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Air pollution reduction via use of green energy sources for electricity and hydrogen production

Mikhail Granovskii, Ibrahim Dincer*, Marc A. Rosen

Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario, Canada L1H 7K4

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Abstract

The implementation of renewable wind and solar energy sources instead of fossil fuels to produce such energy carriers as electricity and hydrogen facilitates reductions in air pollution emissions. Unlike from traditional fossil fuel technologies, air pollution emissions from renewable technologies are associated mainly with the construction of facilities. With present costs of wind and solar electricity, it is shown that, when electricity from renewable sources replaces electricity from natural gas, the cost of air pollution emission abatement is more than ten times less than the cost if hydrogen from renewable sources replaces hydrogen produced from natural gas. When renewable-based hydrogen is used instead of gasoline in a fuel cell vehicle, the cost of air pollution emissions reduction approaches the same value as for renewable-based electricity only if the fuel cell vehicle efficiency exceeds significantly (i.e., by about two times) that of an internal combustion vehicle. The results provide the basis for a useful approach to an optimal strategy for air pollution mitigation.

Keywords: Air pollution; Emissions; Renewable energy; Hydrogen; Electricity; Life cycle assessment

1. Introduction

Modern power generation and transportation systems powered by hydrocarbons are characterized by growing air pollution and greenhouse gas emissions. It is generally accepted that the effects of air pollutants are significant. Nitrogen oxides (NO_x) in combination with volatile organic compounds (VOCs) cause the formation of ground level ozone and smog. Healthy people can suffer eye irritation and a decrease in lung function when exposed to smog. NO_x and VOCs react in the presence of sunlight to produce ozone. Elevated levels of ozone can cause lung and respiratory disorders and noticeable leaf damage in many crops, plants and trees. Carbon monoxide (CO) emissions impact the ability of red blood cells to transport oxygen to body tissues (e.g., EC, 2005). Numerous other environmental impacts are associated with emissions of NO_x, VOCs and CO (Dincer, 2002; Rosen, 2002, 2004). Table 1 presents, for these airborne pollutants, impact weighting coefficients (relative to NO_x) obtained by the Australian Environment Protection Authority (Beer et al., 2006) using cost-benefit analyses of health effects.

Rising concerns about the effects of global warming, air pollution and declining fossil fuel

*Corresponding author.
E-mail addresses: mikhail.granovskiy@uoit.ca (M. Granovskii), ibrahim.dincer@uoit.ca (I. Dincer), marc.rosen@uoit.ca (M.A. Rosen).

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Nomenclature

AP	air pollution emissions, g
C	cost, US$
E	energy, MJ
El	electricity cost, US$
LCA	life cycle assessment
m	mass, g
NO_x	nitrogen oxides
P	pressure, atm
R	universal gas constant, $J\,mol^{-1}\,K^{-1}$
T_0	environment temperature, K
VOC	volatile organic compound
w	weighting coefficient of air pollutant

Greek symbols

η	energy efficiency
β	ratio in prices of electricity production

Subscripts

AP	air pollution
atm	atmosphere
cmp	compressor
el	electric
g	gasoline
H	hydrogen
i,j	indexes
max	maximum
ng	natural gas
r	renewable
s	solar
w	wind

stocks have led to increased interest in renewable energy sources such as wind and solar energies. The prospects for generating electricity, hydrogen or synthetic fuels by employing only renewable energy sources are good. In some ways, electricity generation technologies including wind turbines and photovoltaic cells are as developed as hydrogen production via water electrolysis. Pure hydrogen can be used as a fuel for fuel cell vehicles, which are rapidly improving nowadays, or converted into synthetic liquid fuels by means of such processes as Fischer–Tropsch reactions (Dry, 1999).

