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WHY WE SHOULD USE NUCLEAR ENERGY FOR TRANSPORTATION

ROBERT E. UHRIG

University of Tennessee

ruhrig@utk.edu

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Annual Emission of Carbon Dioxide by Gasoline, Hybrid Electric and Hydrogen-Fueled Light Transportation Vehicles

133,000,000 Automobiles

and

92,000,000 Light (4-Wheel) Utility Vehicles that Utilize Gasoline

(SUVs, Pickups, Panel Trucks, Delivery Vans, Minibuses, etc)

“Situation” is “Obscenely Out of Whack” *

* Tom Gage, AC Propulsion, “FLEETS & FUELS” November 14, 2005

Consumption of Gasoline per Person per Year

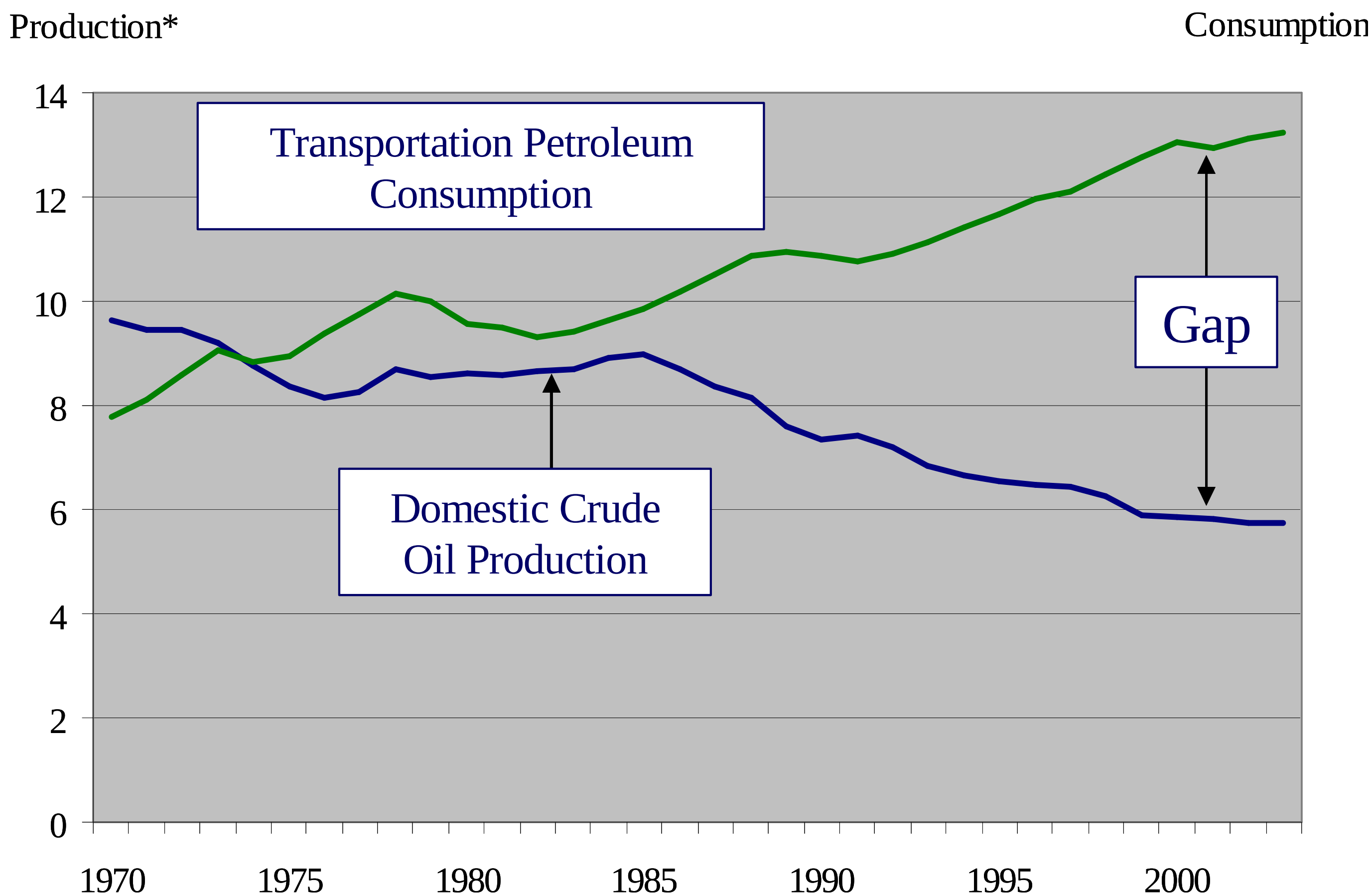
– United States	453 gallons
– European Community	133 gallons**
– Japan	124 gallons
– World Average	47 gallons
– World Average (w/o U.S.)	28 gallons
– China	10 gallons
– India	2 gallons

