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Transparent Photovoltaic Vehicle Integration

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ABSTRACT: Concerns regarding climate change continue contributing to new technological developments toward more renewable and sustainable energy generation. Transparent photovoltaic solar panels to replace windows and generate electricity are one example of emerging technologies for building applications. In the transportation sector, vehicle electrification appears to be the best solution to gasoline and diesel. However, if the electricity is supplied by fossil fuel power plants, then very little advantages are gained. Furthermore, the limited driving range and infrastructure for electric vehicles present additional challenges to adoption. By integrating renewable energy systems like photovoltaics into electric vehicles, energy can be generated to charge and power vehicles, potentially increasing range and decreasing charging times. This paper investigates the theoretical integration of transparent photovoltaic solar panels onto a stationary electric vehicle in the Midwestern United States, replacing the vehicles windows. The investigation proved that energy generation from integration is possible from all sides of the vehicle. Due to high system cost and low electricity rates, the integration is not economically responsible due to the negative life cycle savings. If system costs decrease, electricity rates increase, or a sunnier location is utilized, then the energy payback may be able to achieve a positive life cycle savings.

KEYWORDS: Renewable Energy, Sustainability, Electric Vehicles, Solar Photovoltaics

I. BACKGROUND

Climate change is motivating the shift away from fossil fuels towards more renewable and sustainable sources of energy. Many governments, businesses, and organizations are setting standards to reduce carbon emissions and other forms of pollution while maintaining or improving modern comforts. The push away from fossil fuels is leading to increases in new technological developments and adoption including electric vehicles (EV's), solar photovoltaics (PV's), wind turbines, and more [1, 2].

On the surface electric vehicles appear to be a sustainable form of transportation. However, the sustainability of electric vehicles and indeed all products comes down to the overall life cycle assessment including the materials, manufacturing, energy, and disposal. All processes have pros and cons, creating different environmental benefits and hazards. Out of all life cycle processes, the use phase of electric vehicles followed by production contributes to the largest environmental impacts [3]. However, by using renewable and sustainable forms of energy, the impact of electric vehicles can be significantly reduced compared to fossil fuel power plants [4, 5].

Electric vehicles also face challenges regarding charging time, driving range, and infrastructure. Charging (refueling) can take over 3 times as long with less driving range and infrastructure compared to a gasoline vehicle. To combat some of the issues, infrastructure continues growing and charging times are being reduced. Another concept being investigated is the integrating solar and wind energy systems into vehicles [1]. Wind energy appears to be less feasible while solar integration is increasing in popularity with the Toyota Prius and others. The integration of renewable energies into electric vehicles provides a method for generating electricity without needing to connect to the power grid. Vehicles can be charged dynamically while driving or parked if sunlight is present [2, 6, 7].

One invention emerging on the market is transparent photovoltaic (TPV) solar panels. Like a traditional photovoltaic (PV) solar panel, sunlight is collected and converted into electricity. However, transparent photovoltaics are designed to replace windows in buildings to provide natural lighting while also collecting energy [8, 9]. A concept that has seen little investigation is the integration of transparent photovoltaics into vehicles. Regular solar panels are already being

placed on vehicle body panels and by using the windows the overall area would increase, improving charging capabilities and energy generation [1, 2].

This article investigates the theoretical integration of transparent solar photovoltaic panels into a vehicle, replacing the windows to determine energy output and economics. The panels are assumed to be 100% transparent with no tinting, damage, or alterations. For the purposes of the investigation vehicle material and safety requirements for windows are not considered for integration. The vehicle is also assumed to be stationary with no dynamic charging or shading from trees, buildings, etc. No external charging is used either and there are assumed energy losses and assumptions for the analysis. All energy generated by the panels is assumed to be consumed by the vehicle, saving cost from external charging.

