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Municipal Fleet Vehicle Electrification and Photovoltaic Power In the City of Pittsburgh

FINAL RESEARCH REPORT

Constantine Samaras (PI),

Avi C. Mersky, Constantine Samaras

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Executive Summary

This document reports the results of a cost benefit analysis on potential photovoltaic projects in Pittsburgh and electrifying the city's light duty civilian vehicle fleet. Currently the city of Pittsburgh has a civilian passenger vehicle fleet of 118 vehicles travelling 718,000 miles a year. This leads to an average (5 days a week) travel of 23.4 miles per work day per vehicle. We used a gasoline price of range of $1.50, $2.00 and $2.50 a gallon and electric price range of 4, 6 and 10 cents per kWh. We found that conventional vehicles would likely cost less to operate over 15 years than electric vehicles. This is due to the increased capital costs involved in purchasing the vehicles and charging stations, as well as the amount of miles these vehicles travel per year. To account for the of impacts of vehicle electrification on emissions we calculated the CO_2, NOx and SO_2 emissions from both a conventional and electric fleet. For electricity emissions we investigated several electric grid assumptions including current regional grid average, current regional grid marginal at night, current regional grid with 30% RECs, and a regional grid starting with 30% RECs and increasing to 100% over 15 years. The city is currently purchasing RECs for 30% of its municipal power needs. For GHG emissions, we found that EVs in Pittsburgh save GHGs compared to conventional gasoline vehicles in 3 of our 4 current electricity grid assumptions. As the GHG-intensity of the grid improves over the next 15 years, BEVs have clear GHG advantages over conventional gasoline vehicles in Pittsburgh. The City of Pittsburgh has indicated if will transition to purchasing RECs for 100% of governmental energy use by 2030. While there challenges with attributing local air pollutant reductions directly to RECs on a one-to-one basis, the combination of existing and proposed EPA power plant regulations and REC purchases highly increase the likelihood of a cleaner grid profile going forward. Yet SO_2 emissions from the power sector remain problematic in a social net present cost analysis. SO_2 was the highest cost pollutant for vehicle externalities and is not emitted in significant amount from gasoline combustion. Because of the SO_2 emissions, vehicle electrification was also found to be likely to have higher total social emissions costs than gasoline options under most cases. A faster reduction in power plant air emissions improves the outlook for electrification.

One way of offsetting these emissions is to ensure that a portion of the needed electricity is generated from renewable or low-emission sources. Photovoltaic (PV) generation is one possible renewable source to consider for distributed generation in an urban region. One potential location for PV cells would be on city-owned parking facilities. Canopies could be built over city-owned surface lots or on the tops of city-owned garages. Currently the Pittsburgh Parking Authority maintains 10 downtown parking garages, with parking on the roofs, and 1 unshaded downtown surface level lot. The total surface area of these garages' roofs and the lot was found to be approximately 52,000 square meters. We estimated a peak capacity of about 6,000 kW of PV is possible on these facilities. The amount of electricity potentially generated from these PV systems could power between 24 and 27 million miles of electric vehicle travel per year, which is more than 30 times the yearly travel of the city's civilian passenger vehicle fleet. The PV systems were found to have positive net present values, including the value of decreased pollution,

only under best case assumptions. If the city of Pittsburgh wanted to create an emergency refueling and logistics center, it would require several sources of distributed energy to enhance resiliency. If PV were included on a municipal energy emergency center, the panels could be utilized everyday, not solely in emergencies. Using the 2nd Avenue location as an example we found that an emergency center could generate nearly 60,000 EV miles worth of electricity, on the peak day. In terms of the BEV's 23 kWh Battery capacity, that would be nearly 800 full cycles. On the worst day, however, it would only generate 1,500 miles or 66.5 BEV battery cycles worth of charge.

1.1 Introduction and Motivation

Urban air quality remains a considerable challenge in local environmental policy. Pittsburgh has long had challenges with urban air quality. Due to both local sources and upwind power plants in the Ohio River Valley, the city has consistently been ranked among cities with the highest levels of air pollutants in the US, failing to attain federal air quality standards (*1*, *2*). Two possible methods to improve air quality are vehicle electrification increasing the penetration of low-polluting electricity sources such as photovoltaic (PV) solar power. Previous research has indicated that the current composition of some power grids may degrade air quality via vehicle electrification (*3*), which is why simultaneous consideration of transitioning to electric vehicles (EVs) and improving the environmental attributes of the power system is warranted. This report summarizes the results of an environmental systems assessment and cost benefit analysis of the electrification of the City of Pittsburgh's municipal vehicle fleet and also installing PV systems on the City's parking facilities.

1.2 Current Local Electrification Infrastructure

Currently Pennsylvania has 0.36 EVs per 1,000 people, which is similar to Ohio, but only half of New Jersey and almost ten times less than California (*4*). Pennsylvania however, with 0.05 public charging stations per EV, does have about three times as many charging stations per registered EV than California and nearly twice as many as New Jersey (*5*). The availability of electric vehicle charging stations is essential to broad consumer adoption of electric vehicles. While there are more than 150,000 gasoline stations in the U.S., there has been a rise in the number of public electric vehicle charging stations across the country. There are now more than 30,000 charging outlets nationwide, and at least 425 charging stations in Pennsylvania. Pittsburgh had historically lagged behind this trend, but has recently begun an effort to increase the number of charging stations in the City in partnership with the Pittsburgh Clean Cities Coalition. There are now approximately 50 charging stations within the City of Pittsburgh, and additional installations are planned. However, downtown Pittsburgh is the second largest central business district in the Commonwealth of Pennsylvania and yet only about a dozen EV charging stations exist out of more than 23,000 traditional parking spaces. These existing downtown stations are primarily located in a mix of Pittsburgh Parking Authority garages and office building garages. Because of the density downtown and multi-modal transportation options in and adjacent to the central business district, there is a large opportunity for an expanded network of electric vehicle charging stations. Figure 1 shows the locations of downtown Pittsburgh Parking Authority (PPA) Facilities, investigated in this reports, and the current number of EV chargers.

Figure 1: Current Pittsburgh Parking Authority (PPA) Facilities and EV Infrastructure. Red circles denote PPA facilities with EV charging infrastructure. Additional charging infrastructure is planned for installation in the Second Avenue Parking Plaza.

