REDUCING THE ENVIRONMENTAL FOOTPRINT AND ECONOMIC COSTS OF AUTOMOTIVE MANUFACTURING THROUGH AN ALTERNATIVE ENERGY SUPPLY

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ABSTRACT

The automotive industry consumes a significant amount of energy in the manufacturing stage and generates substantial greenhouse gas emissions and a variety of air pollutants. With more than two thirds of these emissions generated from purchased electricity, an effective way to reduce the environmental footprint of automotive manufacturing is to use alternative energies to partially supply the power needs for the current manufacturing processes. This paper assesses three alternative energy technologies, including solar photovoltaic, wind, and fuel cells, as potential power sources to reduce facility emissions from automotive manufacturing. In our assessment, we have the used the energy supply based on in Detroit, MI, region in the United States, where much of the U.S. automotive manufacturing industry is centered. Cost of ownership and environmental savings from the three technologies are evaluated and compared with the local electricity supply. The analysis results favor wind over solar and fuel cells in terms of both ownership cost and environmental savings.

INTRODUCTION

The automotive industry consumes a significant amount of energy in the manufacturing stage. It is estimated that a typical vehicle requires approximately 120 giga joules of energy input to be manufactured (Maclean 1998). In 2004, together Ford Motor Co. and General Motors Corp. (GM) consumed a total of 55.2 x 10^9 kwh of energy (Ford 2006; GM 2006). With 85% of U.S. energy supplied by fossil fuels (US DOE 2006), the consumed energy, directly or indirectly, generates a large amount of greenhouse gas emissions, such as CO_2, CH_4, N_2O, and so on, and a number of air pollutants, including SO_2, CO, NO_x, VOC, PM, and so on.

The automotive industry has made a great effort to reduce greenhouse gas emissions and air pollutants from its facilities, products, and processes. It is reported that GM's facilities have achieved a 15.5% reduction of greenhouse gas emissions, down from 13.83 million metric tons in 2001 to 11.68 million metric tons in 2005 (GM 2007). This reduction has been achieved mainly by the energy-efficiency improvement as the CO_2 emission per vehicle built by GM has dropped by 11.5% from 2.6 metric tons in 2001 to 2.3 metric tons in 2003 (GM 2005). Ford has maintained its CO_2 emission per vehicle built roughly around 1.3 metric tons from 1998 to 2004 (Ford 2005). The Alliance of Automobile Manufacturers, formed by nine major automotive manufacturers in the world, committed to achieving a 10% reduction in greenhouse gas emissions per numbers of vehicle produced from their U.S. automotive manufacturing facilities by 2012 from a base year of 2002 (US DOE 2007). Greenhouse gas and air pollutant emissions from automotive manufacturing include direct emissions, which are generated from direct consumption of fossil fuels by the manufacturing facilities, and indirect emissions, which are generated from the purchased electricity. Statistical data show that approximately 70% of the facility CO_2 emissions from Ford and GM are indirect emissions, namely from purchased electricity (Ford 2005; GM 2005). Considering the U.S. energy supply structure and fossil fuel composition, we can estimate that roughly the same proportion of air pollutants from automotive manufacturing are indirect emissions as well. Further reduction of greenhouse gases and air pollutants emissions from automotive manufacturing has to be attained through reduction of fossil fuel energy consumption, and this can be achieved through improved energy efficiency, reduction of production scale, or the use of alternative energies.

This paper evaluates the possibility of using alternative energies to partially supply the energy needs of automotive manufacturing, and to reduce greenhouse gas and other environmental pollutants emissions. Three alternative energies are assessed and compared based on cost of ownership and environmental savings analyses: solar photovoltaic, wind, and fuel cells with state-of-the-art technologies. Due to the fact that there are various solar, wind, and fuel cell power systems available on the market, here we select the alternative energy technologies mainly based on commercial availability, technology advancement, and manufacturer's reputation, by assuming the economic and environmental performance of the products of the leading manufacturers are representatives of the assessment scope.

ALTERNATIVE ENERGY CHARACTERISTICS

While solar and wind energy are site-specific, fuel cells depend on a fuel supply to generate power. In this paper, we have used the energy supply figures for the Detroit region where much of the U.S. automotive manufacturing industry is centered. The characteristics of the three alternative energies are presented in the following sections.