China and India have large and growing populations and use of gasoline is growing very rapidly

**Includes diesel fuel

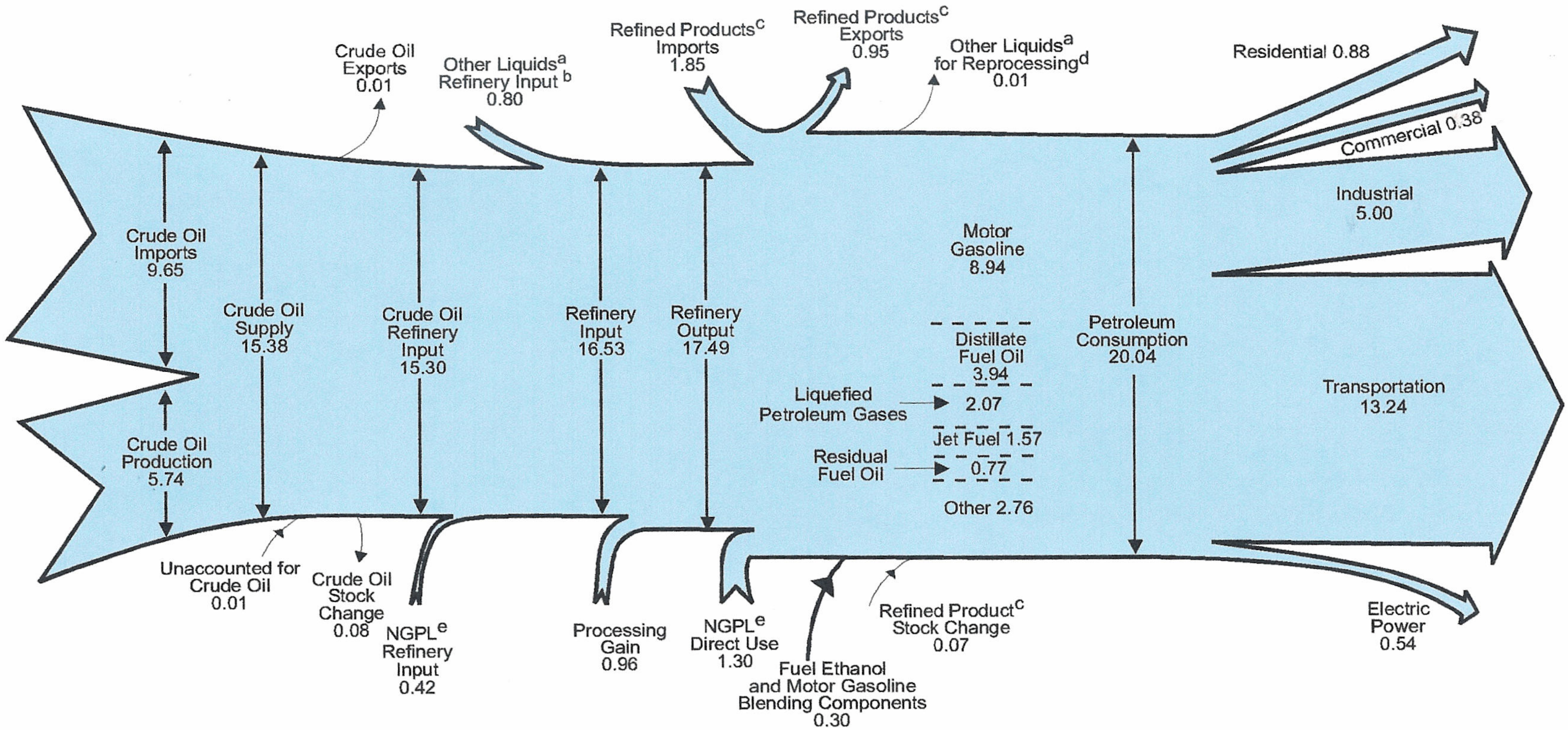
Transportation Sector

(million barrels per day)



*Graph assumes all the domestic oil production is devoted to the transportation sector.