2. Approach and Methods

2.1 Municipal light duty fleet analysis

A number of state and local governments have released broad readiness plans for electric and plug in electric vehicles. These include the San Francisco Bay Area, Delaware Valley, New York City and Province of Manitoba (*6*–*9*). Most of these are primarily focused on supporting infrastructure, trend forecasting and policies to encourage private deployment. A direct cost benefit analysis, breaking down private and public value is rarer and only seen New York City's report.

Fleet cost optimization is a mature field. Most research tends to be in terms of sizing and costs as List et al.'s general fleet model and Yoon and Cherry's EV specific models are (*10*, *11*). These models generally assess the capital, maintenance and fuel costs to optimize for the fleet operator costs. Others like Price et al, (*12*) focus on other aspects, such as the batteries and end of life options. Many, such as Freire and Marques's work, include external costs, via GHG effects (*13*). This report focuses on capital and fuel costs for the fleet operator and GHG effects and human health impact for external costs.

Quantifying PV potential for multiple buildings in a geographic area is often done via aerial or satellite photography. Wiginton et al. devised such a method to estimate total PV power capacity of Ontario, absent cost concerns (*14*). Vardimon, similarly, investigated PV power potential of Israel, using aerial photography and local solar irradiance (*15*). Specific research on cost and sizing of PV canopies, suitable for parking facilities, is rarer. Hunter et al investigated the cost effectiveness of PV canopies for climate change mitigation purposes in Boston (*16*). PV canopies, as a mitigation method, are of particular interest as they can make use the space of parking facilities without compromising their capacity and also can reduce the urban heat island effect (*17*).

Our analysis focuses on the Pittsburgh municipal fleet of light duty civilian vehicles. Currently the city of Pittsburgh has a civilian passenger vehicle fleet of 118 vehicles travelling 718,000 miles a year (*18*). This leads to an average (5 days a week) travel of 23.4 miles per work day per vehicle for the civilian passenger vehicle fleet. This civilian fleet does not include police or other emergency vehicles.

Two dominating financial components of a vehicle fleet are the initial purchase price and the cost of the fuel needed for daily operations. Therefore the prices of both gasoline and electricity are relevant to understand the costs of managing a municipal vehicle fleet containing electric vehicles. Table 1 shows the purchase price and fuel economy characteristics of conventional, hybrid, plug-in hybrid electric (PHEV), and battery electric (BEV) vehicles similar to those currently in use by the city of Pittsburgh. Regular wholesale gasoline prices were $2.017 a gallon, in July 2015 (*19*). Therefore this report will use a range of $1.50, $2.00 and $2.50 a gallon for cash flow analysis. As the City of Pittsburgh currently pays an average of 6 cents per kWh the electric price range was 4, 6 and 10 cents a kWh.

Table 1: Vehicle Characteristics

Vehicle Model	MSRP, or Known City Purchase Price ($)	All Gasoline City Fuel Economy	All Electric City Fuel Economy	All Electric Range (
2016 Ford Focus Electric	$28,000 $29,170 (8)	n/a	30.64 kWh/100 mi (9)	76 mi (9)
2016 Ford Fusion Energi Plug-in Hybrid	$33,900 (*20*)	2.5 gal/100 mi (*21*)	37 kWh/100 mi (*21*) (combined)*	19 mi (*21*)
2016 Ford Fusion Hybrid FWD	$25,000 $25,990 (*22*)	2.27 gal/100 mi (*23*)	n/a	n/a
2016 Ford Focus S Sedan	$17,255 (*24*)	3.33 gal/100 mi	n/a	n/a

(conventional)				

*Source does not separate PHEV's electric fuel economy into City and Freeway measures

The City of Pittsburgh currently has a contract to buy wind power for 30% of its municipal electricity needs and is planning to increase its renewable purchases to 100% by 2030. We assumed that the purchased wind power is from local sources, and therefore displacing local fossil fuels, and ignore additional emissions resulting from intermittency when calculating time-dependent marginal costs. In the Pittsburgh regional residential market wind power has about a $0.015 premium per kWh over conventional electricity (*25*). As the current purchase price of 6 cents per kWh includes the 30% wind renewable energy credits (RECs) we applied the $0.015/kWh premium to increases beyond 30% RECs.

In addition to direct cost of the vehicle and its fuel, electric vehicles, both BEV and PHEVs, require charging infrastructure. Level 1 charging requires a standard 120-volt outlet and can charge a battery about 4.5 miles worth of electricity per hour, depending on the vehicle and battery state of charge. Level 2 charging requires a 240-volt outlet and additional equipment and can charge up to 70 miles an hour, though many mass market cars only allow for under 20 miles per hour of charging (*26*). Level 3 charging, or DC fast charging, is much faster, but requires much more electric infrastructure and vehicle support. However they can supply up to 240 miles worth of charge per hour (*26*). A Level 3 charger can cost anywhere from $20,000 to $80,000 in equipment and installation (*8*). We expect that few vehicles would need DC charging in the civilian fleet, even with a wide usage distribution. Due to the expense, we did not consider Level 3 charging here and will examine under future work. For this analysis we assumed that each vehicle would require one Level 2 charger. After a review of current literature and EV manufacturer guidance, we found a range of possible costs for equipment and installation of Level 2 charging units in garages. We decided to use $1,250 as a low estimate, $4,625 as a middle estimate and $8,000 as a high estimate (*8*, *27*, *28*). Additionally, to account for the possibility of Federal infrastructure capital subsidies, our cash flow analysis used values of $0, $4,000 and $8,000.

For our net present value (NPV) analysis, Pittsburgh Municipal bond and U.S. Treasury rates were used to estimate a discount rate. Current 20 and 30-year US treasuries carry coupon rates of 2.62% and 2.93% (*29*), while Pittsburgh Municipal bonds are 5%, for the municipality (*30*) and 7.25%, for the water authority (*31*). This paper assumes that the lowest discount rate is 3%, the middle 5% and the highest discount rate 7%. The NPV analysis considered 3 scenarios and 3 timeframes, 10, 12 and 15 years. In all scenarios each vehicle was assumed travel the fleet average yearly amount of travel.

