-70% of the heat of combustion, whereas direct heating by fossil-fuel combustion wastes only 10-20%.

Given the uncertainties in the analysis of greenhouse gas emissions, and the importance of improving urban air quality, one can conclude that the use of LPG or natural gas is likely to help improve urban air quality (especially PM and ozone air quality), without harming (and perhaps benefiting) the global environment. It is important to look beyond end-use emissions and consider the entire lifecycle, because emissions from "upstream" fuelcycle activities, and from the lifecycle of materials, can be significant relative to end-use emissions. Findings for one sector, such as highway vehicles, do not necessarily apply to other sectors, such as offroad engines or residential heating, on account of important differences in end-use energy efficiency and emissions.

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REFERENCES

Beardsley, M. and C.E. Lindhjem, *Exhaust Emission Factors for Nonroad Engine Modeling -- Compression Ignition,* Report No. NR-009A, Environmental Protection Agency, Office of Mobile Sources, Assessment and Modeling Division, February 13, 1998, revised June 15 (1998).

California Energy Commission, Web pages: (www.energy.ca.gov/efficiency/appliances/); (www.energy.ca.gov/energydoctor/); (www.energy.ca.gov/reports/title24/); accessed January (2000).

Clinton, W.J. and A.J. Gore, *The Climate Change Action Plan,* Office of the President of the United States, Washington, D.C., October (1993).

Delucchi, M.A., *Lifecycle Energy Use, Greenhouse-Gas Emissions, and Air Pollution from the Use of Transportation Fuels and Electricity,* working draft, Institute of Transportation Studies, University of California, Davis, March (2000a).

Delucchi, M.A., Environmental Externalities of Motor-Vehicle Use in the U.S., *Journal of Transport Economics and Policy,* 34:135-168, May (2000b).

Delucchi, M.A., *LPG and other alternative fuels for highway vehicles, forklifts, and household heating: A fuelcycle analysis of emissions of urban air pollutants and greenhouse-gases,* UCD-ITS-RR-XX, Institute of Transportation Studies, University of California, Davis, March (2000c).

Delucchi, M.A., *Motor-Vehicle Lifecycle Cost and Energy-Use Model,* UCD-ITS-RR-99-4, report to the California Air Resources Board, revised final report, Institute of Transportation Studies, University of California, Davis, (April 28 1999).

Delucchi, M.A. and T.E. Lipman, *Emissions of Non-CO_2 Greenhouse Gases from the Production and Use of Transportation Fuels and Electricity,* UCD-ITS-RR-97-5, Institute of Transportation Studies, University of California, Davis, February (1997).

Delucchi, M.A., *A Revised Model of Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity,* UCD-ITS-RR-97-22, Institute of Transportation Studies, University of California, Davis, November (1997).

Delucchi, M.A. and D.R. McCubbin, *The Contribution of Motor Vehicles and Other Sources to Ambient Air Pollution,* UCD-ITS-RR-96-3(16), Institute of Transportation Studies, University of California, Davis, August (1996).

DeLuchi, M.A., *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity,* Appendices A-S, ANL/ESD/TM-22, 2, Center for Transportation Research, Argonne National Laboratory, Argonne, Illinois, November (1993).

DeLuchi, M.A., *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity,* ANL/ESD/TM-22, Volume 1, Center for Transportation Research, Argonne National Laboratory, Argonne, Illinois, November (1991).

Energy Information Administration, U.S. Department of Energy, Washington, D.C., (http://www.eia.doe.gov/cneaf/solar.renewables/alt_trans_fuel97/table1.html), accessed March (2000)

Energy Information Administration, *A Look at Residential Energy Consumption in 1997,* DOE/EIA-0632(99), U.S. Department of Energy, Washington, D.C., November (1999).

Energy Information Administration, *Annual Energy Review 1997,* DOE/EIA-0384(97), U.S. Department of Energy, Washington, D.C., July (1998a).

Energy Information Administration, *Fuel Oil and Kerosene Sales 1997,* DOE/EIA-0535(97), U.S. Department of Energy, Washington, D.C., August (1998b).

Energy Information Administration, *Petroleum Supply Annual 1997*, DOE/EIA-0340(97/1), U.S. Department of Energy, Washington, D.C., June (1998c).

Energy Information Administration, *A Look at Commercial Buildings in 1995*, DOE/EIA-0625(95), U.S. Department of Energy, Washington, D.C., October (1998d).

Environmental Protection Agency, Office of Policy, Planning, and Evaluation, *Inventory of U.S. Greenhouse-Gas Emissions and Sinks: 1990-1997*, EPA 236-R-99-003, Washington, D.C., April (1999a).