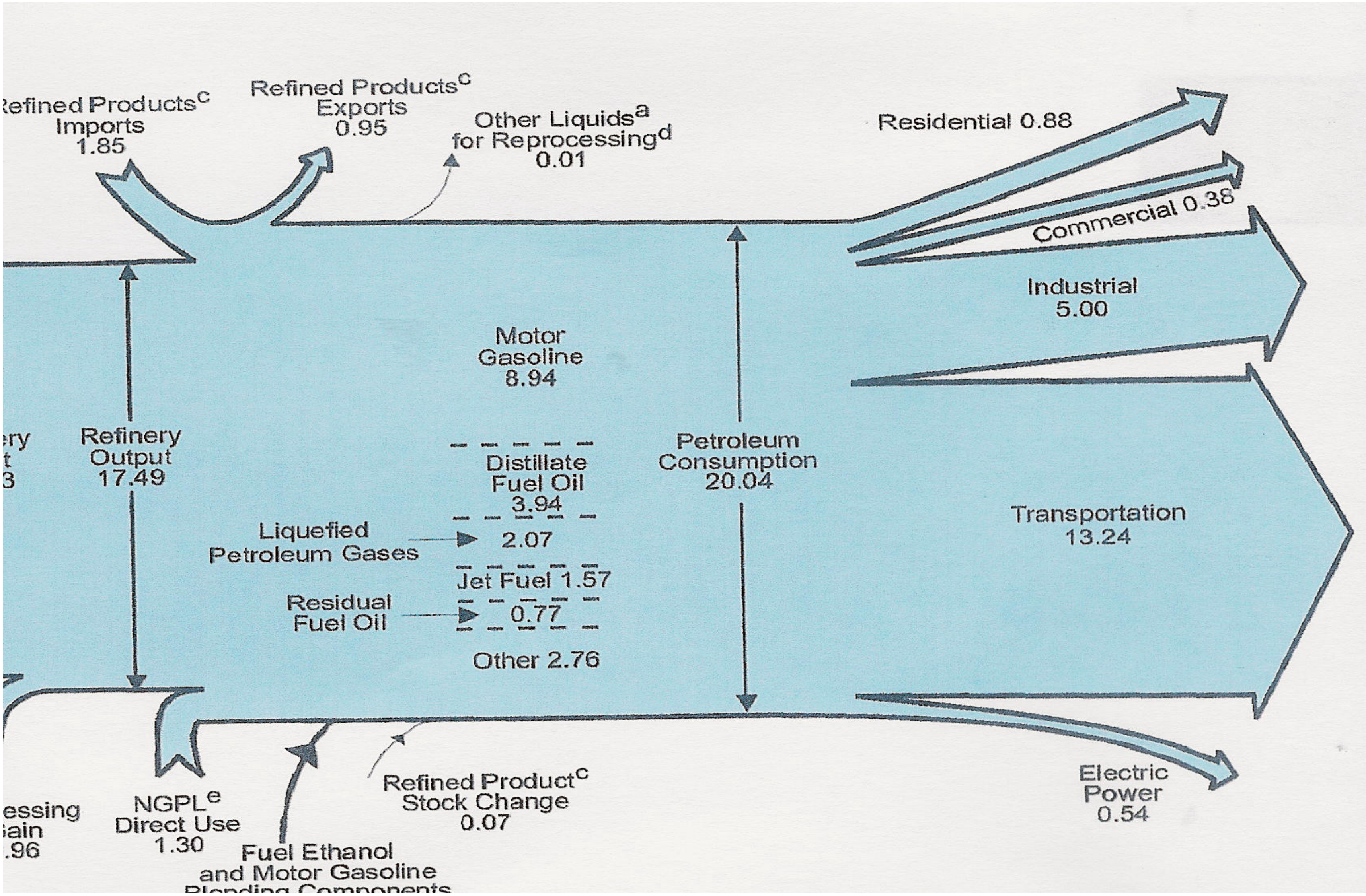
Diagram 2. Petroleum Flow, 2003
(Million Barrels per Day)



[a] Unfinished oils, motor gasoline blending components, aviation gasoline blending components, and other hydrocarbons and oxygenates.
[b] Field production (0.12), net imports (0.71), net change in stocks (-0.03), and reprocessing (0.01).
[c] Finished petroleum products, liquefied petroleum gases, and pentanes plus.
[d] Unfinished oils requiring further refinery processing, and aviation blending components.
[e] Natural gas plant liquids.