The best case scenario was defined as the combination of factors most likely to favor electric vehicles, while the base case scenarios were defined as the ones most likely to occur and the worst case with the ones least likely to favor electric vehicles. The parameter values for each of these scenarios are summarized in Appendix 1. The results are summarized in Table 2, where the net present value (costs) is written for each vehicle and the vehicle with the least cost is highlighted. If the BEV was the least costly option then the lowest 2 options were highlighted, in case a BEV would not be appropriate for that vehicle usage patterns. The private NPV represents only the present value of the capital and operating costs of the vehicle to the City of Pittsburgh. The private NPV under these conditions is summarized in **Error! Reference source not found.**Table 1, with the vehicle choice with the lowest NPV in each scenario highlighted in green. The conventional vehicle option dominates in all scenarios, when it comes to the private cost.

Table 2: 15 year vehicle private NPV

Scenario	Conventional	Hybrid	PHEV	BEV
Worst Case	-$20,000	-$27,000	-$45,000	-$38,000
Base Case No REC	-$21,000	-$28,000	-$40,000	-$33,000
Base Case RFC/PJM	-$21,000	-$28,000	-$40,000	-$33,000
Base Case Transition	-$21,000	-$28,000	-$40,000	-$33,000
Best Case Transition	-$27,000	-$32,000	-$37,000	-$29,000

While conventional vehicles appear to be dominant when only looking at private cash flow, government entities and institutions also typically are interested in the social costs and benefits (the externalities) of a technology choice. In particular, the monetized values of emissions from electricity and gasoline combustion on air quality and greenhouse gas (GHG) emissions are of high importance. Emissions from gasoline and various assumptions about the local electricity grid are listed in Table 3. It is notable that sulfur dioxide emissions are not measurably emitted from conventional gasoline vehicles, but will be indirectly emitted by electric vehicles, due to the current grid containing some coal-fired generation. The electric vehicle analysis literature generally reports the average and/or marginal emissions characteristics of the grid, and we use both the grid average and the grid marginal emissions compositions. In the short term, additional electricity demand is supplied by power plants with excess capacity, and will be fulfilled by the cheapest units during the hour demanded. These marginal units change based upon load, time of day, season, and relative fuel prices. We use two data sources for grid emissions in Pittsburgh- the Regional Transmission Organization PJM, and the NERC region RFC. These two areas include the Pittsburgh region and overlap, but are commonly used because of data availability. In the RFC grid marginal emissions are higher than average emissions (*32*). RFC's marginal sulfur, nitrogen and GHG emissions are higher than PJM's average emissions. The same is true in terms of nighttime (7PM-7AM) marginal emissions vs. whole day averaged marginal emissions (*32*). Because of the high human health damages associated with SO_2 and NOx,, there are higher social costs per MWh for emissions tend than for CO_2 emissions.

The social costs of these air pollutants are summarized in Table 4. High and low estimates of costs for SO_2 and NOx, are from an EPA impact analysis on proposed standards for existing power plants (*33*), while base case assumptions came from a USDOT and EPA analysis (*34*). CO_2 costs are from an EPA report on the social costs of carbon (*35*). All values were converted to 2015$ using the Bureau of Labor Statistics CPI calculator (*36*).

We compare the emissions per mile driven of EVs versus conventional and hybrid vehicles using these ranges. Figure 2 though Figure 4 showcase the vehicle emissions under current grid conditions, including a separate case for when renewable emissions credits are accounted for. These credits are assumed to reduce 30% of each pollutant per kWh. We assume PHEVs for the Pittsburgh municipal fleet travels on electricity for 81.2% of travel and 18.9% gasoline, accounting for the 19 mile EV range and 23.4 mile average daily travel (*18*) (*21*) . Figure 5 through Figure 7 show the yearly emissions of a vehicle as the current grid linearly moves from 30% RECs credits to 100% RECs. Emissions for gasoline-powered vehicles do not change under different grid conditions.

Table 3: Emissions from various power sources

Source	SO_2 emissions	NOx emissions	CO_2 emissions
Gasoline (g/gal) (*37*)	0	16.7	8879
PJM Average (g/kWh) (*38*)	1.01	0.41	502
RFC Marginal (7PM-7AM) (g/kWh) (*32*)	3.38	0.95	735
RFC Marginal (8AM-5PM) (g/kWh) (*32*)	3.08	0.90	706

Table 4: External Cost of Emissions

Scenario	SO_2 emissions ($/g)	NOx emissions ($/g)	CO_2 emissions ($/kg)
Worst Case	0.042	0.005	0.012
Base Case	0.047	0.008	0.040
Best Case	0.115	0.029	0.242