Environmental Protection Agency, Office of Air and Radiation and Office of Mobile Sources, *Regulatory Announcement -- Proposed Finding on Emission Standards for New Large Spark-Ignition Nonroad Engines*, EPA420-F-99-004, Washington, D.C., January (1999b).

Environmental Protection Agency, Office of Air Quality Planning and Standards, *National Air Quality and Emissions Trends Report, 1997*, EPA-454/R-98-016, Research Triangle Park, North Carolina, December (1998).

Environmental Protection Agency, Office of Air Quality Planning and Standards, *National Air Pollutant Emissions Trends, 1900-1996*, EPA-454/R-97-011, Research Triangle Park, North Carolina, December (1997a).

Environmental Protection Agency, Office of Air and Radiation, *Emission Standards Reference Guide for Heavy-Duty and Nonroad Engines*, EPA420-F-97-014, Washington, D.C., September (1997b).

Environmental Protection Agency, Office of Research and Development, *Air Quality Criteria for Ozone and Related Photochemical Oxidants*, EPA/600/P-93/004F, Washington, D.C., July (1996a).

Environmental Protection Agency, Office of Research and Development, *Air Quality Criteria for Particulate Matter*, EPA/600/P-95/001F, Washington, D.C., April (1996b).

Environmental Protection Agency, Office of Air Quality Planning and Standards, *Compilation of Air Pollutant Emission Factors, Vol. I, Stationary Sources*, AP-42, fifth edition, Research Triangle Park, North Carolina, January (with supplements through 1998) (1995).

Environmental Protection Agency, Office of Air and Radiation, *Nonroad Engine and Vehicle Emission Study - Report*, 21A-2001 (NTIS PB92-126960/AS), Washington, D.C., November (1991).

Environmental Protection Agency, Office of Air Quality Planning and Standards, *AIRS Facility Subsystem Source Classification Codes and Emission Factor Listing for Criteria Pollutants*, EPA 450/4-90-003, Research Triangle Park, North Carolina, March (1990).

Federal Highway Administration, *Highway Statistics 1998*, FHWA-PL-99-017, U.S. Department of Transportation, Washington, D.C., November (1999).

Federal Register, **64**(25), Environmental Protection Agency, 40 CFR Part 83, *Control of Emissions from New Nonroad Spark-Ignition Engines Rated Above 19 Kilowatts and New Land-Based Recreational Spark-Ignition Engines*, pp. 6008-6013 February 8 (1999).

Federal Register, **63**(205), Environmental Protection Agency, 40 CFR Parts 9, 86, and 89, *Control of Emissions of Air Pollution from Nonroad Diesel Engines*, pp. 56967-57203, October 23 (1998).

Hammitt, J.K., A.K. Jain, J.L. Adams and D.J. Wuebbles, A Welfare-Base Index for Assessing Environmental Effects of Greenhouse-Gas Emissions, *Nature*, **381**:301-3023, May 23 (1996).

Intergovernmental Panel on Climate Change, *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 3: The Greenhouse Gas Inventory Reference Manual*, Paris, France (1997).

Intergovernmental Panel on Climate Change, *IPCC, Climate Change 1995: The Science of Climate Change*, J.T. Houghton et al. (eds.), Cambridge University Press, Cambridge (1996a).

Intergovernmental Panel on Climate Change, *IPCC, Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*, R.T. Watson et al. (eds.), Cambridge University Press, Cambridge (1996b).

Kandlikar, M., Indices for Comparing Greenhouse-Gas Emission: Integrating Science and Economics, *Energy Economics*, 18, 265-281 (1996).

Kreucher, W.M., *Economic Environmental, and Energy Life-Cycle Inventory of Aumotive Fuels*, Society of Automotive Engineers Technical Paper Series, #982218, Society of Automotive Engineers, Warrendale, Pennsylvania (1998).

Lindhjem, C.E., *Nonroad Engine Population Estimates*, Report No. NR-006A, Environmental Protection Agency, Office of Mobile Sources, Assessment and Modeling Division, December 9, 1997, revised June 15 (1998).

Lindhjem, C.E. and M. Beardsley, *Median Life, Annual Activity, and Load Factor Values for Nonroad Engine Emissions Modeling*, Report No. NR-005A, Environmental Protection Agency, Office of Mobile Sources, Assessment and Modeling Division, December 9, 1997, revised June 15 (1998).

MacLean, H.L. and L.B. Lave, Environmental Implications of Alternative-Fueled Automobiles: Air Quality and Greenhouse-Gas Tradeoffs, *Environemtnal Science and Technology*, 34(2):225-231 (2000).

MacLean, H.L. and L.B. Lave, A LifecycleModel of an Auotmobile, *Environmental Sciece and Technology*, 32(13):A322-A330 (1998).

McCubbin, D.R. and M.A. Delucchi, The Health Costs of Motor-Vehicle Related Air Pollution, *Journal of Transport Economics and Policy*, 33:253-286 (1999).

