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Economic and environmental impacts of providing renewable energy for electric vehicle charging – A choice experiment study

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HIGHLIGHTS

- U.S.-wide online survey of Plugin Electric Vehicle owners and lessees is conducted.
- Economic benefit of charging electric vehicles using renewable energy is assessed.
- Choice experiment is used to elicit willingness-to-pay for renewable energy charging.
- Results.
- show significant environmental benefit from emissions reductions.

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ABSTRACT

This study evaluates the potential economic and environmental benefits available by providing renewable energy for electric vehicle charging at public electric vehicle service equipment (EVSE). Willingness to pay (WTP) for charging an electric vehicle using renewable energy was collected through a U.S.-wide online survey of Plugin Electric Vehicle owners and lessees using the choice experiment method. The results indicate a 433% increase in the usage of charging stations if renewable energy was offered. Results also show a mean WTP to upgrade to renewable energy of $0.61 per hour for Level 2 EVSE and $1.82 for Direct Current Fast Chargers (DCFC). Using Blink public EVSE network as a case study, these usage and WTP values translate directly to an annual gross income increase of 655% from $1.45 million to $9.5 million, with an annual renewable energy credit acquisition cost of $13,700. Simulation results also show significant environmental benefit from emissions reductions.

1. Introduction

Transportation in the developed world is powered predominantly by liquid fuels refined from petroleum. In the U.S. for example, 97% of transportation is powered by petroleum [1]. The high energy density and abundance of these fuels have made them a very effective and relatively affordable transportation energy source. However, motivations for finding alternate sources of transportation energy are numerous, including economic security, mitigation of anthropogenic climate change, and lessening military conflict in the oil-rich parts of the world. These motivations extend to reducing risk to human and environmental health posed by vehicle exhaust, hydrologic fracturing and oil transportation. There are a number of technologies currently at various stages of research and development with the ability to supplement or replace petroleum with a transportation energy source that is renewable, reduced in greenhouse gas (GHG) emissions, and economically feasible. The most currently developed of these technologies include biofuels, hydrogen fuel cells, and plugin electric vehicles (PEVs) powered with renewably generated electricity.

Each of these technologies has its benefits and drawbacks. Most biofuels offer a drop-in replacement liquid fuel requiring little or no modification of the current internal combustion engine technology and fueling infrastructure. However, the land, water, fertilizer, and energy requirements limit feasibility, energy gain, and GHG emission avoidance of biofuels for most feed stocks, for supplementing a majority portion of transportation energy [2]. Algae differs from most feed stocks in that it grows more densely and on inarable land. Meeting U.S. transportation energy needs with corn, canola or switchgrass would require more than 70% of U.S. arable land [2], with the U.S. having more arable land per capita than most developed nations. While algae is a feed stock with great

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potential, current knowledge and technology put algae biofuel production estimates at a low net energy gain of 6% [2] and a cost of \$10.87–\$13.32 per gallon [3], with these numbers falling towards the center of a wide range of such published values. Corn ethanol and soybean biodiesel currently supplement 5% of U.S. land transportation fuel [1]. However corn ethanol has a low net energy gain estimated at 22% and an estimated 27% GHG reduction [2].

While the prices remain high, a few automotive manufacturers have started leasing hydrogen fuel cell based vehicles in limited numbers. The hydrogen for these vehicles can be sourced from natural gas or electrolysis of water. Relative to gasoline, sourcing from natural gas results in a 21% life cycle GHG reduction, while water electrolysis with grid electricity increases GHG emissions by 25% [4]. Electrolyzing with electricity generated by renewables reduces GHG emissions by greater than 99% [4].

With present technology, all-electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) offer a relatively cost-effective means of transportation with significantly reduced GHG emissions [5,6]. EVs priced for the mass market such as the Nissan Leaf, Ford Focus EV and Smart ForTwo ED are currently limited to a driving range of about 60–85 miles per charge, with high end EVs such as the Tesla Model S traveling greater than 250 miles per charge. PHEVs such as the Chevy Volt and Ford C-Max Energi provide 20–40 miles of electric driving per charge in addition to a gasoline-powered driving range, which is most often similar to that of conventional internal combustion engine vehicles (CVs). For the majority of U.S. drivers, PHEVs offer enough electric driving range for daily commutes, while offering extended range when needed. EVs and PHEVs are collectively referred to as plugin electric vehicles (PEVs). Charge times for PEVs are typically 3–6 h when using 240 V AC Level 2 electric vehicle supply equipment (EVSE). Most EVs can also charge to about 80% capacity in 30 min on Direct Current Fast Chargers (DCFCs). Powered by the average U.S. grid electricity mix, PEVs electric energy life cycle GHG emissions are approximately two thirds that of gasoline powered transportation [4], while the energy costs are below that of gasoline. Powered by renewable energy sources, such as wind or solar energy, the energy life cycle GHG emissions of PEVs amount to less than 1% that of gasoline and with an energy cost still well below that of gasoline [4]. Consumer preference is important in the EV market and in promoting the adoption of EVs [7]. EV charging infrastructure is essential in encouraging the adoption of EVs and enhancing the environmental benefit of EVs [8].

There are many studies on the environment impact of EVs [9–12]. There is also an increasing amount of engineering and science studies that analyze the integration of renewable energy and PEVs from the perspectives of engineering design, environmental impact, and energy planning [13–15]. A few papers use engineering methods to analyze charging from on-site solar in terms of optimal system design [16,17]. However, there are no papers that empirically quantify the economic demand for renewable electric vehicle charging, which is needed for charging companies to evaluate such charging options and thus potentially increase the use of renewable energy.