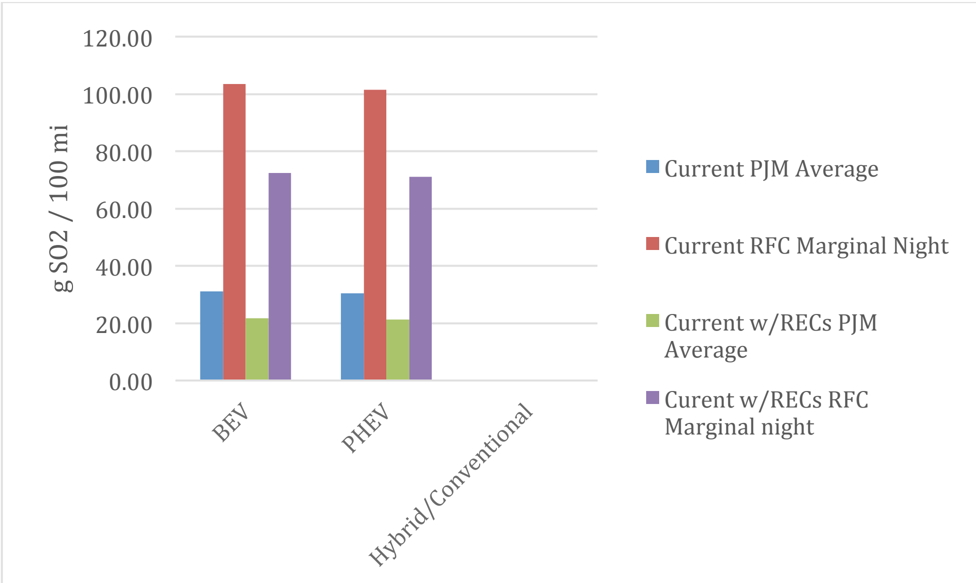

Figure 2: Sulfur Dioxide Emissions from Vehicles under Constant Grid Conditions

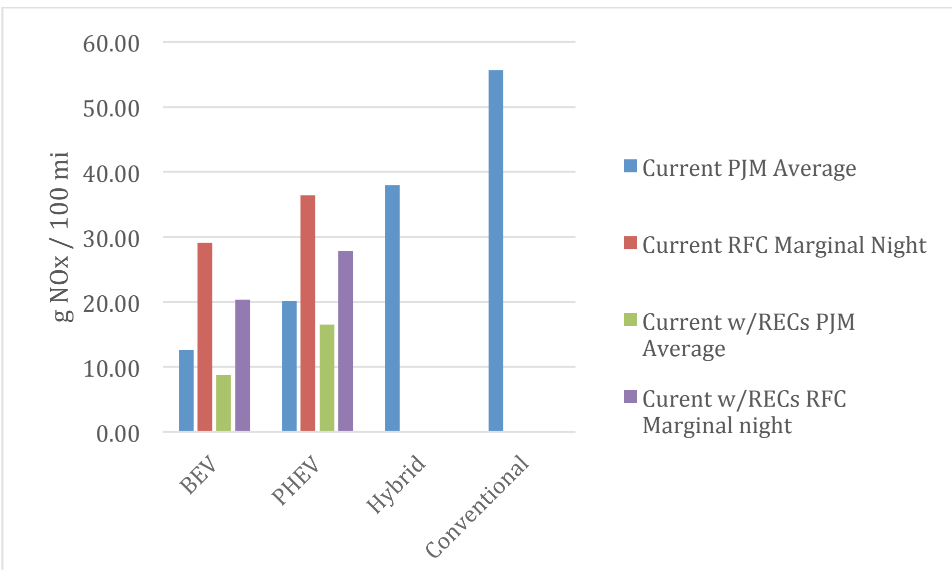

Figure 3: Nitrogen Oxide Emissions from Vehicles under Constant Grid Conditions

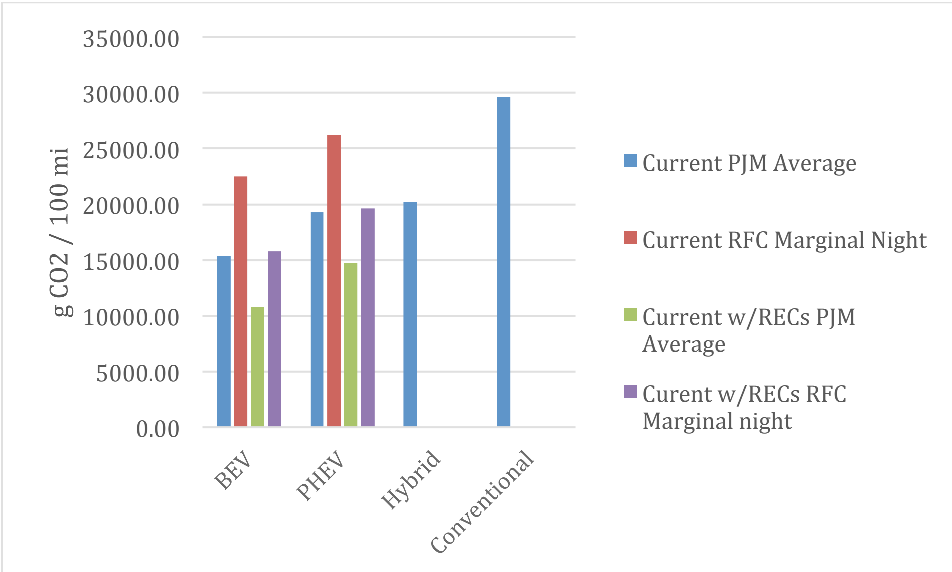

Figure 4: Carbon Dioxide Emissions from Vehicles Under Constant Grid Conditions

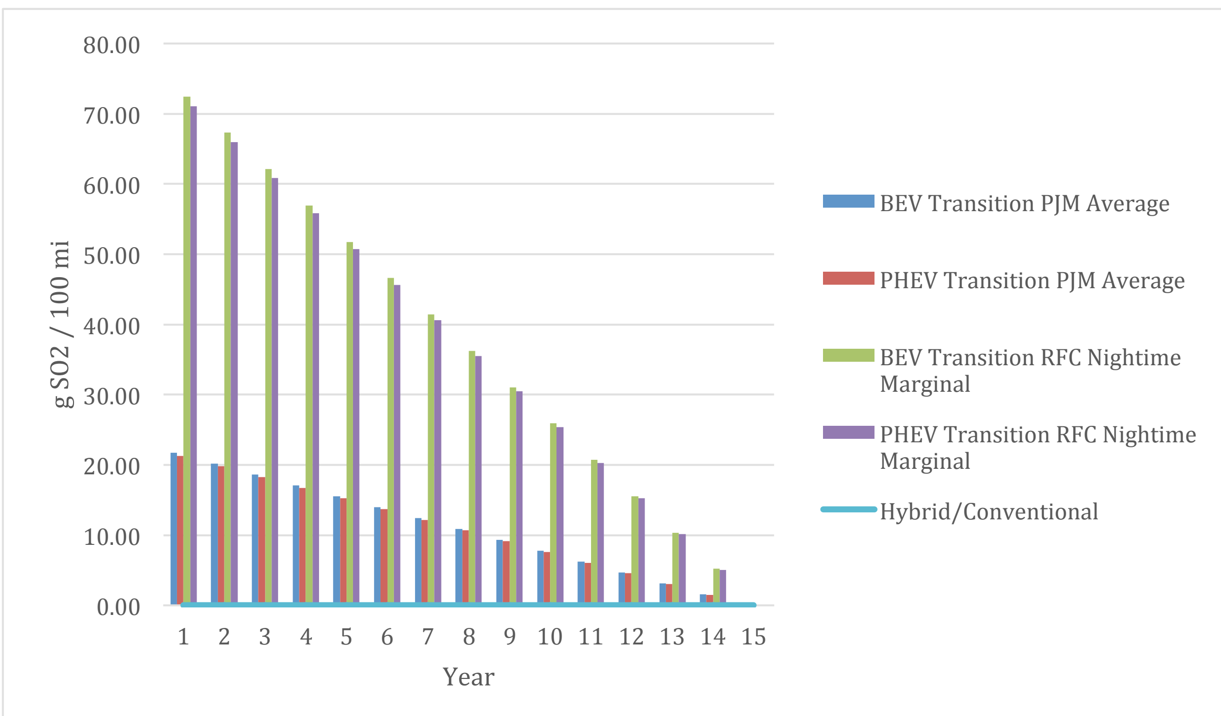

Figure 5: Sulfur Dioxide Emissions from Vehicles Under a Grid Transitioning to 100% RECs