Notes: • Data are preliminary. • Totals may not equal sum of components due to independent rounding.
Sources: Tables 5.1, 5.3, 5.5, 5.8, 5.11, 5.13a-5.13d, 5.16, and *Petroleum Supply Monthly*, February 2004, Table 3.

Petroleum Flow 2003 (Millions of Barrels per Day)



GREENHOUSE GASES (CO_2)

Sunlight enters the Atmosphere, striking the earth and is reflected back towards space as infrared radiation (heat energy)

Greenhouse gases. Particularly carbon dioxide, absorb this infrared radiation (heat energy), trapping the heat in the atmosphere

Until about 150 years ago, the amount of energy absorbed was about the same amount as`that radiated back into space

At that time, the equilibrium was upset, and the concentration, particularly carbon dioxide (CO_2), began to increase and continues to increase at a rate that seems to parallel the increase in production of CO_2

At the same time, the average temperature of the atmosphere increased with subsequent climate changes that are thought by many to be a cause-effect relationship

GREENHOUSE GASES (CO_2)

- The principal greenhouse gases are:
  - Water vapor (60-65%) and Carbon Dioxide (CO_2) (20-25%)
- Water vapor stays in the atmosphere for a relative short time, a matter of hours or days
  - Water vapor remains at a relatively constant level related to the rate at which it is produced
- Carbon Dioxide has an average residence time of a century or more
  - CO_2 tends to accumulate as the amount emitted increases
- All other greenhouse gases (10-20%) tend to have lesser effects on the atmosphere over time because of smaller quantities and/or shorter residence times.

MODEL USED FOR CALCULATIONS BASED ON PREVIOUS WORK BY AUTHOR*

Vehicles are “average” size and weight

- Attain “average” of 20 miles/gallon
- 225 Million vehicles use 9 million barrels/day
- Travel “average” 12,264 miles/yr

Half of vehicles travel less than 20 miles/day

Assume: Half of Vehicles go 15 miles on electricity per day

Half of Vehicles go 35 miles on electricity and then Operate in a Full Hybrid Mode 17.2 miles per day (based on 9 million barrels of gasoline per day)

*****Robert E. Uhrig, “Using Plug-in Hybrid Vehicles to Drastically Reduce Petroleum-Based Fuel Consumpion and Emissions,” ***The BENT of Tau Beta Pi***, Vol. XCLI, No. 2, Spring,2005

*****Robert E. Uhrig, “Engineering Challenges of the Hydrogen Economy, ”***The BENT of Tau Beta Pi***, Vol. XCL, No. 2, Spring,2004

GASOLINE-FUELED VEHICLES

- **TerraPass**, a vendor dealing in carbon dioxide emission credits, has developed a "carbon dioxide calculator" that gives the emission of carbon dioxide for virtually all American automobiles for the past 20 years
- Experimenting with this calculator shows that the quantity of carbon dioxide emitted per hour is a direct function of the amount of gasoline used in that hour
- This calculator utilized the fact that the **combustion of one gallon of gasoline** will emit **19.56 pounds of carbon dioxide**
- Since the average gas mileage in our model is 20 miles per gallon, the emission of carbon dioxide is

$$[19.56 \text{ lb } CO_2 \text{ / gallon}] \; / \; [20 \text{ miles/gallon}] =$$

0.978 lb CO_2 per mile

CASE 1. GASOLINE FUELED LIGHT VEHICLE

DOE-EIA Data: 20 miles/gallon for 12,264 miles per year

The model for this analysis deals with average vehicles that achieve 20 miles per gallon, so the average greenhouse gas emission would be 0.978 lb CO_2 per mile