This study fills the gap in the literature by estimating the willingness to pay (WTP) for and evaluating the potential economic and environmental benefits of a new PEV charging strategy for companies offering public PEV charging. Such companies include utility companies, charging companies, and PEV manufacturers. The new charging strategy evaluated in this study is to provide renewable energy to electric vehicle drivers at public stations, also known as electric vehicle supply equipment (EVSE). A comprehensive search reveals a small number of solar connected public EVSE with no major U.S. public EVSE companies offering widespread renewably powered vehicle charging. Through an online survey and a choice experiment of U.S.-wide PEV owners and lessees the following information was collected:

1. WTP for upgrading their pay-per-use charge event at a public EVSE to renewable energy from wind or solar sources.
2. Would the availability of renewable energy at such EVSE change their EVSE usage frequency?
3. How likely would they choose an EVSE offering renewable energy over one that does not?

Heterogeneity of the elicited WTP is also examined for trends in the data. A case study quantifying the economic and environment benefits available to one of the largest U.S. public PEV charging companies is included.

2. Background and literature review

2.1. PEV drivers and renewable energy

The California Center for Sustainable Energy conducted a survey of Californian PEV drivers. Among other useful data and using the direct ask surveying method, this study provides the stated mean WTP of Californian PEV drivers for public charging powered by standard grid electricity, see Table 1 [18].

Current prices charged at public EVSE provide another source of pricing information. The most common prices from the largest U.S. public charging companies such as Blink and U.S. average residential utilities are shown in Table 2 [19,20,1]. Within this table, where necessary to convert energy-based pricing to time-based pricing, a 6 kW mean charge rate is used for AC Level 2 EVSE and a 28 kW mean charge rate is used for DCFCs, each of which is typical of today's PEVs using the specified charging technology.

At the pre-9/2014 prices, Blink found their nationally distributed customers did 9% of their charge events at public AC Level 2 EVSE and 5% at public DCFCs. The remaining 86% of the charge events occurred at their personally owned EVSE or outlets, paying utility electricity rates. This usage amounts to 77,640 public charge events on 2762 public EVSE in the second quarter of 2013 [21].

One contingency choice experiment based study [22,23] focused on refrigerators examined WTP for the U.S. EPA Energy Star Label, which represents both private (energy cost savings) and public (environmental) benefits. They found a significant positive WTP well in excess of even undiscounted energy cost savings over the life of the appliance. There was a higher WTP among those with environmental concerns and among those who believed consumers can influence market offerings. Combined, these findings indicate a WTP for environmental benefit. Another contingency choice survey [22,23] examined WTP for refrigerators produced by manufacturers that use renewable energy in comparison to those that use conventional energy sources. The findings show a WTP an extra \$53.18 to \$68.66 for the appliance to be produced by manufacturers powered by renewable energy.

The few studies that have been conducted on PEV drivers and renewable energy have found a higher-than-average interest. A survey of about 1400 PEV owners in California [18] found that 39% of the participants had a photovoltaic (PV) solar system on their home, with another 17% planning on installing PVs in the next year, showing demand for renewable energy. Of those with PVs, about 50% have sized their system to meet the energy demand of their vehicles. Sixty percent of those who have not done so already, plan to expand their PVs in the next year to account for their PEV energy needs, showing demand for charging PEVs with renewable energy.

A more recent U.S.-wide survey [24] of about 1500 individuals consisted of three populations of recent vehicle buyers: CV buyers

Table 1
Stated Californian PEV Driver Public Charging WTP, Standard Grid Electricity [18].

Charging frequency (count per week)	Mean AC Level 2 EVSE WTP ($/h)	Mean DCFC WTP ($/30 min)
3 or more	$0.80	$3.70
1 or 2	$1.17	$5.20
Less than 1	$2.36	$9.28

Table 2
Public Charging Pricing by Public EVSE Providers in 2014 dollars, Standard Grid Electricity.

Charging source	AC Level 2 Price ($/h)	DCFC price ($/30 min charge)
Blink before 9/2014	$1.00	$5.00
Blink starting 9/2014	$2.40	$6.99
ChargePoint	$2.94[a]	$6.86[b]
Sema Charge	$2.94[a]	$6.86[b]
U.S. Residential Utility Average	$0.78[a]	$3.65[b]

[a] Based on 6 kW charge rate.
[b] Based on 28 kW charge rate.

(CVBs), hybrid electric vehicle buyers (HEVBs) and PEV buyers (PEVBs). With typical pricing for each attribute, surveyees were asked to design the next vehicle they would purchase, then to design a home energy source and finally after being introduced to the possibility of powering a PEV with renewable energy, they were given an opportunity to redesign both the vehicle and energy source. Krupa et al. found increased use of renewable energy with electrification of the participants' purchased vehicle, with 18% of CVBs, 44% of HEVs, and 41% of PEVBs currently powering their home with renewable energy. After the introduction to renewable PEV charging, Krupa et al. found the following percentages of participants chose an energy source and vehicle combination allowing for renewable vehicle charging: CVBs-31%, HEVBs-53%, and PEVBs-86%. Krupa et al. also found a 22% increase in PEV demand with the introduction to renewable PEV charging. This study shows a strong interest in charging with renewable energy, particularly among PEV owners.

A comprehensive literature review revealed no public studies on the willingness of PEV drivers to pay for renewable energy and the resultant economic and environmental benefits of providing renewable energy for PEV charging at public pay-per-use EVSE, which is the major contribution of our study.