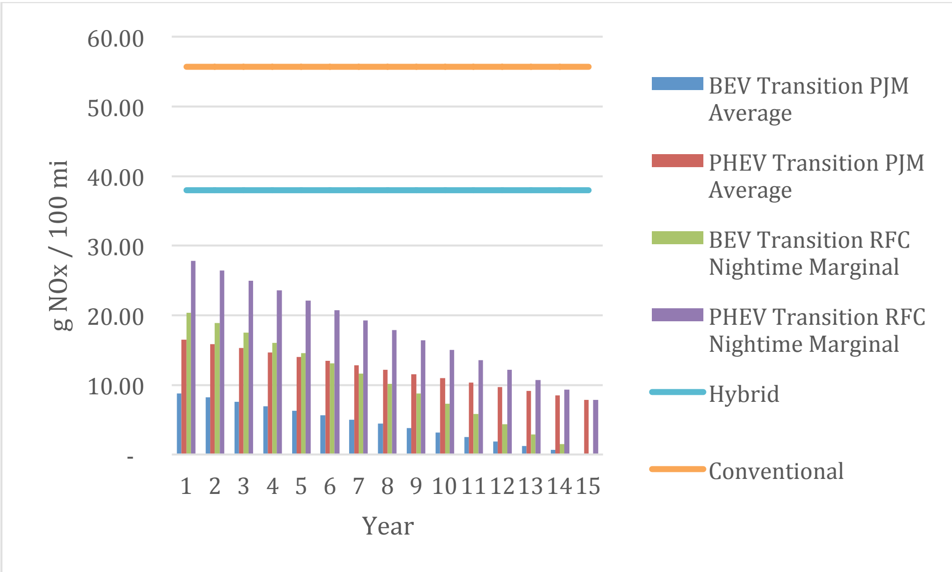

Figure 6: Nitrogen Oxide Emissions from Vehicles Under a Grid Transitioning to 100% RECs

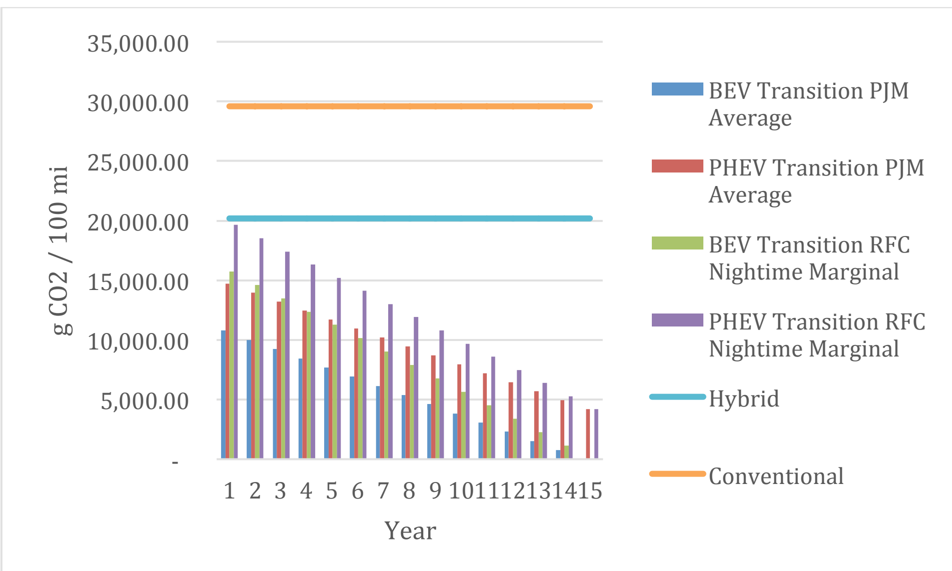

Figure 7 Carbon Dioxide Emissions from Vehicles Under a Grid Transitioning to 100% RECs

Sulfur dioxide pollution generally is the dominating factor in valuing the marginal social costs of vehicle electrification, due to the potential high human health damages associated with SO_2. However, the range of possible costs of SO_2 emissions is much less than carbon and nitrogen emissions. This leads to electrification increasing the costs of air pollution under our worst and base scenarios and decreasing the cost of pollution under the best case scenario. This information was used to calculate the social NPV of vehicle electrification. The cost difference between BEVs and conventional vehicles only approaches parity in the best case transitional scenario. Conventional vehicles remain the least socially cost intensive option all other scenarios. The social NPVs of electrification for 15-year lifetimes are listed in Table 5.

Table 5: 15 Social NPV

Scenario	Conventional	Hybrid	PHEV	BEV
Worst Case	-$20,000	-$27,000	-$46,000	-$39,000
Base Case no REC	-$23,000	-$29,000	-$44,000	-$37,000
Base Case PJM	-$23,000	-$29,000	-$41,000	-$34,000
Base Case RFC	-$23,000	-$29,000	-$43,000	-$36,000
Base Case Transitional	-$23,000	-$29,000	-$42,000	-$35,000
Best Case Transitional	-$33,000	-$36,000	-$43,000	-$34,000

2.2 The Importance of Sensitivity Analysis on Attributing Emissions Reductions to RECs

It is important to note the significance of the local sourcing of renewable power assumption and of ignoring the intermittency effects from renewables. Our price assumptions were based on the general market which includes wind power sourced in Texas. Texas has its own grid, with very limited trading with the eastern interconnect, and does not have the ability to export the amount of excess wind it currently generates in west Texas (*39*). Instead excess wind capacity has reduced power prices in Texas to close to or beyond zero at night, when demand is low (*39*). This means that additional purchases of Texas wind will not have a one-to-one reduction effect on electricity emissions in the Pittsburgh region. An additional consideration is that even renewables on the eastern interconnect, which includes Pittsburgh, may not have a one-to-one effect on reducing emissions in Pittsburgh, depending on locations, prices, and timing. While climate change is affected no matter where the location where GHG emissions are emitted, the location and utilization of coal and natural gas plants directly affects air pollutants and air quality in the region downwind of these plants. This means that fossil fuel plants near Pittsburgh could be partially or completely operationally unaffected by REC purchases in the near-term. Additionally, the intermittency of these sources may also result in additional emissions from natural gas-fired generation for balancing. However, due to low natural gas prices, EPA pollution control and GHG regulations and retiring of existing coal plants, , the local electricity grid will likely get cleaner over the study period. Besides increased amounts of natural gas and renewables, the eastern interconnect is likely to continue to reduce the amount of coal generation, as well as install modern pollution controls on any existing coal plants without these technologies.