- Hence, the total annual emission of carbon dioxide is

0.978 lb CO_2 /mile x 7.56 x 10^9 miles/day x 365 days/year

= 2.699 x 10^{12} lb CO_2 /year

2.699 x 10^{12} lb CO_2 /year / 2200 lb/Metric ton

= 1.227 x 10^9 Tonnes/Year

2.699 x 10^{12} lb CO_2/year / 225 x 10^6 Vehicles

= 11,997 lb CO_2 /vehicle-year for 12,264 miles/year

These are the values against which emissions from all other alternative configurations will be compared

Case 2. Carbon Dioxide Emissions for Micro-, Mild-, and Full-Hybrid Vehicles

Since all of the energy to propel all traditional types of hybrid vehicles ultimately is provided by gasoline, we will utilize the increased fuel mileages previously assigned and reduce the total CO_2 emissions of Case 1 accordingly.

TYPE	GASOLINE MILEAGE		CARBON DIOXIDE
HYBRID	improvement	miles/gal	lb/vehicle-yr
Micro-Hybrid	10%	22	10,906
Mild-Hybrid	25%	25	9,598
Full Hybrid	45%	29	8,274
Ref. Vehicle	0%	20	11,997

Case 3. Plug-In Hybrid Vehicles

Total gasoline used per day is 9×10^6 bbl/day (DOE-EIA data)

(9 x 10^6 bbl/day x 42 gallons/bbl x 20 miles/gallon =
7.56 x 10^9 total miles/day

1st half vehicles 112.5 x 10^6 veh x 15 miles/vehicle-day

= **1.688 x 10^9 miles/day on electricity**

2nd half of vehicles [112.5 x 10^6 veh x 35 miles/veh day

= **3.937 x 10^9 miles/day on electricity**

Total mileage driven as a Full Hybrid is

(7.560 – 1.688 - 3.937) x 10^9 miles/day = **1.935 x 10^9 miles/day**

Percentages for Plug-in Hybrid Vehicles

As shown above, the mileages traveled by light vehicles are:

- **First half** of vehicles: 1.688 x 10^9 miles/day or 616 x 10^9 miles/year using **electricity** from a utility which represents **22.3%** of the total miles traveled per year
- **Second half** of vehicles: 3.937 x 10^9 miles/day or 1437 x 10^9 miles/year using **electricity** from a utility which represents **52.1%** of the total miles traveled per year
- **Full- Hybrid Mode**: 1.935 x 10^9 miles/day or 706 x 10^9 miles/year This represents **25.6 %** of the total miles traveled per year using **gasoline in Full-Hybrid Mode**

HENCE, PLUG-in HYBRIDS CAN SAVE 74.4% OF GASOLINE USED

SOME 6.7 OF 9.0 MILLION BARRELS PER DAY

Case 3A: Plug-In Hybrid-Electric Vehicle with Electricity supplied by Nuclear or Solar Energy

Since nuclear and solar generation of electricity (hydro, wind, and photovoltaic) do not emit carbon dioxide, the only greenhouse gas emission will be from the 708 x 10^9 miles/year as a full-hybrid.

As indicated above, this represents **25.6 %** of the total miles traveled, and the total emissions will be 25.6 % of that produced if the vehicle had operated in a full-hybrid mode all the time, i.e.,

0.256 x 8,274 lb/veh yr =

2,122 lb/vehicle yr

Case 3B:

Electricity Supplied by Fossil Fuels (Natural Gas, Oil, and Coal)

When the electricity is supplied by utilities using fuels that emit carbon dioxide during combustion, this CO_2 from generating electricity must be added to the CO_2 of Case 3A

Data on actual emissions from fossil power plants in the United States for 1999 (the last year for which complete data are available) provided by EPA and DOE [DOE-EIA 1999] show the emission rates below

Fuel used to Generate Electricity	% of Total Generation	Emission Rate lb CO_2/kWh
Coal	51.0	2.095
Oil	3.2	1.969
Natural Gas	15.2	1.321
Other Fossil Fuels (Renewables)	0.6	0.0 (Net)
Nuclear, Solar, Wind, Hydro	30.0	0.0