An adequate evaluation of the effects of introducing a renewable technology needs to include assessments of the environmental impacts and economics of the overall production and utilization life cycle (from "cradle-to-grave"), including the construction and operation stages of renewable plants. Life cycle assessment (LCA) is a methodology for this type of assessment, and represents a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle (ISO, 1997). We reported LCAs previously (Granovskii et al., 2006a, b; Daniel and Rosen, 2002), based on data in the literature, of wind and solar technologies for electricity and hydrogen generation, as well as hydrogen production from natural gas and gasoline from crude oil. The principal technological steps employed in our LCA studies of the utilization in transportation of crude oil, natural gas, and renewable technologies are presented in Fig. 1.

Table 1
Weighting coefficients of airborne pollutants from motor vehicles

Pollutant	Weighting coefficient
CO	0.017
NO_x	1
VOCs	0.64

By introducing a capital investment effectiveness indicator (Granovskii et al., 2006a), it was shown that "renewable" hydrogen is less economically attractive (i.e., it has a higher cost) than hydrogen produced via reforming of natural gas. In this article we utilize the different costs of electricity and hydrogen, depending on the technologies used for their manufacture, together with data on air pollution emissions from our LCA studies, to evaluate the costs of mitigating emissions by industrial-scale implementation of wind and solar energy systems. Numerical estimations are made using expressions introduced for greenhouse gas emissions mitigation in our previous paper (Granovskii et al., 2006c).

2. Analysis

Although wind and solar energies can be considered "free", the quantity of construction materials

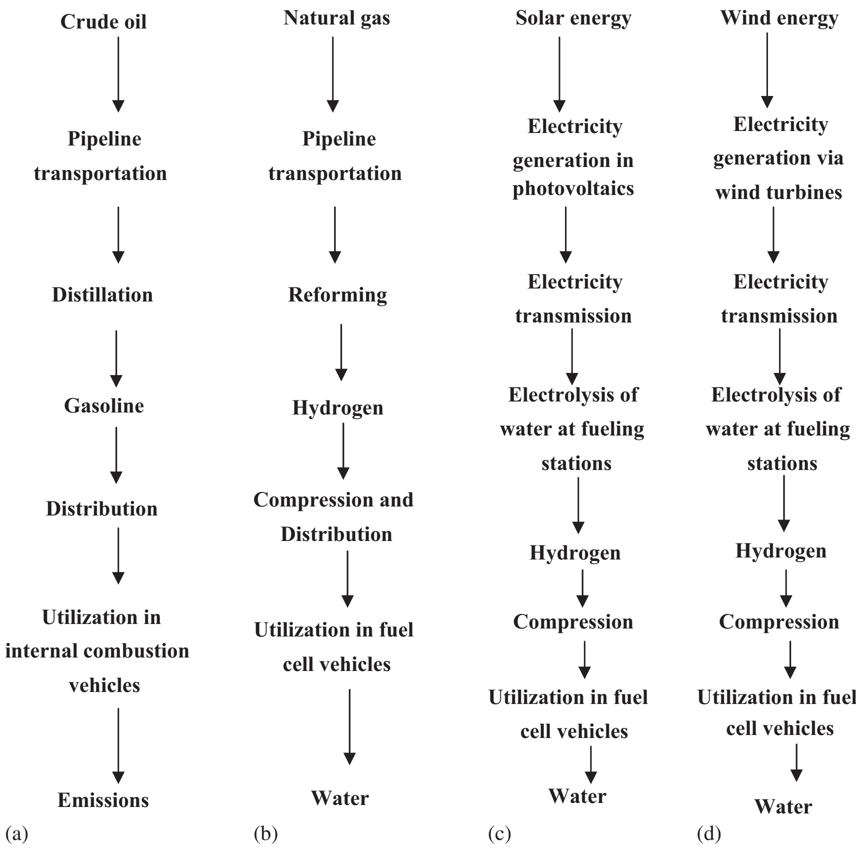

Fig. 1. Principal technological steps in utilizing in transportation (a) crude oil; (b) natural gas; (c) solar energy and (d) wind energy.

consumed per unit of electricity or hydrogen produced for a ‘‘renewable’’ plant is normally much higher than that for more traditional technology for electricity and hydrogen production from natural gas. Taking into account air pollution emissions from the construction and operation stages of power or hydrogen generation plants, and their lifetimes and capacities, the indirect air pollution emissions per unit of produced energy can be calculated. For fossil fuel technologies, this part of the life cycle air pollution emissions is negligible with respect to the direct emissions related to fuel combustion or removing carbon from methane (natural gas) to produce hydrogen.