Solar Photovoltaic

Solar photovoltaic devices use the photoelectric effect on semiconductor materials to convert solar radiation energy directly into electricity. The key performance indicator of solar photovoltaic devices is the energy conversion efficiency, i.e., the ratio of the received solar radiation energy and the generated electric energy by the photovoltaic devices.

The solar photovoltaic product assessed in this paper is General Electric's PVP-200-M 200 w photovoltaic module, which has 54 polycrystalline silicon cells connected in series. The product has 25-year warranty from the manufacturer. The power plant evaluated is at 1 Mw scale, which requires 5000 such modules to be connected in series. The specifications of the GE PVP-200-M solar module are shown in Table 1 below:

TABLE 1. SPECIFICATIONS OF GE PVP-200-M PV MODULE (GE 2006).

Peak Power	Efficiency	Max. Voltage	Max. Current
200 watts	13.73%	26.3 volts	7.6 amps

The total amount of electricity generated by the photovoltaic power plant is determined by the efficiency of the solar photovoltaic device and the total amount of solar energy incident on the photovoltaic device, as expressed below:

$$W = \eta * E \qquad (1)$$

where

W: total amount of energy generated

η: efficiency of the photovoltaic device

E: total amount of solar radiation energy incident on the photovoltaic device

Solar radiation energy is dependent on local meteorological conditions. Figure 1 gives a distribution of the average solar radiation density in the Detroit area on a monthly basis. The data were collected by the U.S. National Renewable Energy Laboratory during a 30-year period from 1961 to 1990. Figure 1 reveals that the strongest radiation levels in the Detroit area occur in June and July, with energy concentrations more than 6 kwh/m^2/day. The weakest radiation levels occur in January, November, and December, between just 1 and 2 kwh/m^2/day.

In the analysis, the solar radiation info in Figure 1 and Eq. (1) are used to calculate the actual output of the 1 Mw solar photovoltaic power plant built in the Detroit area. The electricity generated from the 1 Mw power plant built on GE PVP-200-M photovoltaic modules can be calculated through:

$$W = \frac{\delta \times B \times A \times \eta \times N}{t} \qquad (2)$$

where

W: actual output of the solar power plant, in kw

δ: coefficient, δ = 0.003152

B: solar radiation concentrations, in BTU/m^2/day

A: surface area of the photovoltaic module, A= 1.4568 m^2

η: PV module efficiency, η =13.73%

N: total number of the PV modules, N=5000

t: solar radiation hours, *t* = 8 hr/day

In this paper, the PV panels are assumed to be installed in such a way that the solar radiation would be incident on the whole panel surface, on average, for about 8 hours during a day. Using the Eq. (2) and the solar radiation data presented in Figure 1, the actual output of the 1 Mw solar power plant based on the GE PVP-200-M PV module is calculated and demonstrated on a monthly scale, as seen in Figure 1 as well.

The calculated results show that the actual output of the solar power plant corresponds to the solar radiation energy distribution, with over 760 kw in June and July, but less than 200 kw in January, November, and December. An average of the actual outputs for 12 months is 470.9 kw, which means that the operational efficiency of the 1 Mw PV power plant in the Detroit area is 47.09%, based on annual statistics.

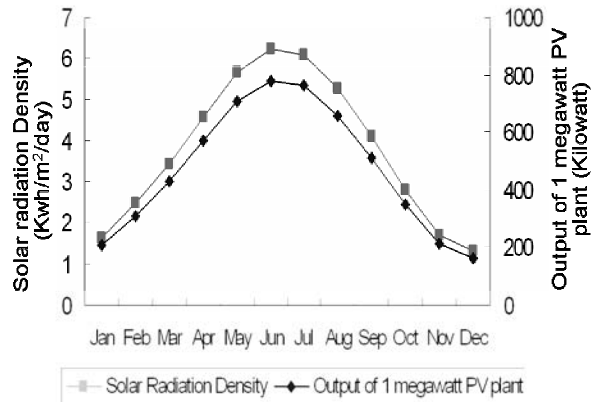

FIGURE 1. SOLAR RADIATION DENSITY AND ACTUAL OUTPUT OF A 1 MEGAWATT PV POWER PLANT IN DETROIT.