2.2. Sources of renewable energy for EVSE

The most plausible means of acquiring renewably generated electricity for use at public EVSE include on-site solar, utility green pricing programs, and renewable energy credits (RECs). While on-site solar is good for marketing, a degree of engineering and installation is required at each site. Upfront cost, loans or long-term solar lease contracts would also be required. This option also does not offer a means to choose how much renewable energy is produced each month. The amount of solar electricity generated could either exceed or fall short of meeting the renewable charging demand.

Local utility green pricing programs (GPP) avoids the installation costs and long term commitment. However, using GPPs for a nationally distributed EVSE network would require signing up for these programs and purchasing from tens to hundreds of different utility companies, while only about half the electric utility customers in the U.S. have access to a GPP [25], making this option unavailable in some locations.

Renewable energy credits are used to track the trade of renewable energy in the U.S., including energy sold in GPPs. Purchasing RECs directly from REC brokers, wind farms, or solar fields, would allow a public EVSE company to use its nationwide renewable energy demand to negotiate a lower price and to make a periodic purchase from a single supplier in a quantity matching usage, without making any changes with their utility companies [25]. Of the renewable energy sold in the U.S., 63% is purchased as RECs separate from the purchase of electricity [25]. The majority of these REC sales are to corporations with an interest in reducing their environmental impact and improving their corporate image, including Whole Foods, Intel, Walmart and others. Representing the renewable qualities of renewable energy, RECs are a third party certified, paper commodity used to track the purchase of renewable energy from the generator to the customer. RECs are necessary since the electric grid cannot physically direct electricity from a specific generator to a specific customer. RECs are also available at a low cost, typically about $0.001 per kW h for nationally sourced wind energy [25]. For these reasons, RECs are used in the case study of profitability in this study.

3. Methodology

3.1. Surveys

Data was gathered by surveying current owners and leases of PEVs within the U.S. The names and postal addresses of PEV owners and leases were purchased from a mail marketing company[1] that obtains their records from the Department of Motor Vehicles in states where this information is available. The company also purchases information from automotive insurance companies and automotive repair shops, amongst other commercial sources.

Postcards requesting participation in an online survey about electric vehicles and renewable energy were sent to 1500 individuals. Of these postcards, 28 were returned as undeliverable. Two hundred and three respondents completed at least the first 20 questions regarding WTP, representing a 13.5% response rate, while 181 respondents answered every question.

The survey was developed and administered with the online survey tools provided by Qualtrics. The 55 question survey collected information on PEV usage, public EVSE usage, motivations, demand and WTP for renewably powered public PEV charging and demographics. Within the surveys, information was gathered for two formats of offering renewable energy. Both every charge being sourced renewably and offering renewable energy as an optional upgrade were examined. The survey examined direct ask WTP, usage and competitive choice likelihood for two methods of offering renewably generated electricity. Renewable energy was described as coming from wind and solar sources. These questions as presented in the survey are shown in Table 3.

3.2. Choice experiment

WTP was assessed through both directly asking and with a choice experiment model. Directly asking for WTP has been shown to generate biased results, such as overstating prices due to prestige effects or understating because of customer collaboration [26]. We used the choice experiment method for a more accurate assessment of the WTP for renewable energy charging. The method more closely simulates a purchase decision by asking the surveyee which of two product options they would choose to buy [27]. With this method, each option has a specified price, and purchasing neither is the third option. The WTP for the individual attributes of the

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[1] Data Masters, www.datamasters.com.

Table 3
Survey questions on competitive choice likelihood, usage and direct ask WTP.

Every charge renewable	Renewable energy option
If 100% renewable energy such as wind or solar was provided by commercial charger with every charge:	If the commercial charger provided as an option 100% renewable energy such as wind or solar:
How much more likely would you choose this charger over one that does not provide renewable energy? 0% meaning it would not influence your decision.100% meaning you would use the renewably powered charger every time	How much more likely would you choose this charger over one that does not provide renewable energy? 0% meaning it would not influence your decision.100% meaning you would use the renewably powered charger every time
How many times per month would you charge on a commercial charger, if they provided renewable energy with every charge?	How many times per month would you charge on this charger that offers the option of renewable energy?
–	How many times per month would you choose to use the option to charge with renewable energy on this charger?
How much extra would you be willing to pay to use a renewably powered 30 min DC Fast charger, per charge? • $0.00 per charge • $0.05 per charge • $0.10 per charge • $0.15 per charge • $0.20 per charge • $0.30 per charge • $0.40 per charge • $0.60 per charge • $0.80 per charge • More than $0.80 per charge	How much extra would you be willing to pay to use the option to charge with renewable energy on a 30 min DC Fast charger, per charge? • $0.00 per charge • $0.05 per charge • $0.10 per charge • $0.15 per charge • $0.20 per charge • $0.30 per charge • $0.40 per charge • $0.60 per charge • $0.80 per charge • More than $0.80 per charge
How much extra would you be willing to pay to use a renewably powered Level 2 charger, per hour? • $0.00 per hour • $0.02 per hour • $0.05 per hour • $0.10 per hour • $0.15per hour • $0.20per hour • $0.25 per hour • $0.30 per hour • More than $0.30 per hour	How much extra would you be willing to pay to use the option to charge with renewable energy on a Level 2 charger, per hour? • $0.00 per hour • $0.02 per hour • $0.05 per hour • $0.10 per hour • $0.15 per hour • $0.20 per hour • $0.25 per hour • $0.30 per hour • More than $0.30 per hour

Table 4
Survey choice experiment WTP instructions and questions. Choice sets were listed in random order.