New Fuels and Vehicles Report, GM Plans Two New Dedicated LPG Vehicles; Both Firsts for Industry, p. 2, February 17 (2000).

Pollack, A.K. and C.E. Lindhjem, Nonroad Mobile Emissions Modeling, paper proposed for presentation at, *The Emission Inventory: Planning for the Future*, Research Triangle Park, North Carolina, October 28-30 (1997).

Society of Automotive Engineers, *Total Lifecycle Conference and Exposition, Proceedings (April 26-28, 2000, Detroit, Michigan)*, Society of Automotive Engineers, Warrendale, Pennsylvania, April (2000).

Sperling, D. and M.A. DeLuchi, *Choosing an Alternative Transportation Fuel: Air Pollution and Greenhouse Gas Impacts*, Organization for Economic Cooperation and Development, Paris (1993).

Stout, A., *Emission Modeling for Large SI Engines*, Memo to Docket A-98-01, Environmental Protection Agency, Office of Air and Radiation, Washington, D.C., January 28 (1999a).

Stout, A., *California Requirements for Large SI Engines and Possible EPA Approaches*, Memo to Docket A-98-01, Environmental Protection Agency, Office of Air and Radiation, Washington, D.C., January 29 (1999b).

Sullivan, J.L., R.L. Williams, S. Yester, E. Cobas-Flores, S.T. Chubbs, S.G. Hentges and S.D. Pomper, *Life Cycle Inventory of a Generic U.S. Family Sedan, Overview of Results of USCAR AMP Project*, Society of Automotive Engineers Technical Paper Series, #982160, Society of Automotive Engineers, Warrendale, Pennsylvania (1998).

Tol, R.S.J., The Marginal Costs of Greenhouse Gas Emissions, *The Energy Journal*, 20(1):61-81 (1999).

United Nations Environment Programme and World Health Organization, *Assessment of Urban Air Quality*, prepared in cooperation with the Monitoring and Assessment Research Centre, London (1988).

U.S. General Accounting Office, *Energy Policy Act: Including Propane as An Alternative Motor Fuel Will Have Little Impact on Propane Market*, GAO/RCED-98-260, Washington, D.C. (1998).

Wang, M.Q., *Greet 1.5 -- Transportation Fuel-Cycle Model*, ANL/ESD-39, Center for Transportation Research, Argonne National Laboratory, Argonne, Illinois, August (1999).

World Health Organization, *Motor Vehicle Air Pollution: Public Health Impact and Control Measures*, WHO/PEP/92.4, Geneva, Switzerland (1992).

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[1] The *Total Lifecycle Conference and Exposition* (Society of Automotive Engineers, 2000) presents current lifecycle analyses of motor vehicles and motor fuels. Generally, these analyses examine individual or limited sets of fuels and vehicles (e.g., "biodiesel" vs. conventional petroleum diesel; hybrid electric vehicles vs. conventional gasoline vehicles), specific parts of the lifecycle (e.g., vehicle manufacture, or end of life), and specific classes of pollutants (e.g., some urban air pollutants, or some greenhouse gases). Wang (1999) reviews lifecycle analyses of alternative transportation fuels prior to 1999.

[2] A recent report by the U.S. General Accounting Office (GAO) (1998) report gives some indication of the complexities involved in trying to model how changes in propane use affect price, and then how changes in price affect use. The report found that "the petrochemical sector is likely to reduce its propane consumption if the price of propane rises because a significant portion of the propane that sector sues can be replaced with other feedstocks, such as naphtha and ethane. However...switching feedstocks would also lead to increases in the prices of substitutes, resulting in an increase in industrial consumers' production costs" (U.S. GAO, 1998, p. 12).

[3] The emission factor of 375 g-CO/b-kWh corresponds to about 94 g-CO/fuel-kWh, or 40 g-C (in CO) per kWh of fuel. One kWh of conventional gasoline contains about 66 grams of carbon; thus, the EPA emission factor implies that more than half of the fuel carbon is incompletely burned!

[4] Is the difference in end-use emission factors reasonable? Heaters, like utility boilers, are external combustion devices, whereas car engines are internal combustion devices, and it does seem reasonable that external combustion is more complete, and hence produces less organic pollution (CH_4, CO, and NMOC), than does internal combustion. The EPA's emission factors for utility boilers, which are based on a large number of tests, show the same pattern as do the emission factors for space heaters: CH_4 emissions are a tiny fraction -- less than 0.01% -- of fuelcycle CO_2-equivalent emissions for natural-gas power plants. Moreover, the CH_4 emission factors for natural-gas turbines, which are internal combustion devices, are about 100 times those for utility boilers. CO and NMOC emissions have the same patterns.