- In a previous article [Uhrig, 2005], it was established that 0.603 kWh/mile was a reasonable average expenditure of electrical energy for vehicles that would be comparable to a vehicle getting 20 miles per gallon of gasoline using an internal combustion engine. Therefore:
- The annual mileage for the **first half** of vehicles on electricity was 616 x 10^9 miles/year that would require
  - 616 x 10^9 miles/year x 0.603 kWh/mile = **371.5 x 10^9 kWh/year**
- The annual mileage for the **second half** of vehicles on electricity was 1,437 x 10^9 mile that would require
  - 1,437 x 10^9 miles/year x 0.603 kWh/mile = **866.5 x 10^9 kWh/year**
- Hence, the emissions can be obtained for the various fossil fuels by multiplying the appropriate emission rates by the amount of electricity required. The results are shown below.

EMISSIONS FOR 12,264 MILES PER YEAR

Emissions for	**Natural Gas**	**Oil**	**Coal**	**Non-Fossil Fuels**
	Millions of Tonnes/Year	Millions of Tonnes/Year	Millions of Tonnes/Year	Millions of Tonnes/Year
1st Half of Cars (Electricity)	223	333	354	0
2nd Half of Cars (Electricity)	519	774	824	0
2nd Half of Cars (Gasoline)	217	217	217	217
Total Emissions	**959**	**1,324**	**1,395**	**217**
Emissions/Vehicle [lb/year]	**9,398**	**12,956**	**13,650**	**2,122**

Comparison of Carbon Dioxide for Hybrid Vehicles

(Vehicles travels 19,749 km (12,264 miles) per year

Vehicle Emissions of Carbon Dioxide……………………….lb CO_2 /veh yr

Reference gasoline vehicle utilized an average (20 miles/gallon) ….12,000

Micro-Hybrid Vehicle (22 miles per gallon)…………………………...10,900
Mild-Hybrid Vehicle (25 miles per gallon)………………………….. 9,600
Full-Hybrid Vehicle (29 miles per gallon……………………………8,300

Plug-in Hybrid Vehicle (Electricity Generated with Nuclear)…,,,,,,,,,,,..2,100
(Electricity Generated with Solar Energy)…...2,100
(Electricity Generated with Renewables……,,2,100

Plug-in Hybrid Vehicle (Electricity Generated with Natural Gas).........9,400
(Electricity Generated with Oil)………….…..13,000
(Electricity Generated with Coal)……………..14,000

Hydrogen Fueled Vehicles

The emission of carbon dioxide from vehicles utilizing electricity generated with fuel cells operating on hydrogen is negligible except for the emissions from the various processes used to produce the hydrogen.

These emissions of carbon dioxide from the production processes must be taken into account to give a valid comparison with emissions of greenhouse gases from the other vehicle configurations and their potential impact upon climate and weather modification

Steam Methane Reforming (SMR) Some 95% of hydrogen produced today is produced by SMR using natural gas (~98% methane—CH_4). The two steps of SMR are

$$CH_4 + H_2O + \text{Heat (206 kJ/mol)} \xrightarrow{\text{Catalyst}} CO + 3H_2$$

Steam Reforming (Endothermic) Reaction

$$CO + H_2O \xrightarrow{\text{Catalyst}} CO_2 + H_2 + \text{Heat (41kJ/mol)}$$

Water-Gas Shift (Exothermic) Reaction

- The hydrogen comes from the methane and the steam.
- The steam reforming reaction is endothermic with the required 206 kJ/mol heat energy normally produced by combustion of some of the methane.
- The water-gas shift reaction is exothermic providing 41 kJ/mol heat energy that reduces the amount of methane burned to that required to provide the net 165 kJ/mol.
- This 165 kJ/mol represents ~17% of the total methane is consumed to provide the required heat.
- About 3.3 mols of hydrogen (~83% of the theoretical maximum of 4 mols of hydrogen in CH_4) are produced for each mole of methane used.
- A well-designed SMR plant will yield hydrogen having about 80% of the energy of the methane supplied.
- Unfortunately, SMR produces CO_2 in both the methane combustion and in the water-gas shift reaction.