Level 2 charger	DC fast charger
For each combination in the following, there are two options of charging your electric vehicle at a Level 2 commercial charging station. The two options differ in: (1) Percentage of electricity coming from renewable sources such as wind or solar at this charging station. (2) Price of charging per hour. There are 10 combinations in total. For each combination, please choose your preferred alternative of charging or choose “Neither of these”	For each combination in the following, there are two options of charging your electric vehicle at a 30 min DC Fast commercial charging station. The two options differ in: (1) Percentage of electricity coming from renewable sources such as wind or solar at this charging station. (2) Price of charging per hour. There are 10 combinations in total. For each combination, please choose your preferred alternative of charging or choose “Neither of these“
• 50% Renewable energy $1 per hour • 50% Renewable energy $1.06 per hour • Neither of these	• 50% Renewable energy $5 per hour • 50% Renewable energy $5.15 per hour • Neither of these
• 75% Renewable energy $1.06 per hour • 0% Renewable energy $1 per hour • Neither of these	• 75% Renewable energy $5.15 per hour • 0% Renewable energy $5 per hour • Neither of these
• 50% Renewable energy $1.18 per hour • 50% Renewable energy $1.24 per hour • Neither of these	• 50% Renewable energy $5.45 per hour • 50% Renewable energy $5.60 per hour • Neither of these
• 100% Renewable energy $1.24 per hour • 25% Renewable energy $1.12 per hour • Neither of these	• 100% Renewable energy $5.60 per hour • 25% Renewable energy $5.30 per hour • Neither of these
• 100% Renewable energy $1.18 per hour • 25% Renewable energy $1.06 per hour • Neither of these	• 100% Renewable energy $5.45 per hour • 25% Renewable energy $5.15 per hour • Neither of these
• 25% Renewable energy $1.06 per hour • 75% Renewable energy $1.18 per hour • Neither of these	• 25% Renewable energy $5.15 per hour • 75% Renewable energy $5.45 per hour • Neither of these
• 0% Renewable energy $1.12 per hour • 100% Renewable energy $1.18 per hour • Neither of these	• 0% Renewable energy $5.30 per hour • 100% Renewable energy $5.45 per hour • Neither of these
• 25% Renewable energy $1 per hour • 75% Renewable energy $1 per hour • Neither of these	• 25% Renewable energy $5 per hour • 75% Renewable energy $5 per hour • Neither of these
• 0% Renewable energy $1.12 per hour • 100% Renewable energy $1.24 per hour • Neither of these	• 0% Renewable energy $5.30 per hour • 100% Renewable energy $5.60 per hour • Neither of these
• 75% Renewable Energy $1.24 per hour • 0% Renewable Energy $1.12 per hour • Neither of these	• 75% Renewable Energy $5.60 per hour • 0% Renewable Energy $5.30 per hour • Neither of these

product are assessed by varying the attributes of interest and pricing presented, while holding any other attributes constant.

For our survey, the attribute being assessed is the addition of renewable energy to public pay-per-use PEV charging. The surveyees were presented with various fractions of their charge being powered by renewably generated electricity from sources such as wind turbines and solar systems. The fraction of renewable energy was varied from 0% to 100%, with prices for the charge varying from $1 per hour to $1.24 per hour for AC Level 2 charging and $5.00 to $5.60 per 30 min charge for DC fast charging (see Table 4). These prices were chosen based on the Blink network prior to September 2014 prices, REC prices, and the results of a pilot-scale survey of 19 individuals at public EVSE in the Phoenix, Arizona metropolitan area. In the full-scale survey, 10 such choice experiment model questions were asked for AC Level 2 charging and 10 for DC fast charging. The choice design is based on efficient rppanel design, created using Ngene software. We use the Db-efficient design algorithm to generate the options in the choice experiments. This algorithm was chosen because it is more efficient for mixed logit models using panel data which seeks to minimize the determinant of the variance-covariance matrix of the parameter estimators.

In order to aid in the analysis of the choice experiment results, there are three choice sets in each of the experiments that can measure whether the survey respondent made irrational choices or not. In Table 4, for Level 2 Charger, the three choice sets measuring irrationalness are (1) 50% renewable energy at $1 per hour versus 50% renewable energy at $1.06 per hour, (2) 50% renewable energy at $1.18 per hour versus 50% renewable energy at $1.24 per hour, and (3) 25% renewable energy at $1 per hour versus 75% renewable energy at $1 per hour. In these three choice sets, if the survey respondent chooses an option of paying a higher price for the same amount of renewable energy or an option for less renewable energy for the same price, then the respondent made irrational choices, resulting is a coding of the dummy variable "Made irrational choice" to a value of one for that respondent. For DC Fast Charger, there are three similar choice sets that similarly measure irrationalness.

3.3. Economic model

The commonly used discrete choice modeling framework was applied in this study, assuming that the respondents base their purchasing decisions on maximizing utility. The Random Utility Model [28] describes the utility U provided by a product option j has to an individual i as the sum of the observable component V and the unobservable part ε:

$$U_{ij} = V_{ij} + \varepsilon_{ij}$$

To estimate the choice experiment model WTP we used a utility function including only the attributes presented in choice experiment questions:

$$V_{ij} = \beta_{i,REF} REF_{ij} + \beta_{Price} CEPrice_{ij}$$

$$\beta_{i,REF} = \beta_{REF} + \mu_{i,REF}$$

REF_{ij} is the product attribute of renewable energy fraction. β_{REF} is a population mean coefficient for REF and $\mu_{i,REF}$ represents the stochastic deviation of the individual's preference from the population mean. $CEPrice_{ij}$ is the product alternative price. β_{Price} is the coefficient for $CEPrice_{ij}$. $\beta_{i,REF}$, the coefficient for renewable fraction, is random in order to investigate the heterogeneity of individual preferences for renewable energy. This random coefficient is assumed to be normally distributed, as the parameter showed some central tenancies in our pilot scale study. A normal distribution is also the most widely used in mixed logit models. Several other model specifications of the observable utility were applied to explore the possible correlations with characteristics of the respondents, by including or excluding variables for demographics and current charging habits.