Attributing pollution from electric demand is a complex task (*40*). This is important, not only because this project is primarily concerned with the costs borne by Pittsburgh, but also because the cost of pollution varies regionally. Therefore, these renewable purchases may not reduce pollution in Pittsburgh, unless the renewables replace supply from local sources, or sources in the regional grid whose pollution affects Pittsburgh.

Without clean electric sources BEVs can increase air pollution, compared to conventional vehicles. It is possible that the city's renewable energy purchases might allow electric vehicles to decrease air pollution in the city. However, if these purchases are not structured to ensure reduction in Pittsburgh then BEVs could increase local air pollution.

Under generalized assumptions and strict economic accounting, paying a premium for renewables to fuel BEVs that have an existing (but declining) cost premium, is less effective at reducing emissions than just paying for renewables in general. This renewables contract is, not for the entire grid, but instead for one consumer in it. The BEVs pollute and cost more when using normal grid power. One could reduce pollution even more by not electrifying the fleet and spending the saved costs and the cost budgeted for the BEVs electricity on renewable power for another use. This would lead to a higher social benefit that buying the renewables for the BEVs and the BEVs. However, we recognize that policies have multiple objectives, and that municipalities require mobility services in addition to a goal of pollution reduction, and hence a reallocation to the most efficient pollution reduction strategies should be examined wholly within a service category (mobility, electricity, heating, etc.).

2.3 Fleet Electrification Sensitivity

Table 6 lists the decreases in grid air and GHG pollution necessary for a BEV to run cleaner than a conventional or hybrid vehicle, for both grid scenarios. It does not include the city's current 30% RECs. Applying the current, or future, reduction can be done via simple subtraction. Leaving the numbers without current RECs allows easy comprehension of how much cleaner the grid needs to be made to see environmental improvement. This could be accomplished through either full grid improvements or RECs.

Table 7 lists the changes that a single variable, electric price, annual miles traveled, purchase price or gasoline price, would need to undergo to make a BEV the best option under the listed scenario. Electricity would need to be free for social profitability, in the best case scenario. In the other scenarios no non-negative electric price would allow for social. No non-negative electric price would allow for private profitability in any scenario. The changes necessary in annual VMT, purchase price and gasoline price are implausibly large, except in the best case scenario. VMT would need to increase well beyond a vehicles expected lifetime, BEVs would need to be cheaper than conventional vehicles and gasoline prices would need to increase beyond real levels ever seen in the United States (*41*).

Table 6: Fleet Electrification Sensitivity Summary: Per mile External Cost

Input and Output Tested	Best Case no REC, Value to break even	Base Case, No REC, Value to Break Even	Worst Case, no REC, Value to Break Even
Across the board % decrease in PJM Average Grid Pollution, Per Mile Value of Pollution BEV vs. Conventional	0%	≈25%	≈60%
Across the board % decrease in PJM Average Grid Pollution, Per Mile Value of Pollution BEV vs. Hybrid	≈25%	≈50%	≈75%
Across the board % decrease in RFC Nighttime Marginal Grid Pollution, Per Mile Value of Pollution BEV vs. Conventional	≈55%	≈75%	≈90%
Across the board % decrease in RFC Nighttime Marginal Grid Pollution, Per Mile Value of Pollution BEV vs. Hybrid	≈70%	≈85%	≈95%

Table 7: Fleet Electrification Sensitivity Summary: 15 Year Social NPV

Input and Output Tested	Best Case Transition, Value to break even	Base Case, current REC, RFC Marginal Nighttime, Value to Break Even	Worst Case, no REC, Value to Break Even
Electricity price / kWh, Social NPV	≈100% reduction to $0.00	<$0.00, no positive price	<$0.00, no positive price
Electricity price / kWh, Private NPV	<$0.00, no positive price	<$0.00, no positive price	<$0.00, no positive price
Annual Miles Traveled Increase, BEV vs. Conventional/Hybrid	≈10% increase to 6,700 mi/year	≈385% increase to 30,000 mi/year	>385% increase
BEV Purchase Price Reduction, BEV vs. Conventional/Hybrid	5% reduction to $26,600	≈45% reduction to $15,000 or $2,000 under Conventional	≈65% reduction to $10,000 or $7,000 under Conventional
Gas % Price Increase, BEV vs. Conventional/Hybrid	10% increase to $4.40/gal	≈280% increase to $7.60/gal	≈660% increase to $11.40/gal

3.1 Integrated renewable garage

We discussed the per-vehicle emissions differences of switching to electric vehicles in a municipal light duty fleet were discussed in section 2. One particular finding was that while electrification may decrease GHG and NOx, emissions it will definitely increase SO_2 emissions. This is because gasoline vehicles produce negligible SO_2 emissions, while unscrubbed coal-fired power plants for electric generation have significant SO_2 emissions. One way of reduce these emissions is to increase the portion of electricity that is generated from renewable or low-emissions sources. Photovoltaic (PV) generation is one possible renewable source to consider for distributed generation in an urban region. One potential location for PV cells would be on city-owned parking facilities. Canopies could be built over city-owned surface lots or on the tops of city-owned garages. This would reduce real estate costs could reduce the urban heat island effect over such facilities (*17*).

Currently the Pittsburgh Parking Authority owns and operates ten parking garages, with parking on the roofs, and 1 unshaded surface level lot downtown (*42*). The total surface area of these garages' roofs and the lot was estimated to be 52,000 square meters, using Google Earth satellite images. If 80% of this area were to be used for photovoltaic cells and using the 0.145 kW_p/m^2 power intensity for commercial buildings (*43*), this would lead to a peak power capacity of 6,000 kW. According to NREL's System Adviser tool solar irradiance in Pittsburgh is approximately 3.81 $\frac{kW\ hr}{m^2\ day}$ (*44*). This estimate is averaged from 1991 to 2010 and from the TMY3 data set for Pittsburgh International Airport (*44*). Using the 14.5% PV efficiency provided in NREL's PV cost summary (*43*) we estimate electricity production of about 8.4 million $\frac{kWh}{year}$, ignoring shade. NREL's PVWatts tool estimates a similar instillation in Pittsburgh would provide about 7.3 million $\frac{kWh}{year}$ (*45*). This amount of electricity could potentially power between 24 and 27 million miles of electric vehicle travel per year, which is more than 30 times the yearly travel of the city's civilian passenger vehicle fleet (*18*).