The calculated air pollution emissions per megajoule of produced electricity and hydrogen, from our LCA studies, are presented in Table 2. To characterize air pollution with one measure, the masses m_i of air pollutants in Table 2 are multiplied by the weight coefficients w_i in Table 1 and summed to obtain the generalized indicator of air pollution AP_j for the entire life cycle of the fuels (gasoline from crude oil, hydrogen from natural gas, wind and solar energies):

$$\mathrm{AP}_j = \sum_{1}^{3} m_i w_i. \tag{1}$$

In order to transmit hydrogen or use it in a fuel cell vehicle, it needs to be substantially compressed to reach an appropriate volumetric energy density. For instance, the pressure of gaseous hydrogen in the tank of Honda’s fuel cell car is about 350 atm (Wilson, 2002). Data regarding hydrogen compression in Table 2 have been modified according to an assumption that electricity for ‘‘renewable’’ hydrogen compression comes from the same renewable energy sources and electricity for compression of hydrogen from natural gas is generated in a natural gas power generation plant. As can be seen in Table 2, the environmental impact of hydrogen compression using renewable-based electricity is negligible compared to that for the stages of electricity production and electrolysis.

Table 2
Air pollution emissions (in g/MJ of electricity, hydrogen and gasoline) for various production technologies

Technology	m_{CO}	m_{NOx}	m_{VOCs}	AP_j
Electricity from natural gas				
Electricity from natural gas with a thermal efficiency $\eta = 40\%$	0.094	0.11	0.72	0.57
Hydrogen from natural gas				
Natural gas pipeline transportation and reforming to produce hydrogen at pressure $p = 20$ atm[a]	0.022	0.026	0.054	0.061
Hydrogen compression from 20 to 350 atm	0.0042	0.0050	0.032	0.026
Total for $p = 350$ atm	0.026	0.031	0.086	0.087
Electricity and hydrogen from wind energy				
Electricity generation	0.0030	0.0035	0.00027	0.0038
Hydrogen production via electrolysis	0.0017	0.0020	0.000159	0.0022
Hydrogen compression to $p = 20$ atm	0.00014	0.00017	1.3×10^{-5}	0.00018
Hydrogen compression to $p = 350$ atm	0.00027	0.00033	2.54×10^{-5}	0.00035
Total for $p = 20$ atm	0.0048	0.0057	0.00044	0.0062
Total for $p = 350$ atm	0.0050	0.0058	0.00045	0.0063
Electricity and hydrogen from solar energy				
Electricity generation	0.0073	0.0087	0.00068	0.0092
Hydrogen production via electrolysis	0.0042	0.0050	0.00039	0.0053
Hydrogen compression to $p = 20$ atm	0.00034	0.00041	3.19×10^{-5}	0.00044
Hydrogen compression to $p = 350$ atm	0.00067	0.00080	6.23×10^{-5}	0.00085
Total for $p = 20$ atm	0.012	0.014	0.0011	0.015
Total for $p = 350$ atm	0.012	0.015	0.0011	0.015
Gasoline from crude oil				
Crude oil pipeline transportation and distillation to produce gasoline	0.012	0.061	0.023	0.015
Gasoline delivery to fuelling stations	0.00044	0.0028	8.26×10^{-5}	0.11
Gasoline utilization in ICE vehicles[b]	0.86	0.05	0.15	0.11
Total	0.87	0.11	0.17	0.24

[a]Hydrogen is produced by natural gas reforming at the typical pressure of 20 atm.
[b]Taken from Walwijk et al. (1999).

The typical pressure of hydrogen at the reforming plant outlet is about 20 atm (Spath and Mann, 2001).