We analyzed the choice experiment results using the mixed logit model, which allows the random components of the choice alternatives to be correlated and takes into account the repetitive nature of choice experiment responses [29]. This method has been found effective for such discrete experiment data [30].

WTP for a renewable energy premium on a one unit change in renewable energy faction be can calculated from the marginal rates of substitution between the REF and the price. With the linear utility function we have applied, the marginal rate of substitution between these attributes is the ratio of their coefficients. The WTP for a renewable energy premium is:

$$WTP = -\frac{\frac{\partial V}{\partial REF}}{\frac{\partial V}{\partial CRPrice}} = -\frac{\beta_{REF}}{\beta_{Price}}$$

The standard deviation of the estimated WTP can be estimated from the standard deviation of the stochastic coefficient $\beta_{i,REF}$.

4. Descriptive survey results

There are 181 surveyees that completed every question of our survey and choice experiment. The surveyed demographics of the study sample indicate PEV drivers are predominantly male (77%), while 15% are aged 30–39 years, 21% aged 40–49, 35% aged 50–59 and 21% aged 60–69. The vast majority have college degrees, with 33% having a bachelor's, 41% having a master's and 16% having a doctorate. Those surveyed also are middle to high income, where 12% have a household income of $50–70k, 20%: $70–$100k, 26%: $100–$150k and 40%: more than $150k. These demographics combined with residential PV usage match fairly well with other surveys of PEV owners as provided by the California Center for Sustainable Energy [18] and Ecotality North America [21] as shown in Table 5, giving some assurance of a representative sample. The California study and the survey findings of this study clearly reveal a high interest in renewable energy amongst PEV owners, relative to the general population [31,32].

Sixty-two percent of the respondents stated that they own or lease an EV, while the other 38% have a PHEV. Of the households surveyed, 48% own two vehicles, 24% own three, 9% own 4 and 6% own five or more. For 12% of households, their PEV is their only vehicle. Four percent of households own or lease an EV as their only vehicle. The dominant motivations for purchasing a PEV include environmental reasons, fuel cost savings, energy independence and new technology interest, as shown in Table 6. Looking at these top four motivations, 60% gave environmental reasons as their primary or secondary reason. This value is 52% for fuel cost savings, 38% for energy independence and 26% for new technology.

The PEV usage shows a broad range of mean daily vehicle distance traveled, largely staying conservatively within the per-charge battery range limits of today's mass market PEV's, with 7% traveling less than 10 miles per day, 19%: 10–20 miles, 24%: 20–30 miles, 21%: 30–40 miles, 18%: 40–60 miles and 7%: 60–80 miles. Interestingly, 76% of participants average zero charge events per month at commercial pay-per-use EVSE, with 23% using commercial EVSE 1–10 times per month. Approximately half the commercial EVSE usage comes from the top 2% of the most frequent users. The far majority of the commercial EVSE usage is at AC Level 2 EVSE, with only 4% of participants using DCFCs and no participants averaging more than one DC fast charge per month. Low public EVSE usage rates have also been seen by The EV Project [21]. Commercial EVSE usage is expected to increase as EVSE and PEVs become more prevalent.

As stated, the survey examined direct ask WTP, usage and competitive choice likelihood for two methods of offering renewably generated electricity. These methods include every charge being powered renewably and providing an option for renewable energy. Since the survey started with the choice experiment questions, these questions came after 20 questions on pricing. The survey queried the likelihood that the participant would choose an EVSE offering renewable energy over one that does not, with 0% representing indifference and 100% indicating choosing the renewable offering EVSE every time. These two cases gave similar values with a mean likelihood of 79% with every charge being renewable and 81% for optionally renewable, while 100% likelihood was the most chosen, showing that offering renewable energy provides a significant advantage in competitive markets. The results were bimodal distributions, likely due to differing levels of price sensitivity and differing interest in renewable energy. For the every charge renewable case, 12% chose a likelihood of 0–19%, 1% chose 20–39%, 2% chose 40%–59%, 9% chose 60%–79%, 12% chose 80–99% and 64% chose 100%.

Comparing the respondents current commercial EVSE usage to stated usage if renewable energy was offered, there is a 419%

Table 5
Demographics and residential PV comparison.

Study	ECOtality EV project survey	California PEV owner survey	This study all	This study rational	This study irrational
Study population	U.S. PEV owners	CA PEV owners	U.S. PEV owners	U.S. PEV owners	U.S. PEV owners
Respondent count	6156	2039	203	169	34
Male	63%	71%	77%	75%	91%
Mean annual household income	$149k	$140k	$117k	$116k	$121k
Mean education (yrs)	16.9	17.3	17.2	17.1	17.4
Mean age (yrs)	50.9	–	52	52.8	49.4
Have residential PV	–	39%	23%	–	–
General population have residential PV	–	CA: 0.77%	U.S.: 0.15%	–	–

Table 6
Reason for purchase of current PEV.