Case 4. Vehicle using Hydrogen produced by Steam Methane Reforming

In an earlier publication [Uhrig, 2005], it was established that **0.367 kWh/mile** of mechanical energy at the tire-pavement interface

This corresponded to 20 miles/gallon

If we use the following efficiencies:

70% efficiency for the electric motor drive,
(the same used in the above reference),

60 % efficiency for the fuel cell, and

85% efficiency is distributing and dispensing the hydrogen

Then, the energy of the hydrogen input to the fuel cell is

[0.367 kWh/mile / (0.70 x 0.60 x 0.85)] =
1.028 kWh of hydrogen energy/mile

Average total miles per vehicle is 12,264 miles/year.
Hence, the total kWh per year is

[12,264 miles/year x 1.028 kWh of H_2 energy/vehicle mile]
= **12,607 kWh of H_2 energy/year**

Since the heat energy of hydrogen (lower heating value) is 51,600 Btu/lb, the amount of H_2 used per year is

[12,607 kWh/vehicle yr x 3413 Btu H_2/kWh] / [51,600 Btu/lb H_2]
= **834 lb H_2/ vehicle year**

The fuel mileage of a vehicle, of course, is a function of its characteristics—size, weight, air resistance, etc. A vehicle getting 20 miles per gallon is the reference size used in this paper and the author's reference paper. [Uhrig, 2005]

Goswami indicates that SMR produces a net of 0.43 mols of CO_2 for each mol of H_2 produced using SMR

[Goswami, 2005]

Since the molecular weights of CO_2 and H_2 are 44 and 2 respectively, then

[0.43 mol CO2/mol H_2] x {[44 gm/mol CO_2] / [2 gm/mol H_2]}

= 9.46 gm CO2 / gm H_2 = **9.46 lb CO2 / lb H_2**

Therefore, the total emission of CO_2 per vehicle-year is

[834 lb H_2 /vehicle year x 9.46 lb CO_2 / lb H_2] =

7,888 lb CO_2 per vehicle year

Case 5. Vehicle using Hydrogen produced by SMR with Heat Supplied by High Temperature Nuclear Reactor

Recent work in Japan has demonstrated the feasibility of substituting high temperature heat from a gas cooled nuclear reactor to replace the heat supplied by the combustion of methane.

This eliminates the combustion of methane and increases the output **4 mols** of Hydrogen and **1 mole** of carbon dioxide per mole of methane.

This external heat eliminates the CO_2 produced by combustion of methane, but not the CO_2 produced by the water-gas shift reaction.

Hence, the CO_2 emission per vehicle year is

Steam Methane Reforming (Goswami)	0.43 mol CO_2 / mol H_2
SMR with Nuclear Heat Supplied	0.25 mol CO_2 / mol H_2

$$\frac{[7{,}888 \text{ lb/veh yr} \times 0.25 \text{ mol } CO_2 / \text{mol } H_2]}{[0.43 \text{ mol } CO_2 / \text{mol } H_2]} = 4{,}586 \text{ lb/veh yr}$$

- **Case 6. Vehicle using Hydrogen produced by Electrolysis and Thermo-Chemical methods using Electricity and Heat respectively generated using Fossil and Nuclear Fuels**
- Conventional electrolysis of water to produce hydrogen is a well developed technology, and production units as large as 10 MWe are commercial available today
- However, the typical overall efficiency of hydrogen production using electrolysis based on the thermal content of the fuel is about 25% today, consisting of two components—about 33% efficiency in converting fossil or nuclear fuel to electricity, and about 75% in using electricity to separate water into hydrogen and oxygen
- If a high-temperature gas-cooled reactor or a modern high efficiency gas-fired combined cycle plant is used, the overall efficiency in producing hydrogen could approach 40%

- A leading manufacturer of electrolysis equipment indicated that 1 MW of electricity can generate 0.52 tons (1040 lb) of hydrogen per day, or **1.04 lb/kW day** [Stuart, 2001]
- In Case 4, it was calculated that the hydrogen required per year for a vehicle using hydrogen was **834 lb/year**. Hence, the amount of electricity required per year is

$$[834 \text{ lb } H_2\text{/year x 24 hr/day}] \;/\; [1.04 \text{ lb } H_2 \text{ / kW day}] =$$

19,230 kWh/year

- The carbon dioxide emitted in hydrogen production is the carbon dioxide emitted in producing the required electricity.
- The choices of fuel for generating electricity are coal, oil, natural gas, nuclear energy, solar (wind, photovoltaics, and hydro).
- Hence the emissions of carbon dioxide are the product of the kWh per year and the appropriate emission per kWh of electricity for the fuel used.