The electrical energy required, E_{el}, to compress one mole of hydrogen is calculated according to the formula for isothermal compression with an efficiency coefficient for a compressor $\eta_{cmp} = 0.65$:

$$E_{el} = \frac{RT_0}{\eta_{cmp}} \ln (P_{max}/P_{atm}), \tag{2}$$

where the environment temperature is $T_0 = 298$ K, R is the universal gas constant, P_{max} is the required pressure of hydrogen and the atmospheric pressure is $P_{atm} = 1$ atm.

The AP emissions from producing a unit of electricity from natural gas is calculated assuming that electricity is generated from natural gas with an average efficiency of 40% (which is reasonable since the efficiency of electricity production from natural gas varies from 33% for gas turbine units to 55% for combined-cycle power plants, with about 7% of the electricity dissipated during transmission).

A positive environmental impact (i.e., AP emissions reduction in the present case) as a result of the introduction of a renewable technology depends on the replaced technology. The efficiency of such an introduction can be determined as the cost of AP emissions reduction/kg (C_{AP}), in line with the formula

$$C_{AP} = \frac{1000}{AP_{ng} - AP_R}(C_R - C_{ng}), \tag{3}$$

where AP_f and AP_R are AP emissions (in grams/MJ of electricity or lower heating value (LHV) of hydrogen) produced using fossil fuel (natural gas) and renewable technologies, respectively, and C_{ng}

and C_R are the costs/MJ of electricity or hydrogen produced using natural gas and renewable technologies, respectively.

Fig. 2 lists the costs of the major energy carriers for 1999–2004 (EIA, 2005). The contemporary cost of fossil fuel-based electricity assumes that the electricity cost in Fig. 2 is consistent with its generation from natural gas with an average efficiency of 40% (like for the greenhouse gas emissions evaluation). Data are not widely available for the cost of hydrogen, but according to an analysis (Padro and Putsche, 1999) the ratio of the cost of hydrogen to its LHV is about two times that of natural gas. In line with Fig. 2 the cost of gasoline is about two times that of crude oil. The efficiency of producing gasoline from crude oil is slightly higher than that for hydrogen from natural gas (Granovskii et al., 2006a). As the relative cost of natural gas is slightly lower than that of crude oil (see Fig. 2), we assume here that the ratio of the cost to LHV of hydrogen produced by natural gas reforming at a typical pressure (20 atm) is equal to that of gasoline. The average costs of natural gas, crude oil, gasoline, hydrogen and electricity for 1999–2004 that are employed here are listed in Table 3.

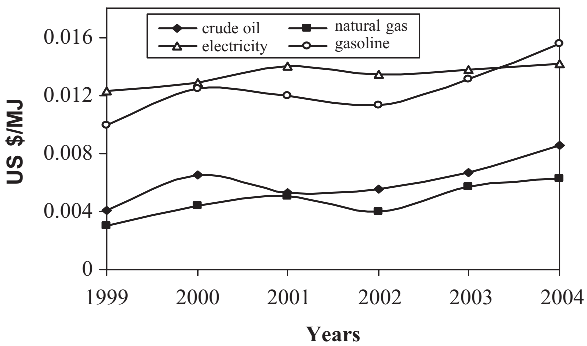

Fig. 2. Unit costs of selected energy carriers from 1999–2004. Based on the data from EIA (2005).

Table 3
Average unit costs (in US$/MJ) of the main energy carriers for 1999–2004[a]

Energy carrier	Average unit cost (US$/MJ)
Natural gas	0.00473
Crude oil	0.00611
Gasoline	0.0124
Electricity	0.0134
Hydrogen (at 20 atm)	0.0124

[a]Based on data in Fig. 2.