II. METHODOLOGY

A vehicle is assumed to be parked in West Lafayette, Indiana facing south. The vehicle has assumed window sizes, orientation, and inclination acting as transparent photovoltaics to collect energy. The transparent photovoltaics are assumed to cost \$8/W which includes all system components. Assuming a solar irradiance of 1000 W/m² of sunlight and a 10% panel efficiency, the cost of each panel can be calculated using equations 1 and 2 below. Table 1 provides a summary of each panel’s parameter.

$$\text{System Size (W)} = 1000 \text{ W/m}^2 * \text{Area} * \text{Efficiency} \tag{1}$$

$$\text{System Cost (\$)} = \text{System Size (W)} * \text{cost (\$/W)} \tag{2}$$

Table 1: Energy Analysis Parameters

MATLAB	North	East	South	West
Area (m ²)	1	0.75	1	0.75
System Size (kWdc)	0.1	0.075	0.1	0.075
Orientation [Gamma] (degrees)	180	-90	0	90
Inclination [Beta] (degrees)	30	75	30	75
System Cost (\$)	800	600	800	600

With an established size, location, orientation, and inclination of each panel, energy modeling was able to be conducted. Energy modeling was conducted using two methods for validation. The first method utilized MATLAB with the Lui and Jordan models for solar irradiation and energy output of solar photovoltaic panels. Equations 3 through 12 listed by Duffie and Beckman (2013) provide methods for estimating the system’s energy output. Overtime, the panels are assumed to experience performance degradation, reducing energy output. Degradation calculations use the present worth equation 13 to account for annual exponential energy losses. Other system inefficiencies contributing to energy losses are also assumed and accounted for in the overall energy calculations.

The second method utilized the National Renewable Energies Laboratory’s (NREL) System Advisory Model (SAM) software to ensure similar results for energy analysis. Within SAM is a program called PVWatts for calculating solar PV array energy outputs and costs. Solar irradiance data was acquired from NREL’s database and used to obtain the energy results for both energy modeling methods. Once calculating and validating the energy results, the data was used to analyze the economics of transparent photovoltaic vehicle integration.

$$\text{Solar Time} = \text{Standard Time} + \frac{4*(L_{st}-L_{loc})}{60} + \frac{E}{60} \tag{3}$$

Where:

Solar Time – suns position relative to the study location

Standard Time - local time without daylight savings correction

L_{st} = Longitude of Standard Time Zone

L_{loc} = Longitude of Location

$$E = 9.87 * \sin(2 * B) - 7.53 * \cos(B) - 1.5 * \sin(B) \tag{4}$$

$$B = 360 * (n - 81) / 365 \tag{5}$$

n = day of the year

$$R_b = \frac{\cos \theta}{\cos \theta_z} \tag{6}$$

Where:

$$\begin{aligned} \cos \theta &= \sin(\delta) * \sin(\phi) * \cos(\beta) - \sin(\delta) * \cos(\phi) * \sin(\beta) * \cos(\gamma) + \\ &\cos(\phi) * \cos(\delta) * \cos(\beta) * \cos(\omega) + \cos(\gamma) * \sin(\phi) * \cos(\delta) * \sin(\beta) * \cos(\omega) + \\ &\sin(\gamma) * \cos(\delta) * \sin(\beta) * \sin(\omega) \end{aligned} \tag{7}$$

$$\cos \theta_z = \cos(\phi) * \cos(\delta) * \cos(\omega) + \sin(\phi) * \sin(\delta) \tag{8}$$

$$\delta = 23.45 \sin\left(360 \left(\frac{284 + n}{365}\right)\right) \tag{9}$$

solar declination

β = panel inclination (tilt angle)

$$\omega = 15 * (\text{Solar Time} - 12) \tag{10}$$

hour angle

ϕ = latitude

γ = orientation (azimuth)

$$I_T = I_b R_b + I_{d,iso} \left(\frac{1 + \cos(\beta)}{2}\right) + \rho_g I \left(\frac{1 - \cos(\beta)}{2}\right) \tag{11}$$

Where:

I_T = total irradiance incidence on a surface

I_b = beam irradiance obtained from TMY data (DNI)