Reason	Participant fraction	
	Primary motivation (%)	Secondary motivation (%)
Environmental	37	22
Fuel cost	22	30
Energy independence	17	22
New technology	15	11
Other	3	2
Fun to drive	2	10
HOV lane access	2	1
Vehicle cost	1	1
Influence of friend or family	0	0

increase in monthly charging events for the every charge renewable case based on summing usage across all respondents. This value represents a mean increase from 1.1 to 4.8 charge events per month per respondent. The optionally renewable case gave very similar results with a 448% total increase and a mean of 5.0 charge events per month. The average of these two usage increase values was used in the case study, equaling a 433% increase or 4.9 commercial charges per month. These usage values are compared as histograms in Fig. 1. As a whole, respondents indicated that for 99.5% of the charge events they would choose to use the renewable energy option. Before calculated the above summarizing usage statistics, the authors found it necessary to perform some data cleaning with the stated usage survey responses. There were nine of the 181 responses that had indicated a usage rate when renewable energy was offered that exceeded 30 charges per month. In all these cases, the stated usage value was equal to the value given by the respondent to the previous question. This preceding question asked for a percent likelihood, while the usage question asked for a number of charges per month. We chose to eliminate these nine responses from the usage data and performed all calculations without them.

Given the role of these usage values in our case study in calculating financial income and environmental emissions, we will put these values into context. On average, PEV drivers travel 745 miles and charge 39 times per month, while averaging 27 miles between charges [21]. Our respondents and other studies have shown the far majority of charging happens at their residence [21]. The stated increase of 433% in commercial charger usage represents a driver charging away from home on a commercial, pay-per-use charger 4.9 times per month rather than 1.1 times per month. This rise in commercial charging could displace home charging and/or add up to an estimated 100 miles of driving per month, which is still will within typical U.S. vehicle usage. Financially, if we look at the more frequently used Level 2 chargers as an example, the average charge lasts 4.5 h, costing $4.5 [33]. Forgoing a price increase for renewable energy for the moment, adding 3.8 chargers per month would raise the average driver's monthly commercial charging expense from $4.95 to $22.50, which is well within reason for the mid to high income individuals that own PEVs. The time they spend commercially charging which would likely occur as the driver is working, shopping or dinning would likewise rise from 5.0 to 22.5 h per month or 5.25 h per week, also quite feasible. In terms of interest in renewable energy, PEV drivers are 50–150 times more likely to power their home with renewable energy than the general public [18]. Of course, these usage increase values were obtained by directly asking in a survey, and it is possible to get some bias with this method. Performing regional or small scale trials with PEV drivers actually making purchases could confirm or improve these estimates and is a logical next step in evaluating the potential of renewably powered PEV charging presented in this study.

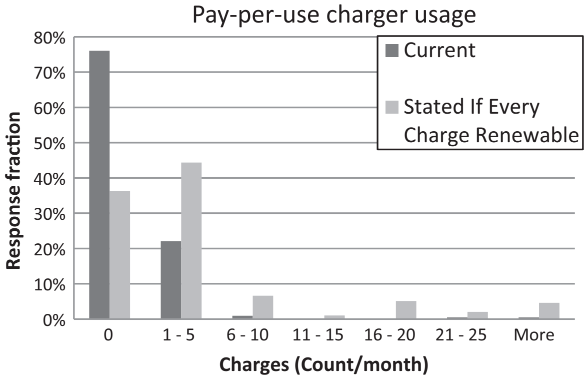

Fig. 1. Influence of renewable energy offering on charger usage.

At 66%, the majority of participants prefer that the EVSE offer renewable energy with every charge, while 19% prefer renewable energy be provided as an option, 14% like these options equally and 0.5% prefer the chargers not offer renewable energy.

5. Modelling results and discussion

5.1. Choice experiment findings on WTP

Several model specifications were fitted in the choice experiment WTP survey results using mixed logit model, each with the inclusion or exclusion of different independent variables. Tables 7 and 8 show the results and form of these models. Models 1–5 are different model specifications for the mixed logit models. In Model 1, the basic economic model is $V_{ij} = \beta_{i,REF}REF_{ij} + \beta_{Price}CEPrice_{ij}$ as discussed in Section 3.3. In models 2–5, more variables as indicated by variables in the left column of the table are added into this basic economic model in order to explain the random utilities of the survey respondent when choosing different charging options. Estimated mean and standard deviation values are given only for the variables included in each of these models. These variables are added in order to test whether these variables have impact on the choice of charging options and thus the estimates of WTPs.

WTP was assessed for AC Level 2 and DCFCs using the choice experiment and direct ask methods. We will focus our discussion on the choice experiment results, which are less prone to bias and expected to be a closer approximation to actual WTP. The direct ask results are available in Appendix A. The choice experiment WTP values are estimated with several models with the

Table 7
AC Level 2 EVSE choice experiment analysis results.

Mean and standard errors of coefficients	Model 1	Model 2	Model 3	Model 4	Model 5
Price ($)	−32.358***	−32.273***	−33.056***	−31.865***	−32.704***
	(2.196)	(2.299)	(2.320)	(2.204)	(2.340)
Renewable fraction (unit is one, not%)	19.638***	19.975***	15.786***	19.558***	18.890***
	(1.992)	(2.370)	(5.248)	(2.207)	(2.461)
Renewable fraction ∗ Currently use commercial chargers[a] (dummy)		5.36***	3.305*		
		(1.404)	(1.884)		
Renewable fraction ∗ Currently use Level 2 commercial chargers[b] (dummy)				5.090***	5.023***
				(1.273)	(1.150)
Renewable fraction ∗ Income			0.07***		
			(0.015)		
Renewable fraction ∗ Education			−0.416		
			(0.340)		
Renewable fraction ∗ Female			6.803***		
			(1.871)		
Renewable fraction ∗ Age			0.01		
			(0.056)		
Renewable fraction ∗ Made irrational choices[c] (dummy)					−1.399
					(1.665)
Willingness to pay estimate					
Mean	0.607	0.646	0.798	0.634	0.582
Lower bound for the 95% interval	0.512	0.599	0.754	0.589	0.543
Upper bound for the 95% interval	0.702	0.692	0.842	0.679	0.620
Standard deviations of the random coefficient					
Renewable fraction	12.828***	14.719***	13.216***	13.647***	11.071***
	(1.514)	(2.270)	(1.740)	(1.773)	(1.494)
N	6090	6090	5970	6090	6090
LR chi2(2)	1659.6	1617.98	1465.7	1610.95	1597.48
Log likelihood	−702.956	−706.358	−678.779	−705.837	−705.554