Wind

Wind is another form of solar energy, as it is generated by the uneven solar heating of earth land and sea surfaces. Wind is widely used in the United States to generate electricity, with a 18302.68 Mw capacity currently in place and another 5736.3 Mw under construction (AWEA 2006).

Michigan has high wind energy potential. The most wind-rich areas are along the lakeshores, while Detroit has utility-scale wind potential around its urban area. Wind energy density is dependent on wind speed, air temperature, atmospheric pressure, and altitude. The following empirical function correlates wind speed with wind energy density (Slaymaker 2005).

$$D = 0.6125 \times v^3 \times \alpha \times \beta \qquad (3)$$

where

D: wind energy density, watt/m^2

v: wind speed, m/s

α: altitude coefficient

$$\alpha = 1 - \frac{A}{28682.5}$$

A: altitude, in feet.

β: temperature coefficient

$$\beta = \frac{519.67}{H + 459.67}$$

H: temperature, in Fahrenheit.

Based on Detroit's geographic and meteorological conditions, its wind power density is calculated for 50 m, 70 m, and 100 m height above ground using Eq. (3). The results are given in Table 2 below:

TABLE 2. WIND ENERGY DENSITY IN THE DETROIT AREA.

Wind Turbine Height (m)	Wind Speed* (m/s)	Wind power density# (watt/m^2)
50	5.6 ~ 6.4	107 ~ 160
70	6.5 ~ 7.0	167 ~ 208
100	7.0 ~ 7.5	208 ~ 255

*: Wind speed data is from AWS Truewind.
#: Calculated based on an altitude of 627 feet and a temperature of 48.6 °F (US NREL 1995).

In this paper, the wind power system subject to analysis is GE's 1.5sl Mw wind turbine. The technical specifications of the GE 1.5sl Mw wind turbine is shown in Table 3 below:

To attain the rated power output, the wind speed must be 11 m/s or above, which is beyond the actual conditions of the Detroit area, as shown in Table 2. With an average wind speed at 7 m/s in the Detroit area at 85 m height above ground, the expected output from the GE 1.5sl wind turbine is approximately 420 kw in the Detroit area.

TABLE 3. GE 1.5SL MEGAWATT WIND TURBINE SPECIFICATIONS (GE 2006).

Cut-in speed	Hub height	Rotor diameter	Swept area
3.5 m/s	85 m	77 m	4657 m^2

Fuel Cells

Fuel cells have excellent potential to address energy and environmental issues by using hydrogen as fuel to generate electricity. A fuel cell is an electrochemical device, similar to a battery, using hydrogen (or hydrogen fuels) to produce electricity. Since hydrogen can be obtained from many renewable sources such as water, biomass, and the like, fuel cells are regarded as a clean and renewable energy technology.

Currently available fuel cell power plants use natural gas as their fuel to generate electricity. Although the natural gas supplied to the fuel cell power plant is only involved in a chemical oxidation process, instead of burning, in the electricity generation process, the carbon composition of the natural gas is turned into CO_2 emissions, as shown by following reaction:

$$CH_4 + 2H_2O = CO_2 + 4H_2$$

In this paper, two types of fuel cell power plants are evaluated: the DFC 1500 Fuel Cell Power Plant manufactured by FuelCell Energy Inc, and the PureCell 200 Fuel Cell Power Plant manufactured by United Technologies (UTC). The specifications of the two power plants are given in Table 4.

TABLE 4. SPECIFICATIONS OF FUEL CELL POWER PLANTS.

Model	Fuel Type	Power Output	Heat
DFC 1500	Natural Gas @7800 scf/hr	1 Mw	1400000 BTU/hr
PureCell 200	Natural Gas @2050 scf/hr	200 kw	925000 BTU/hr