I = total irradiance normal to the earth obtained from TMY data (GHI)

$$I_{d,iso} = I - I_b \tag{12}$$

Horizontal diffused irradiance

ρ_g = ground reflectance (coverage) ratio

$$\text{Present Worth: } PW_N(A) = \frac{A(1+i)^{N-1}}{(1+d)^N} \tag{13}$$

The economic analysis utilized a time value of money assessment with several parameters and variables for estimating overall life cycle cost. A summary of financial assumptions for the analysis can be found in Table 2. System cost was assumed to be \$8/W with a fixed annual maintenance of 5% of the total system cost. Assuming a standard loan for 5 years with 0% down payment and interest rate of 4%. Inflation and escalation rates of 3%, discount rate of 10%, and electricity rate of \$0.12/kWh. When using PVWatts, additional parameters and assumptions had to be utilized for both the energy and economic analysis. Appendix A and B show the full comparison of inputs for both MATLAB and PVWatts analysis. The economic analysis uses equations derive from common engineering economic practices to estimate financial costs and savings (Duffie & Beckman, 2013). Equations 14 and 15 provide present worth factor calculations required for equations 16, 17, and 18.

Table 2: Economic Analysis Assumptions

System cost (Module, inverter, etc.) = \$8/W
Fixed Annual Maintenance Cost = 5% of system cost
Maintenance Escalation Rate = 3%
Standard loan
Down Payment = 0% of initial cost
Loan term = 5 years
Interest rate = 4%
Analysis Period = 10 years
Inflation Rate = 3%
Nominal Discount Rate of 10%
Electricity Escalation = 3%
Electricity Rate = 0.12 \$/kWh

Present Worth Factor:
$$PWF(N, i, d) = \frac{1}{d-i} \left(1 - \left(\frac{1+i}{1+d}\right)^N\right) \quad \text{when } i \neq d \quad (14)$$

$$PWF(N, i, d) = \frac{N}{1+i} \quad \text{when } i = d \quad (15)$$

Where:

N = length of analysis in years

A = Annual cost or energy

i = inflation rate

d = discount rate

Life Cycle Savings (LCS):
$$LCS = P_1 C_E - P_2 C_s \quad (16)$$

Where:

$$P_1 = PWF(N, i, d) \quad \text{Present Worth Factor of future energy payments} \quad (17)$$

C_E = the total cost of energy from the first year after the system is installed

C_s = the total cost of the installed system

P_2 = present worth factor of future costs associated with owning the system

$$P_2 = D + (1 - D) \frac{PWF(N_L, 0, d)}{PWF(N_L, 0, m)} + M_s PWF(N_L, 0, m) \quad (18)$$

Where:

D = ratio of down payment over initial cost

N_L = Length of loan in years

N_1 = Minimum between N_L and N

m = annual interest rate of loan

M_s = system maintenance cost per year as a fraction over the initial system cost

III. RESULTS AND DISCUSSION

Results from the analysis using MATLAB are given below in Table 3. The north and south facing panels produce the most energy with the south achieving the largest value as expected. The larger energy outputs can be attributed to the size, orientation, and inclination of each panel. The east and west facing panels perform similarly, however, the west produces slightly more due to orientation. An assumed 20 percent system energy losses further reduce energy output through electricity travel and conversion. Each panel's energy output is summarized in Figure 1. In terms of economics, the east and west facing panels achieve the lowest overall life cycle savings (LCS) due to size and system cost. However, the south facing panel provides the best output and economics when comparing system cost to Life Cycle Savings (LCS), adding \$90 to the overall cost compared to the other three at over \$100. A summary of energy output, system cost, and life cycle savings are provided in Figure 2.

Table 3: MATLAB Energy and Financial Analysis Results

MATLAB	North	East	South	West
Area (m ²)	1	0.75	1	0.75
System Size (kWdc)	0.1	0.075	0.1	0.075
Orientation [Gamma] (degrees)	180	-90	0	90
Inclination [Beta] (degrees)	30	75	30	75
Annual Energy without losses (kWh)	108	71	171	72
Annual Energy with losses (kWh)	87	57	138	58
System Cost (\$)	800	600	800	600
LCS (\$)	-932	-706	-890	-705