3. Results and discussion

Figs. 3 and 4 present the cost (per kg) of reducing AP emissions, as a result of the substitution of wind and solar energies for natural gas to produce electricity and compressed hydrogen, as a function of the ratio of the costs of electricity:

$$\beta_w = \frac{EL_w}{EL_{ng}}, \tag{4}$$

$$\beta_s = \frac{EL_s}{EL_{ng}}, \tag{5}$$

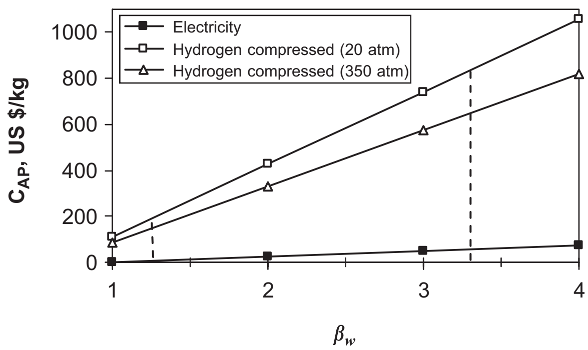

Fig. 3. Unit cost of AP emissions reduction as a result of wind energy substitution for natural gas to produce electricity and compressed hydrogen, as a function of the ratio in electricity costs β_w. The range of present ratios between production costs of "wind" and "natural gas" electricity is shown by dashed lines. Based on data from Newton and Hopewell (2002).

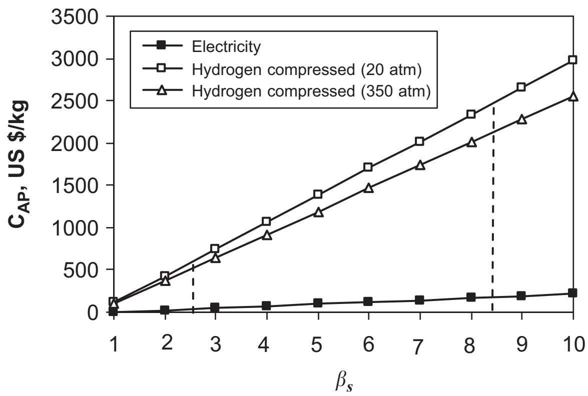

Fig. 4. Unit cost of AP emission reduction as a result of solar energy substitution for natural gas to produce electricity and compressed hydrogen, as a function of the ratio in electricity costs β_s. The range of present ratios between production costs of "solar" and "natural gas" electricity is shown by dashed lines. Based on data from Newton and Hopewell (2002).

where β_w and β_s are the ratios in costs of electricity produced from wind and solar energy sources to the costs of natural gas, respectively, EL_w and EL_s are the costs of electricity generated from wind and solar energy sources, respectively, and EL_{ng} is the cost of electricity produced from natural gas. The cost of natural gas-derived electricity is assumed to be equal to the cost of electricity in Fig. 2. Comparing Figs. 3 and 4 shows that wind-derived electricity allows less expensive abatement of AP emissions. Replacement of natural gas-derived electricity by renewable-derived electricity is more favorable than the same replacement for hydrogen. Elevating pressure favors renewable technologies because the cost of hydrogen is also formed by the cost of electricity required for its compression. The range of contemporary ratios between production costs of renewable and natural gas-based electricity are shown in Figs. 3 and 4 by dashed lines, based on data of Newton and Hopewell (2002).

The cost of a reduction in AP emissions by the introduction of hydrogen as a fuel for a fuel cell vehicle instead of gasoline is evaluated by using average cost values for wind and solar electricity of $\beta_w = 2.25$ and $\beta_s = 5.25$. For this evaluation, Eq. (2) has been modified as follows:

$$C_{AP} = \frac{1000}{AP_g - AP_H/\eta}\left(\frac{C_H}{\eta} - C_g\right), \quad (6)$$

where η is the ratio in efficiencies of fuel cell and internal combustion vehicles, C_g and AP_g are the cost/per MJ of gasoline and the corresponding AP emissions, and C_H and AP_H are the cost/MJ of compressed (350 atm) hydrogen and the corresponding AP emissions.