COST OF OWNERSHIP

Cost of ownership is a complete economic analysis method, which is used in this paper to evaluate the economic performance of the alternative energy supply patterns, to compare their ownership cost with that of local power supply, for reducing the environmental footprint of automotive manufacturing. The costs considered here are equipment cost, setup cost, and annual cost for operation of the equipment. Equipment costs include those for purchasing the equipment; setup costs include installation, transportation, and engineer training; and annual costs include those for maintenance, consumables, and space consumption. For each alternative energy supply, the cost of ownership is calculated through:

$$CoO = \frac{(C_1 + C_2 + C_3) \times N \times 100}{W \times T \times L} \text{ cents/kwh} \quad (4)$$

where

C_1: equipment costs, \$
C_2: setup costs, \$

$$C_2 = I + T + \sum G \times F$$

C_3: annual costs, $/year

$$C_3 = S \times R_s + E \times R_E + \sum O + D_d \times R_M$$

I: installation fee, $
T: transportation fee, $
G: number of people to be trained
F: training fee for P, $
S: footprint for the equipment, ft^2
R_S: footprint cost rate, $/$ft^2$/year
P: fuel consumption, scf/year
R_E: fuel price, $/scf
O: cost of various consumables, $
D_d: downtime, hours
R_M: maintenance cost, $/hour
N: number of the unit
W: average power output of power plant, kw/year
T: annual working hours
L: lifetime of the power plant, years

To encourage the use of renewable energies, both federal and state governments provide a number of incentives to compensate for the gap between the ownership cost and the local electricity price. In this paper, we use the economic and incentive values collected in 2006 for cost of ownership calculations. Incentives considered here are the Business Energy Tax Credit, Renewable Energy Production Incentive, Renewable Energy Systems and Energy Efficiency Improvement Incentive, as well as the Michigan Next Energy Authority Act incentive. In addition to these incentives, fuel cell power plants also generate heat values that could be recovered to save power use in various heating applications. In the assessment, the heat value recovery efficiency is assumed to be 80% of the electricity heating efficiency. The cost of ownership results for each of the alternative energy supply patterns are shown in Figure 2.

The cost of ownership analysis reveals that solar electricity is the most expensive energy supply pattern. On the other hand, wind electricity, with an ownership cost of 6.9 cents/kwh before incentives and 4.1 cents/kwh after incentives, is the most economical clean energy source among the four supply patterns. The ownership costs of fuel cells fall in between. The clean energy incentives provided by the federal and state governments were found to lead to a significant reduction in the ownership cost for clean energy technologies, bringing it down from 15% to 40% in this paper's analysis. In this study, the heat value of fuel cells, when efficiently recovered for appropriate heating applications, can further reduce the ownership cost of the fuel cell technologies by 25%~50%.

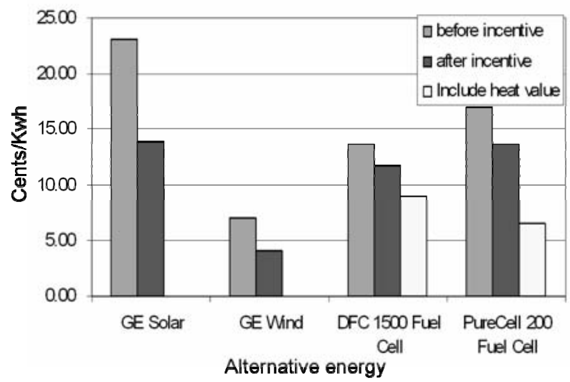

FIGURE 2. OWNERSHIP COSTS OF ALTERNATIVE ENERGY ELECTRICITY.

The local electricity price in Michigan was 6.08 cents/kwh for industrial end-users as of December 2006 (EIA 2007). Current wind technology has already provided an economically viable alternative to the local electricity supply in the Detroit area, and this can significantly reduce the environmental footprint of automotive manufacturing. For a further understanding of the ownership cost for the alternative energy supply patterns, a breakdown analysis is performed and the results are shown in Figure 3.

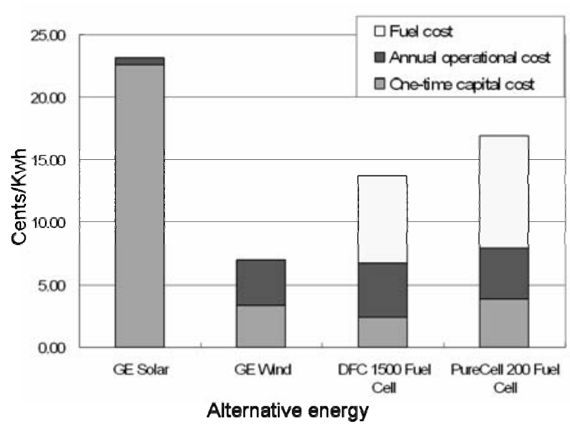

FIGURE 3. BREAKDOWN COST OF ALTERNATIVE ENERGIES.