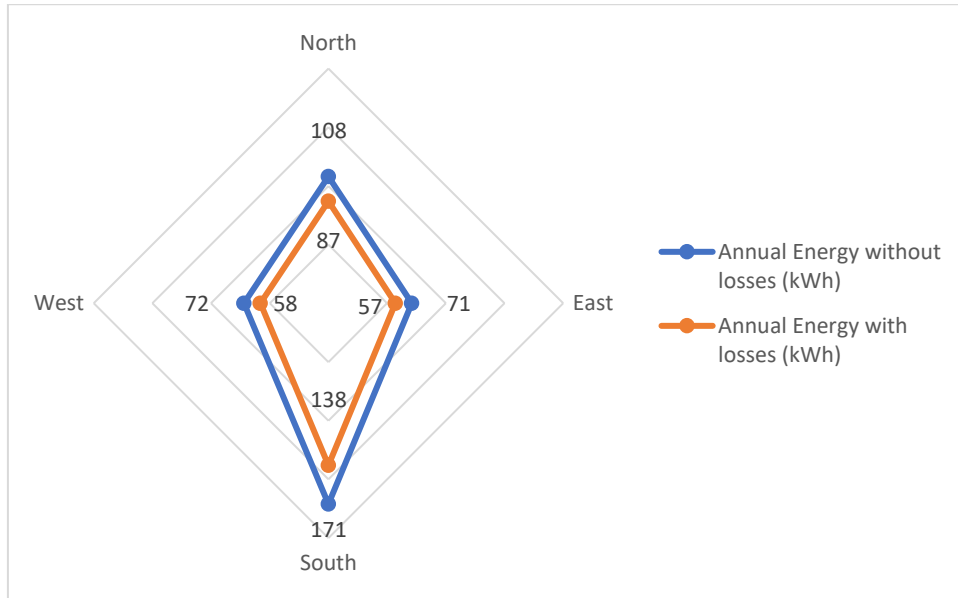


Figure 1: MATLAB Annual Energy Output

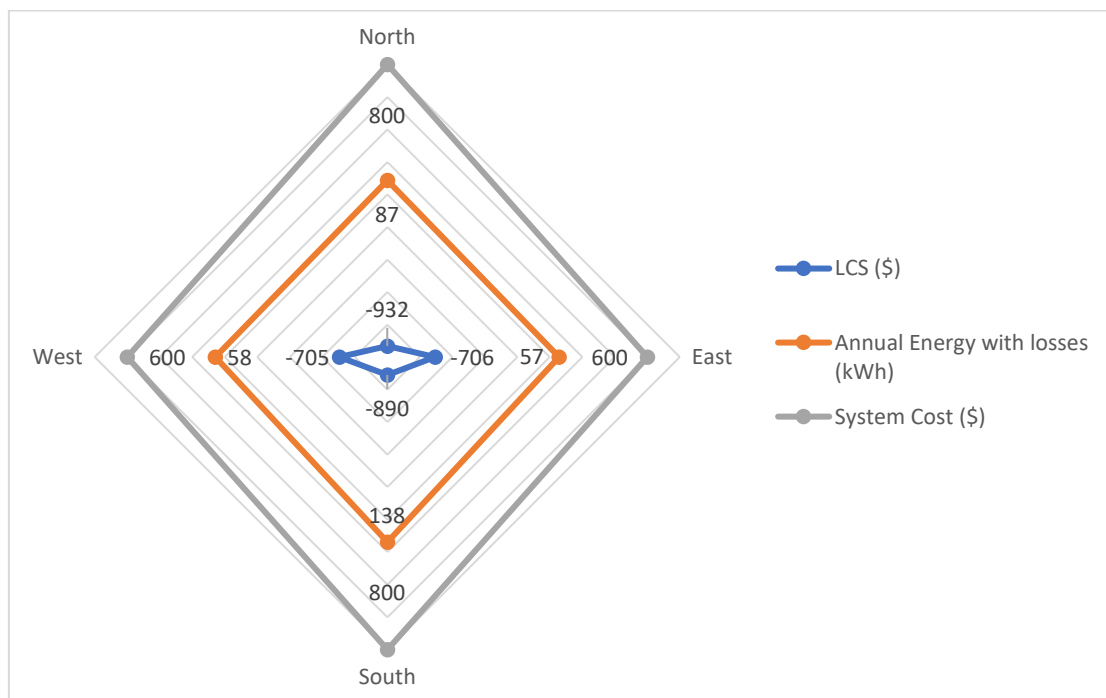


Figure 2: MATLAB Annual Energy Output vs Life Cycle Savings and System Cost

The negative life cycle savings are due to the high system cost of the newer, transparent photovoltaic materials as well as the increasing interest, maintenance, and degradation. The low cost of electricity along with season at the location also plays a role in energy output as shown by Figure 3. The colder winter months produce less sunlight due to the earth's location and orientation relative to the sun, resulting in less energy. Other factors like cloudy days can also be attributed to the loss in energy generation, affecting overall economics.

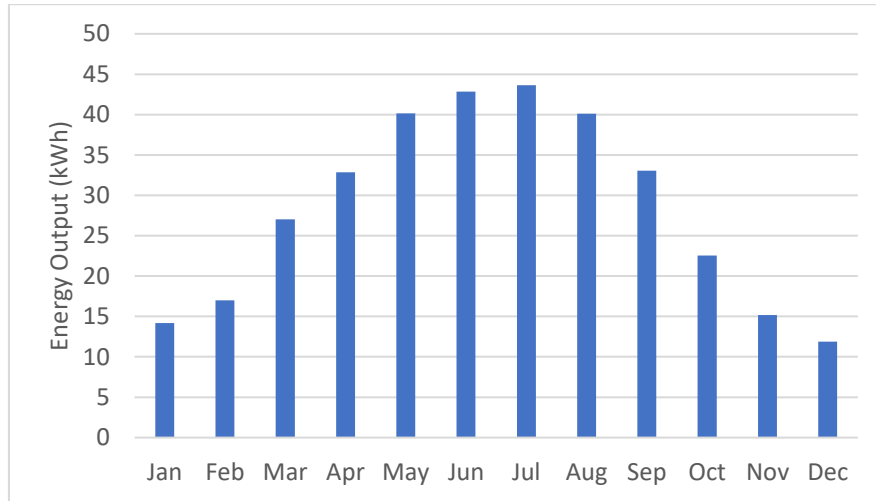


Figure 3: MATLAB Monthly Energy Output

After establishing performance using MATLAB, a validation was conducted using NREL’s SAM software with PVWatts. PVWatts utilizes slightly different numbers and assumptions for orientation, system losses and more. All assumptions used for the program can be found in the Appendices.

The results from using PVWatts are provided in Table 4, showing similar results to the MATLAB analysis. The south panel produces the most energy while achieving the best life cycle savings when compared to cost. Figure 4 provides a visual comparison between the two analysis methods. Due to the similar performance, the analysis appeared to be valid and further testing was conducted.

Table 4: PVWatts Energy and Financial Analysis Results

PVWatts	North	East	South	West
Area (m ²)	1	0.75	1	0.75
System Size (kWdc)	0.1	0.075	0.1	0.075
Orientation [Azimuth] (degrees)	0	90	180	270
Inclination [Tilt] (degrees)	30	75	30	75
Annual Energy without losses (kWh)	95	74	168	75
Annual Energy with losses (kWh)	81	63	143	64
System Cost (\$)	800	600	800	600
LCS (\$)	-917	-686	-861	-685