The cost of reducing AP emissions (per kg) as a result of gasoline substitution with hydrogen is presented in Fig. 5 as a function of the ratio in efficiencies η of fuel cell (hydrogen powered) and internal combustion (gasoline powered) vehicles. It can be seen from this figure that when "renewable" hydrogen is used instead of gasoline, the cost of air pollution emissions abatement approaches the same for "renewable" electricity only if the efficiency of the fuel cell vehicle significantly (about two times) exceeds that of an internal combustion engine. On the contrary, the low positive and negative values for hydrogen from natural gas point out that its application in fuel cell vehicles allows a reduction in AP emissions almost without any financial expenditure connected to the fuel production technology. Nowadays, the average efficiencies (mechanical work/LHV of fuels) of an internal combustion and a fuel cell engine are about 0.25 (Cleveland, 2004) and 0.35 (efficiencies of a fuel cell stack and electrical energy conversion into mechanical work are about 0.4 and 0.9), respectively (Larminie and Dicks, 2003).

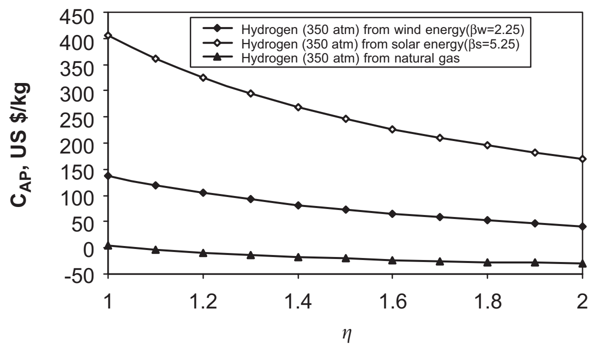

Fig. 5. Unit cost of AP emissions reduction as a result of hydrogen substitution for gasoline, as a function of the ratio in efficiencies η of internal combustion (gasoline powered) and fuel cell (hydrogen powered) vehicles.

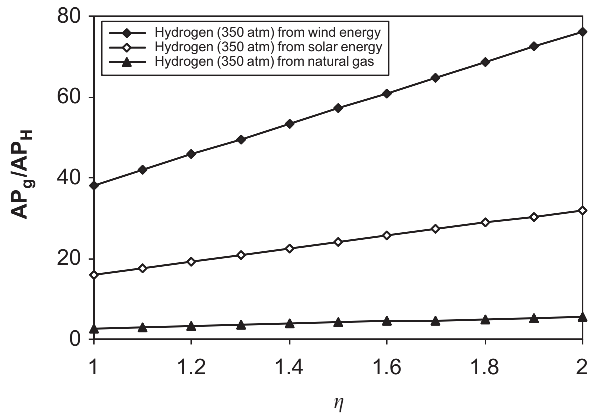

Fig. 6. The respective reduction of AP emissions as a result of hydrogen substitution for gasoline, as a function of the ratio in efficiencies η of internal combustion (gasoline powered) and fuel cell (hydrogen powered) vehicles.

The respective reduction of AP emissions as a result of gasoline substitution with hydrogen AP_g/AP_H as a function of η is presented in Fig. 6. According to this graph, a "renewable" hydrogen introduction instead of gasoline leads to a reduction in air pollution more than ten times (from 38 to 76 for hydrogen derived from wind and from 16 to 32 derived from solar energy). It can be seen that gasoline substitution with hydrogen from natural gas allows a reduction of AP emissions of only 2.5–5 times. An analysis of the results presented in Figs. 5

and 6 suggests that "renewable" hydrogen represents a potential long-term solution to environmentally related transportation problems.

4. Conclusions

Introducing wind and solar renewable energy sources in place of natural gas to produce electricity and hydrogen leads to a reduction of air pollution emissions. Implementation of wind- and solar-based electricity for AP emissions mitigation is less costly than the introduction of wind- and solar-based hydrogen. With present costs of wind and solar electricity, it is shown that, when electricity from renewable sources replaces electricity from natural gas, the cost of air pollution emission abatement is more than ten times less than the cost if hydrogen from renewable sources replaces hydrogen produced from natural gas. The introduction of "renewable" hydrogen as a fuel for fuel cell vehicles instead of gasoline can lead to economically effective reductions of AP emissions only if the efficiency of a fuel cell vehicle is about two times higher than that of an internal combustion one. The results provide a useful economic evaluation of air pollution emissions mitigation by the introduction of renewable wind and solar energy sources.

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