The economics of such a system is dependent upon a rapidly decreasing price of PV modules and systems. In 2010 prices pear W_p of other commercial rooftop prices averaged $4.59 and NREL estimates that they will drop to $1.99 by 2020 (*43*). These assumptions result in a system price between $34,500,000 and $15,000,000. This excludes the cost of the structures required for canopy. As these areas will still be used for parking, canopies with frames are required in order to continue to allow for parking access. Quotes from contractors specializing in these projects with similar scales were between $45 and $250 a square foot (*46*, *47*), including the structure and PV system itself. This suggests a project price of between $25,000,000 and $140,000,000. If the price of electricity is assumed to vary between $0.05 and $0.15/kWh, then revenues would vary between $460,000 and $1,700,000 each year. Additionally the average maintenance cost of commercial rooftop PV projects in the US is about 0.35% of the PV system cost each year, specifically for the tilt-axis sun tracing models (*48*). We assume that the saving in maintenance for a stationary system are equivalent to the increase in structural maintenance for the canopies.

Scenario discount rates used are identical as those used in the fleet electrification analysis and are listed in Appendix 1. A summary of the private NPV of such a system can be seen in Table 8, under different assumed scenarios. As can be seen from a purely private and monetarily focused analysis, such a system only has a positive private NPV under the best case conditions.

Table 8: Private NPV of the PV system

Private NPV	Just PV System	With Canopy
Worst Case	-$25,000,000	-$138,000,000
Base Case	-$14,000,000	-$77,000,000
Best Case	$2,000,000	-$11,000,000

Accounting for the social cost of pollution does not change this conclusion when using the PJM average grid mix. This does, however, considerably lessen the deficit. The same is true when using the RFC marginal Daytime grid, 8AM-5P, as seen in
Table 9 and Table 10.

Table 9: Social NPV of the PV System, PJM Average Grid Mix

Social NPV	Just PV System	With Canopy
Worst Case	-$21,000,000	-$133,000,000
Base Case	-$6,000,000	-$69,000,000
Best Case	$38,000,000	$25,000,000

Table 10: Social NPV of the PV System, RFC 8AM- 5PM Marginal Grid Mix

Social NPV	Just PV System	With Canopy
Worst Case	-$13,000,000	-$126,000,000
Base Case	$6,000,000	-$57,000,000
Best Case	$82,000,000	$69,000,000

4.1 Contribution to a Pittsburgh Municipal Energy Emergency Center

If the city of Pittsburgh wanted to create an emergency refueling and logistics center, it would require several sources of distributed energy to enhance resiliency. If PV were included on a municipal energy emergency center, the panels could be utilized everyday, not solely in emergencies. During daytime emergencies the PV panels could provide some electricity that would slightly reduce the amount of liquid fuels needed for on-site generators The daily variation of solar irradiance is of particular importance as an emergency situation will not utilize the systems annual output, but instead its current output during the time of the grid disruption. The sunniest day in Pittsburgh, from 1991 to 2010, had a solar irradiance of about 342 W/m^2. The least sunny had 29 W/m^2 (*44*), a difference of over 1000%. The hourly variation of both of these is shown in Figure 8 and Figure 9. This leads to a great variability in the amount of power that could be generated from PV at any of the PPA sites for emergency purposes, which is presented up in

Table 11.

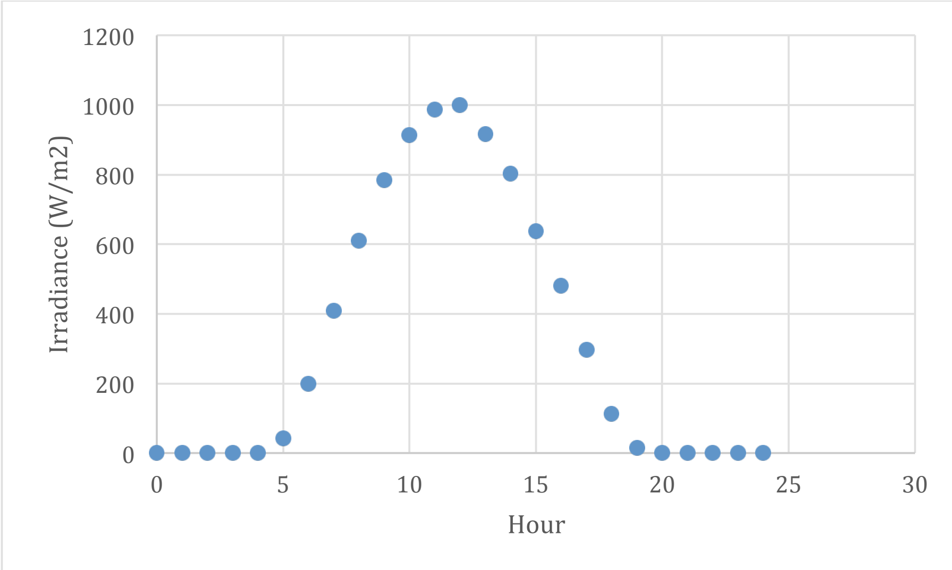

Figure 8: Hourly Solar Irradiance on the Peak Summer Day Experienced Between 1991-2010

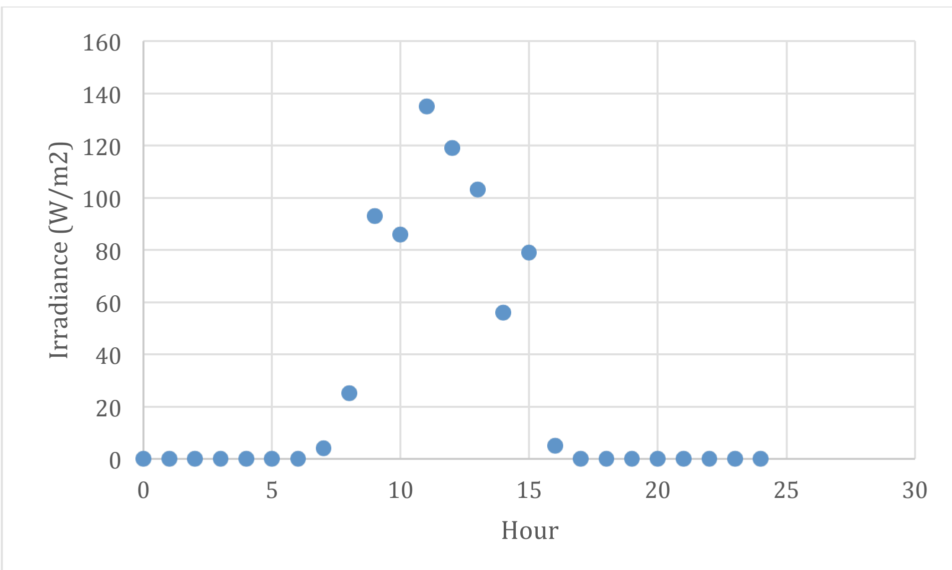

Figure 9: Hourly Solar Irradiance on the Least Sunny Winter Day Experienced Between 1991-2010