Figure 3 indicates that almost 98% of solar electricity ownership cost is attributed to the one-time capital investment. In regard to wind electricity, about 60% of the ownership cost is one-time capital cost and 40% is annual operational cost. However, as to fuel cells, the consumed fuel takes in approximately half of the total ownership cost, while the capital cost and annual operational cost together account for half of the ownership cost.

ENVIRONMENTAL SAVINGS ANALYSIS

Solar, wind, and fuel cells are all considered as clean and renewable energy technologies. In the usage phase, solar and wind technologies are considered as having no emissions into the air; fuel cells have negligible air pollutant emissions. For instance, the DFC 1500 fuel cell power plant generates 0.009 g NO_x per kwh power delivery (Fuelcell Energy 2006), which is only 0.5% of the NO_x emissions per kwh from Michigan local electricity supply. However, the natural gas used in fuel cells leads to generation of extra carbon emissions. In Michigan, 1 kwh electricity consumption on average leads to an indirect generation of 687 g of CO_2 by the local power supply system (McDougall 2001; EIA 2003). Considering the power consumptions of Ford and GM are both at the level of 10^{10} kwh annually (Ford 2006; GM 2006), applications of clean energy technologies may save huge amounts of air emissions (including both air pollutants and greenhouse gases) from local electricity supply. To benchmark the environmental footprint reduction of solar, wind, and fuel cell technologies, the environmental savings on air emissions are calculated based on a $1000 investment in the three clean energy technologies, as shown in Table 5. Per $1 investment, the amounts of CO_2 savings from the four renewable energy supplies over current electricity supply are shown in Figure 4.

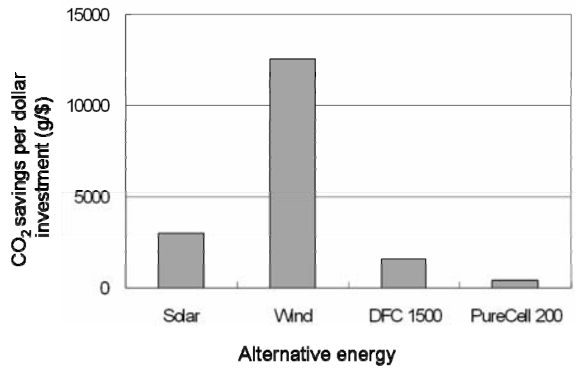

FIGURE 4. AMOUNTS OF CO_2 SAVINGS PER $1 INVESTMENT IN THE FOUR ALTERNATIVE ENERGIES.

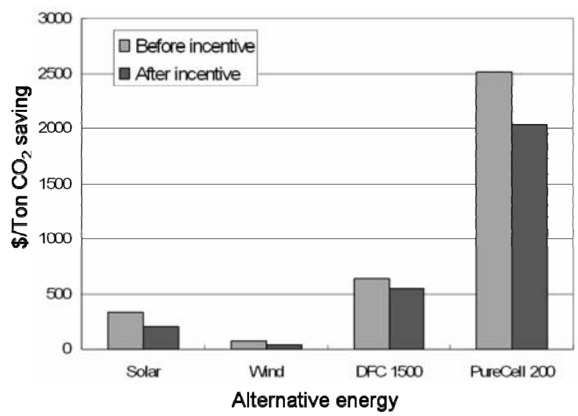

FIGURE 5. COST OF CO_2 SAVINGS FROM ALTERNATIVE ENERGIES.

TABLE 5. ENVIRONMENTAL SAVINGS OF AIR EMISSIONS FROM $1000 INVESTMENT IN SOLAR, WIND, AND FUEL CELL POWER PLANTS.