	Between		LR chi^2(1)	Prob > chi^2
LR test for nested models	Model 1	Model 2	−6.80	1.0000
	Model 1	Model 3	48.35	0.0000
	Model 1	Model 4	−5.76	1.0000
	Model 1	Model 5	−5.20	1.0000
	Model 2	Model 3	55.16	0.0000
	Model 4	Model 5	0.57	0.4521

Note: The simulation uses 500 Halton draws. With the attributes for the status quo option set to zero, the status quo was handled with a dummy variable, which equals one if the option is status quo and zero otherwise. For brevity, this variable is not shown in the table.

[a] Given a value of 1 for those that currently use public pay-per-use chargers, otherwise a value of 0.

[b] Given a value of 1 for those that currently use a Level 2 public pay-per-use charger, otherwise a value of 0.

[c] See Section 3.2.

Standard errors in parentheses.

[*] $p < 0.1$.

[**] $p < 0.05$.

[***] $p < 0.01$.

means and 95% confidence intervals shown in Tables 7 and 8. The distributions for WTP are bimodal, as shown in Fig. 2, with a minor fraction having a lower WTP. The standard deviations of the random coefficient for *Renewable fraction* show that there exits heterogeneity of the WTP among the respondents. For the case study we chose to use model one, which incorporates only parameters presented in the choice sets and provides one of the lower valued choice experiment WTP estimates. The mean WTP estimated by this model is $0.61 per hour to upgrade to renewable energy from the Level 2 EVSE and $1.82 per charge from renewable energy from the DCFC.

To put these WTP values into context in combination with the stated usage values, the average PEV driver charging from Level 2 commercial chargers would see a rise in their monthly pay-per-use charging expense from $4.95 to $36. For the DCFC chargers this monthly expense would increase from $5.50 to $29.53. In both cases, this is feasible for the mid to high income owners of PEVs.

In both the Level 2 and DCFC cases, the following trends emerge:

- Greater WTP for renewable energy for those that use the type of EVSE in question
- WTP increases with an increase in income
- WTP decreases with years of education
- Females are willing to pay more for renewable energy
- WTP increases with age

The numbers for the variable “Currently use commercial chargers” in Table 8 differ between model 2 and model 3. Their methods of estimation differ in that additional variables included in the model for model 3. These additional control variables have an impact on this variable for Model 3 when fitting a model to the respondents’ DCFC charging choices. For example, income and gender could be correlated with respondents’ decisions to charge at DCFC charging stations. In Table 8, the coefficient for the interaction term between “Made irrational choices” and Renewable fraction is positive, meaning that if a person made an irrational choice, they will be more likely to choose an option if there is higher fraction of renewable energy.

We also ran the models on a subset of responses that excludes those who made irrational choices in the choice experiments. The results are listed in Table 9. In addition, the demographics of the rational versus irrational people are listed in Table 5. The elicited WTPs of the rational people are similar to those for the whole

Table 8
DCFC choice experiment analysis results.

Mean and standard errors of coefficients	Model 1	Model 2	Model 3	Model 4	Model 5
Price ($)	−14.725***	−14.442***	−14.550***	−14.770***	−14.757***
	(1.128)	(1.104)	(1.130)	(1.129)	(1.144)
Renewable fraction (unit is one, not%)	26.841***	27.586***	39.127***	31.620***	27.354***
	(2.887)	(3.449)	(7.772)	(3.456)	(2.906)
Renewable fraction * Currently use commercial chargers[a] (dummy)		8.839***	−3.194***		
		(1.847)	(1.117)		
Renewable fraction * Currently use DCFC commercial chargers[b] (dummy)				42.393***	7.468**
				(5.685)	(2.960)
Renewable fraction * Income			0.074***		
			(0.021)		
Renewable fraction * Education			−1.386***		
			(0.446)		
Renewable fraction * Female			13.396***		
			(2.138)		
Renewable fraction * Age			0.098**		
			(0.049)		
Renewable fraction * Made irrational choices[c] (dummy)					0.531
					(1.233)
Willingness to pay estimate					
Mean	1.82283	2.174	2.116	2.258	1.952
Lower bound for the 95% interval	1.507992	2.011	1.968	2.090	1.825
Upper bound for the 95% interval	2.137669	2.337	2.264	2.425	2.079
Standard deviations of the random coefficient					
Renewable fraction	18.426***	20.130***	19.638***	24.211***	19.536***
	(2.347)	(2.800)	(2.426)	(3.057)	(2.642)
N	6090	6090	5970	6090	6090
LR chi2(2)	2357.48	2348.6	2112.12	2338.12	2326.27
Log likelihood	−547.367	−545.731	−529.749	−543.379	−545.014

	Between		LR chi^2(1)	Prob > chi^2
LR test for nested models	Model 1	Model 2	0.13	0.7223
	Model 1	Model 3	35.24	0.0000
	Model 1	Model 4	7.98	0.0047
	Model 1	Model 5	4.71	0.0951
	Model 2	Model 3	35.11	0.0000
	Model 4	Model 5	−3.27	1.0000

Note: The simulation uses 500 Halton draws. With the attributes for the status quo option set to zero, the status quo was handled with a dummy variable, which equals one if the option is status quo and zero otherwise. For brevity, this variable is not shown in the table.