Case 6A. Vehicles using Hydrogen produced by Electrolysis using Fossil Fuels (Coal, Oil, and Natural Gas).

The emissions of carbon dioxide for these fossil fuels are the products of the kWh per year and the appropriate emission per kWh for the fuel as given in Case 3B.

Natural Gas.........19,230 kWh/yr x 1.321 lb CO_2/kWh =
25,384 lb CO_2/year *

Oil…………….....19,230 kWh/yr x 1.969 lb CO_2/kWh =
37,953 lb CO_2/year *

Coal……………..…19,230 kWh/yr x 2.095 lb CO_2/kWh =
40,276 lb CO_2/year *

* These three emissions for fossil fuels seem excessively large, but the **large values** are due to the **many steps involved**, i.e., fossil fuels to electricity to hydrogen, handling losses, to electrical energy to mechanical energy to propelling the car. Each step has losses that ultimately require the use of more fossil fuels.

Case 6B. Vehicles using Hydrogen produced by Electrolysis using Nuclear Energy or Solar Energy (Wind, Photovoltaics, Hydro Energy) or Renewables.

Since none of these energy sources emit carbon dioxide, there is no emission of greenhouse gases associated with these arrangements.

Nuclear Energy…….0 lb CO_2 per vehicle year

Solar Energy (Wind Photovoltaics and Hydro Energy)……….0 lb CO_2 per vehicle year

Renewable Energy...0 lb CO_2 per vehicle year

Case 6. Vehicle using Hydrogen produced by Thermo-Chemical Methods (e.g., using Heat generated using Fossil and Nuclear Fuels

- The overall efficiency of a thermo-chemical process, such as the Sulfur Iodine Process, approaches 50% at 900 ºC while the overall efficiency of the electrolysis process is ~25%.
- Hence, for the same fuel, the **CO_2** emission will be half as much as for electrolysis

Fuel Emissions	lb/veh yr
Natural Gas	12,692
Oil	18,932
Coal	20,138
Nuclear, Solar, & Renewables	0

EMISSIONS OF CO_2 BY HYDROGEN FUELED VEHICLES

Vehicle Emission of CO_2	lb CO_2 / Vehicle Year
Reference Gasoline Vehicle (20 miles/gallon)	12,000
Vehicles using Hydrogen produced by	
Steam Methane Reforming (SMR)	7,900
SMR with Nuclear Heat	4,600
Vehicles using Hydrogen produced by Electrolysis using	
Electricity using Natural Gas	25,400
Electricity using Oil	37,900
Electricity using Coal	40,300
Electricity using Nuclear, Wind, Solar, Hydro, and Renewables	0
Vehicles using Hydrogen produced by Thermo-Chemical Process	
Heat generated using Natural Gas	12,700
Heat generated using Oil	19,000
Heat generated using Coal	20,100
Heat generated using Nuclear Wind Solar, Hydro and Renewables	0

CONCLUSIONS

Greenhouse Gas (CO_2) Emissions

Hybrid Electric Vehicles

Depends upon **how electricity is generated**

- Fossil fuels produce large amounts of greenhouse gases
- Nuclear, Solar, and Renewables generation do not produce greenhouse gases. Hence, the only CO_2 is that associated with operation in the Full Hybrid Mode

Hydrogen-Fueled Vehicles

Depends upon **how hydrogen is produced**

- **Steam Methane Reforming** produces greenhouse gases
- **Electrolysis and Thermo-Chemical** may or may not
  - Fossil fuels produce greenhouse gases
  - Nuclear and Solar generation do not produce CO_2
  - Renewables have a “net zero” production of CO_2

From an Environmental standpoint, Nuclear Power is the only practical source of electricity for Plug-In Hybrid-Electric Vehicles and for producing Hydrogen for Hydrogen-Fueled Vehicles

Greenhouse Gases emissions are very large when any fossil fuels are used to generate electricity or Hydrogen

Wind, photovoltaic,hydro, and renewable sources are intermitant in operation and not practical on the scale needed.

Additional Capacity Required to Replace Gasoline

Hybrid-Electric Vehicles	200-250 GW
Hydrogen-Fueled Vehicles	400-450 GW

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