Unit: g/$1000

	Criteria Air Pollutants					Greenhouse Gases			Hazardous Air Pollutants		
	CO	NOx	Pb	PM	SOx	CO_2	CH_4	N_2O	HCL	HF	Hg
Solar	471.8	7377.4	0.5	4589.4	11023.2	2946675.2	12009.7	17.2	789.2	85.8	0.1
Wind	2009.6	31422.5	2.2	19547.7	46951.0	12550713.0	51152.8	73.1	3361.5	365.4	0.5
DFC 1500	640.1	12546.0	0.9	7846.2	18838.2	1577308.0	20532.1	29.3	1349.3	146.7	0.2
PureCell 200	538.0	10083.1	0.7	6331.1	15206.6	395696.1	16567.5	23.7	1088.7	118.3	0.1

The environmental saving analysis reveals that, per $1000 investment, wind power technology can lead to the greatest savings for all kinds of air emissions, while fuel cells save the least among the four alternative energy supplying patterns due to the process generation of CO_2 from the natural gas consumption. The environmental savings from solar PV falls in the middle of wind and fuel cells. As an illustration, Figure 5 shows the cost per metric CO_2 saving through use of solar PV, wind, and fuel cell technologies from the local electricity supply, respectively, before and after the incentives.

Figure 5 indicates that one metric ton of CO_2 can be saved by an investment of $50 on wind technology after incentives, which is the least costly among the four alternative options. Fuel cells cost the most, between $500~$2500 per metric ton of CO_2 savings. The cost of solar PV falls in the middle of these two technologies, with $203 cost in order to save one metric ton CO_2. For the 10% reduction benchmark in greenhouse gas emissions from the base year of 2002, Ford and GM must cut 4.4 million and 9.6 million metric ton of CO_2, respectively, from their U.S. manufacturing facilities. If we assume that the energy input per vehicle built and the production level of the two auto manufacturers are maintained at the same level, Ford and GM would need an investment of $22 million and $48 million, respectively, in regard to wind technologies.

It is important to note that the manufacturing impacts (materials, energy, greenhouse gas emissions, etc.) associated with the production of these alternative energy technologies, and delivery and setup to the site of use, have not been considered. These impacts can have a significant effect on the “payback time” for these technologies (Reich-Weiser 2008).

The environmental impact of an automobile comes not only from its manufacturing but also from other life cycle stages, including material production, use, and end-of-life. It has been reported that the energy consumed in vehicle manufacturing is roughly on the same level with that in material production and is roughly 7-15% of the total energy consumed in the use phase (Maclean 1998; Sullivan 1998). However, the total energy consumed in the vehicle usage phase spans a decade or longer while the energy consumption of vehicle manufacturing is much more concentrated.

CONCLUDING REMARKS

Automotive manufacturing is very energy intensive and generates a large amount of emissions from the energies that are consumed. Automobile manufacturers have made great efforts to improve energy efficiency in their manufacturing facilities. While some energy consumption systems such as compressed air supply systems can be reconfigured to reduce energy consumption (Yuan 2006), most of the energy consumption in automotive manufacturing are inherent and non-reducible. With 70% of their emissions generated from purchased electricity, an effective way to reduce the environmental footprint of the automotive manufacturing is to use clean energies to partially supply the energy needed for the manufacturing processes.

In this paper, three alternative energies: solar photovoltaic, wind and fuel cells with state-of-the-art technologies are evaluated for electricity generations, so as to reduce the environmental emissions from automotive manufacturing. Cost of ownership and environmental savings analyses are performed for each energy supply pattern. Governmental incentives for each technology are also considered in the evaluations.

Both the cost of ownership and environmental saving analyses here favor the use of wind over the other two technologies. The ownership cost of wind, before incentives, is 6.9 cents/kwh, which is a little bit higher than that of the local electricity price in Michigan; yet after incentives, it is 4.1 cents/kwh which is lower than that of the local electricity price in Michigan. In regard to wind electricity, about 60% of the ownership cost is attributed to the one time capital cost and the other 40% is due to annual operational cost. As evaluated, the cost per metric ton CO_2 savings through the use of wind technology is about $80 before incentives and $50 after incentives.

Current wind technology has provided an economically viable alternative to the local electricity supply, which can reduce the environmental footprint of automotive manufacturing. While the use of wind is more economically competitive than that of solar and fuel cells, the height requirement and noise generated from wind operations may make it difficult for application in urban areas like the Detroit region. In such a situation, hydrogen fueled fuel cells could be an alternative option. Solar photovoltaic needs to cut the cost by 50% or more to be economically competitive in the future.

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