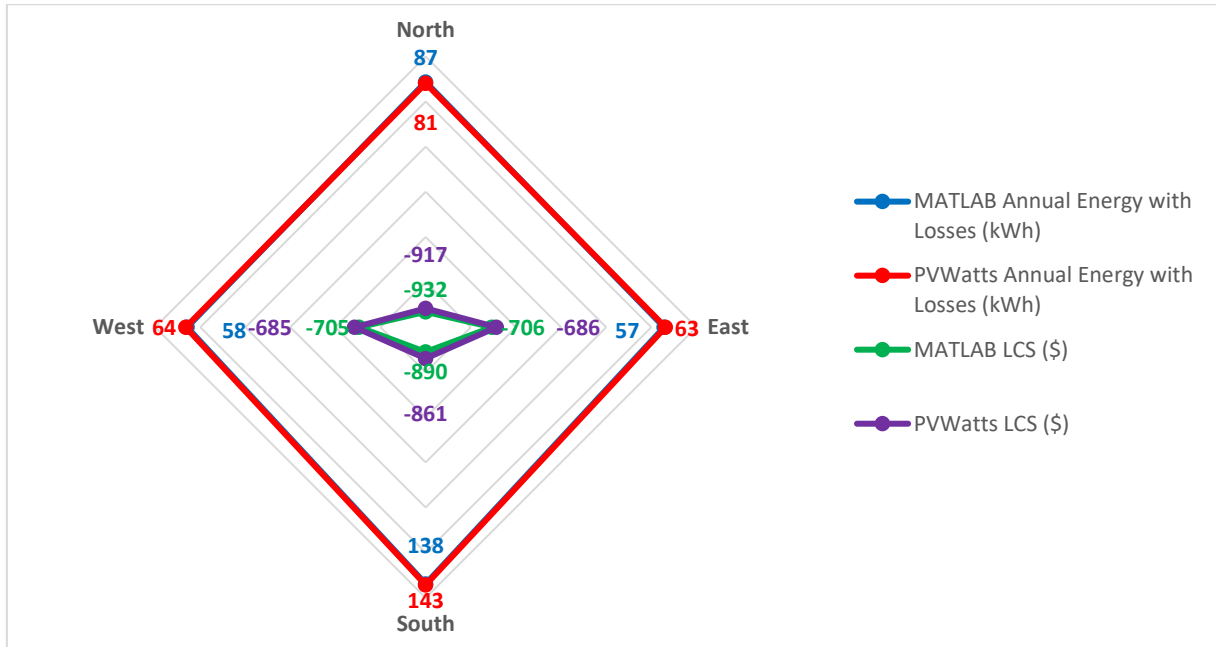


Figure 4: MATLAB vs. PVWatts Comparison

Since neither method provided a break-even quantity for life cycle savings, further analysis was conducted by changing the system cost as well as electricity prices. Table 5 shows the results of altering the system cost from \$8/W to \$2/W (average cost of traditional PV panels), significantly reducing system cost and life cycle savings. Further changes in electricity costs were analyzed until a break-even number was achieved as shown by Table 6 and Figure 5. Both Table 6 and Figure 5 show positive life cycle savings if the system and electricity costs of \$2/W and \$0.38/kWh, respectively.

Table 5: MATLAB results for each panel using \$2/W and \$0.12/kWh

MATLAB	North	East	South	West
Area (m ²)	1	0.75	1	0.75
System Size (kWdc)	0.1	0.075	0.1	0.075
Orientation [Gamma] (degrees)	180	-90	0	90
Inclination [Beta] (degrees)	30	75	30	75
Annual Energy without losses (kWh)	108	71	171	72
Annual Energy with losses (kWh)	87	57	138	58
System Cost (\$)	200	150	200	150
LCS (\$)	-179	-141	-137	-140

Table 6: MATLAB life cycle savings comparison using different financial estimates

LCS parameters	North	East	South	West	Total
\$8/W, \$0.12/kWh	-932	-706	-890	-705	-3233
\$2/W, \$0.12/kWh	-179	-141	-137	-140	-597
\$2/W, \$0.25/kWh	-101	-90	-13	-88	-292
\$2/W, \$0.38/kWh	-23	-39	110	-37	11