Table 11: Individual Solar Capacities and costs of each PPA Facility

Garage Name	Annual Power Generation (kWh/year)	Worst day generation (kWh)	Peak day generation (kWh)	Low Canopy Cost	High Canopy Cost
Grant Street Transportation Center Red	403,823	205	2,382	$ 969,371	$ 5,385,394
Grant Street Transportation Center Blue	501,227	254	2,956	$ 1,203,189	$ 6,684,382
Ft. Duquesne & Sixth Garage	760,962	386	4,488	$ 1,826,677	$ 10,148,205
Mellon Square Garage	N/A	N/A	N/A	N/A	N/A
Smithfield-Liberty Garage	393,718	199	2,322	$ 945,113	$ 5,250,630
Ninth and Penn Garage	625,525	317	3,689	$ 1,501,564	$ 8,342,023
Third Avenue Garage	636,987	323	3,757	$ 1,529,077	$ 8,494,870
Wood-Allies Garage	289,114	146	1,705	$ 694,013	$ 3,855,629
Oliver Garage	N/A	N/A	N/A	N/A	N/A
Monongahela Wharf	N/A	N/A	N/A	N/A	N/A
First Avenue Garage and Station	1,071,061	543	6,317	$ 2,571,065	$ 14,283,695
Second Avenue Parking Plaza	3,099,377	1,570	18,281	$ 7,440,008	$ 41,333,376
Forbes Semple Garage	391,296	198	2,308	$ 939,301	$ 5,218,339
Shadyside Garage	222,445	113	1,312	$ 533,976	$ 2,966,531

Using the 2nd Avenue location as an example we see that an emergency center could generate nearly 60,000 miles worth of electricity, on the peak day. For a BEV with a 23 kWh battery capacity, this would be nearly 800 full cycles (*49*). On the worst day of solar resource however, PV panels would only generate 1,500 miles or 66.5 BEV battery cycles worth of charge. Still, this provides some limited mobility for short-duration emergencies.

5.1 Conclusion

An economic analysis was conducted for both electrifying the City of Pittsburgh's civilian light-duty vehicle fleet and for installing PV systems over the Pittsburgh Parking Authority downtown facilities. Without accounting for the costs of air emissions or climate change, costs for EVs would have to fall or gasoline costs would have to substantially rise in order for the private net present value of the EV option to be higher than the conventional efficient gasoline engine. This is in part due to the capital costs of the vehicle and charger and the fact that Pittsburgh light-duty civilian municipal vehicles travel on average about 6,100 miles per year. This is fewer than miles driven by most light-duty vehicles used by the general population, which travel between 10,000-15,000 miles per year.

For GHG emissions, we found that EVs in Pittsburgh save GHGs compared to conventional gasoline vehicles in 3 of our 4 current electricity grid assumptions. As the GHG-intensity of the grid improves over the next 15 years, BEVs have clear GHG advantages over conventional gasoline vehicles in Pittsburgh. The City of Pittsburgh has indicated if will transition to purchasing RECs for 100% of governmental energy use by 2030. While there challenges with attributing local air pollutant reductions directly to RECs on a one-to-one basis, the combination of existing and proposed EPA power plant regulations and REC purchases highly increase the likelihood of a cleaner grid profile going forward. Yet SO_2 emissions from the power sector remain problematic in a social net present cost analysis. SO_2 was the highest cost pollutant for vehicle externalities and is not emitted in significant amount from gasoline combustion (*37*). Because of the SO_2 emissions, vehicle electrification was also found to be likely to have higher total social emissions costs than gasoline options under most cases. A faster reduction in power plant air emissions improves the outlook for electrification.

Additionally, we the feasibility of installing solar PV on downtown Pittsburgh Parking Authority garages and surface lots. We estimated a peak capacity of about 6,000 kW of PV is possible on these facilities. The amount of electricity potentially generated from these PV systems could power between 24 and 27 million miles of electric vehicle travel per year, which is more than 30 times the yearly travel of the city's civilian passenger vehicle fleet. The PV systems were found to have positive net present values, including the value of decreased pollution, only under best case assumptions. We also investigated how the daily variation in solar potential would affect any plans for using PV to help power an emergency response center, and found difference of over 1000% between the most and least sunny days of the year.

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Appendix 1: Fleet Scenario Parameters

Scenario	Worst Case	Base Case, no REC	Base Case PJM	Base Case RFC	Base Case Transitional	Best Case Transitional
RECs $%	0%	0%	30%	30%	30-100%, increases 5% each year	30-100%, increases 5% each year
Grid Energy Source	PJM Average	PJM Average	PJM Average	RFC Marginal (7PM-7AM)	RFC Marginal (7PM-7AM)	RFC Marginal (7PM-7AM)
Electric Price $/kWh	$0.10	$0.06	$0.06	$0.06	$0.06-$0.075, increasing $0.00075 each year	$0.04-$0.0505, increasing $0.00075 each year
Gasoline Price $/gal	$1.50	$2.00	$2.00	$2.00	$2.00	$4.00
EV Charger Price $	$8,000	$4,000	$4,000	$4,000	$4,000	$0
Social Cost of Carbon $/g	$0.0121	$0.0403	$0.0403	$0.0403	$0.0403	$0.2419
Social Cost of NOx $/g	$0.0054	$0.0081	$0.0081	$0.0081	$0.0081	$0.0292
Social Cost of SO_2 $/g	$0.0421	$0.0470	$0.0470	$0.0470	$0.0470	$0.1146