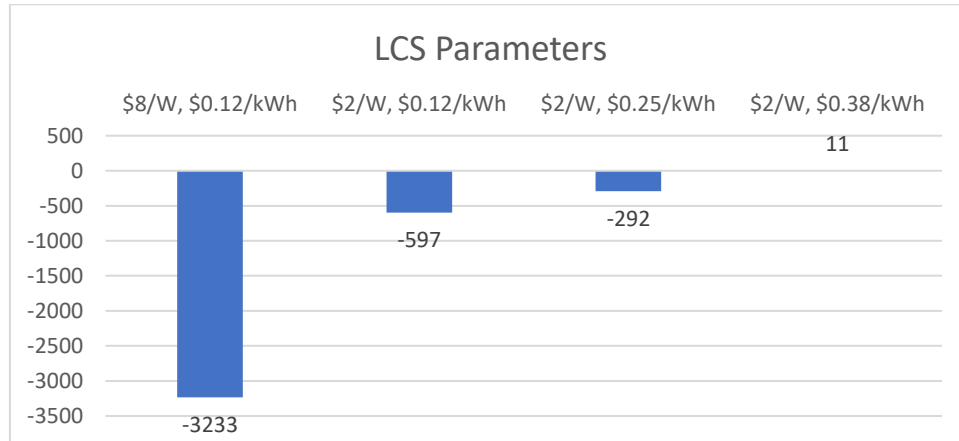


Figure 5: Changing financial parameters to achieve a breakeven scenario.

Another contributing factor to achieve a positive life cycle savings would be the location of the study. Indiana is not known for its sunny skies or expensive electricity. However, by moving to a sunnier location with more expensive electricity, greater energy output could be achieved while improving savings.

IV. CONCLUSION

The integration of transparent photovoltaic solar panels into automobiles has the potential to generate energy that can be used to power electrified vehicles. The generated electricity provides a free source of energy and financial savings as well as potential freedom from charging infrastructures, increased driving range, and reduced charging times. However, the overall economics of the system is not favorable for the chosen location due to the system cost and low electricity rates. The use of transparent photovoltaics in vehicles can be beneficial if system costs are low, electricity rates are high, and large amounts of solar energy are available.

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APPENDIX A. MATLAB ASSUMPTION

Energy Assumptions

Location: West Lafayette, Indiana (40.45N, -86.9W)
 Eastern Time Zone Longitude -75W
 Module Efficiency = 10%
 Ground Reflectance Ratio = 0.2

MATLAB	Front Window (South)	Passenger Side (West)	Rear Window (North)	Drivers Side (East)
Area (m ²)	1	0.75	1	0.75
System Size (kWdc)	0.1	0.075	0.1	0.075
Orientation (degrees)	0	90	180	-90
Inclination (degrees)	30	75	30	75

*System Size = 1 kW/m² * efficiency * Area
 Total system losses to soil, shading, snow, wiring, etc. equal 15%
 Degradation = 0.5% each year

Financial Assumptions

System cost (Module, inverter, etc.) = \$8/W	Inflation Rate = 3%
Fixed Annual Maintenance Cost = 5% of system cost	Nominal Discount Rate of 10%
Maintenance Escalation Rate = 3%	Electricity Escalation = 3%
Standard loan	Electricity Rate = 0.12 \$/kWh
Down Payment = 0% of initial cost	
Loan term = 5 years	
Interest rate = 4%	
Analysis Period = 10 years	

APPENDIX B. PVWATTS ASSUMPTION

Energy Assumptions

Location: West Lafayette, Indiana
 DC to AC Ratio: 1 (no AC used)
 Inverter Efficiency: 99.5% (highest allowed, no AC used, only DC for this application)
 Module Type: Thin Film (10% efficiency)
 Ground Coverage Ratio = 0.2
 Array Type: Fixed open rack

	South	West	North	East
Area (m ²)	1	0.75	1	0.75
System Size (kWdc)	0.1	0.075	0.1	0.075
Orientation [Azimuth] (degrees)	180	270	0	90
Inclination [Tilt] (degrees)	30	75	30	75

System Size = 1 kW/m² * efficiency * Area
 Total system losses to soil, shading, snow, wiring, etc. equal 15%
 Grid limits not used
 Degradation = 0.5%

See APPENDIX A for Financial Assumptions

Additional Financial Assumptions Needed for PVWatts:

Debt fraction = 100% (Down Payment = 0% of initial cost)
Real Discount Rate 6.8 (Nominal Discount Rate of 10% with inflation of 3%)
No Project Tax, Insurance Rates, or Salvage Value
No Tax Deductibles, Tax Credits, Direct Cash Incentives, etc.
Net Energy Metering
No Fixed Charges, Minimum Charges, or Monthly Charges
No Load growth rate



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