[a] Given a value of 1 for those that currently use public pay-per-use chargers, otherwise a value of 0.

[b] Given a value of 1 for those that currently use a DC fast public pay-per-use charger, otherwise a value of 0.

[c] See Section 3.2.

Standard Errors in Parentheses.

[*] $p < 0.1$.

[**] $p < 0.05$.

[***] $p < 0.01$.

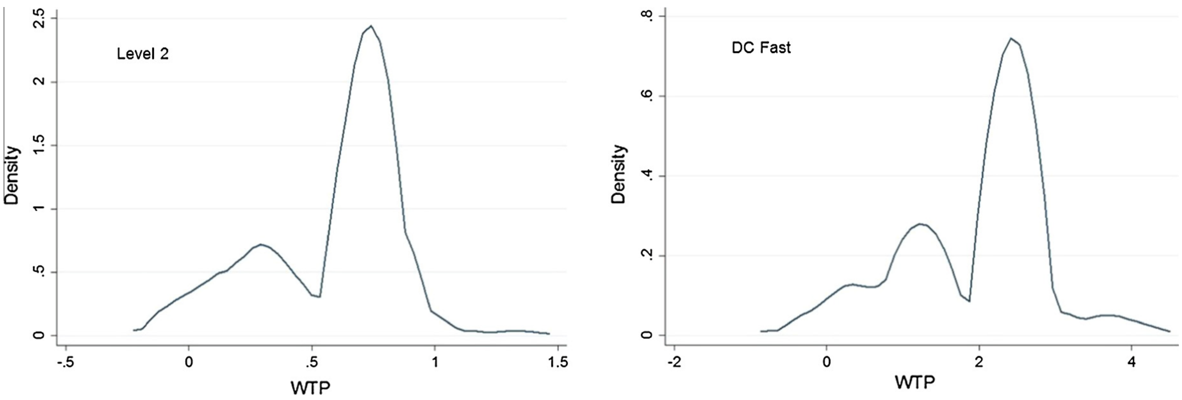

Fig. 2. Distribution of elicited WTP based on Model 5 in Tables 7 and 8.

sample, which implies that whether respondents are rational or not as determined in the choice experiment does not impact much their decisions to charge their EVs with renewable energy. On average, irrational respondents are more likely to be male, have higher income, and are younger.

We've also estimated the WTP using conditional logit models, with the results shown in Appendix B in Table B.1. As can happen with conditional logit models, the results have overestimated the WTP. This further justifies our use of mixed logit models in this study.

Table 9
Choice experiment analysis results of rational respondents.

Mean and standard errors of coefficients	AC Level 2	DCFC		
Price ($)	−43.669***	−45.171***	−24.011***	−24.396***
	(3.490)	(3.547)	(2.283)	(2.469)
Renewable fraction (unit is one, not%)	28.326***	33.904***	46.283***	41.687***
	(3.174)	(3.889)	(5.300)	(5.115)
Renewable fraction ∗ Charge at this type of commercial charging station[a]		15.547***		26.259***
		(2.347)		(5.144)
Willingness to pay estimate				
Mean	0.649	0.763	1.928	1.944
Lower bound for the 95% interval	0.557	0.700	1.632	1.790
Upper bound for the 95% interval	0.740	0.827	2.223	2.100
Standard deviations of the random coefficient				
Renewable fraction	19.528***	24.588***	30.992***	37.683***
	(2.608)	(3.224)	(3.987)	(5.232)
N	5070	5070	5070	5070
LR chi2(2)	1447.64	1423.1	2052.28	2032.99
Log likelihood	−555.399	−553.688	−391.887	−389.912

Note: The simulation uses 500 Halton draws. With the attributes for the status quo option set to zero, the status quo was handled with a dummy variable, which equals one if the option is status quo and zero otherwise. For brevity, this variable is not shown in the table.

[a] Given a value of 1 for those that currently use Level 2 public pay-per-use chargers, otherwise a value of 0 for the analysis of Level 2 charging; Given a value of 1 for those that currently use DC fast public pay-per-use chargers, otherwise a value of 0 for the analysis of DC fast charging;

Standard Errors in Parentheses.

* p < 0.1.

** p < 0.05.

*** p < 0.01.

5.2. Regression findings

An ordinary least squares regression was applied to the following dependent variables (1) all variations of increase in EVSE usage and (2) all variations of renewable charger competitive choice likelihood. This regression analysis allows us to examine the heterogeneity across different PEV drivers. Tobit regression was used for the likelihood of choosing a renewable energy offering EVSE dependent variable. The use of the Tobit method corrects for the censoring created by the survey question, where in the range was defined from 0% to 100%, with 0% indicating indifference. This phrasing does not account for the possibility of a preference for the non-renewable chargers. In all cases, the regression was applied to the results from the 181 respondents that completed every question. Table 10 shows the dependent variables for which there is a statistically significant regression model based on all the independent variables listed. Given the similarity of the results between the every charge renewable and optionally renewable cases for the choice likelihood variables, regression results are solely shown for the every charge

Table 10
Regression analysis results.

Dependent variable	Every charge: Likelihood choose over non-renewable charger		Optional: Charger use increase	
Adjusted R Square	0.220		0.068	
Significance F	0.000		0.033	
Coef	Mean	Std Err	Mean	Std Err
Intercept	131.01***	28.979	7.076	9.839
EV vs PHEV[a] (dummy)	1.974	5.477	−0.426	2.847
Travel Distance (mi/day)	−0.232	0.113	0.055	0.059
Current commercial charger use (events/mo.)	0.178	1.109	−0.242	0.577
Current level 2 charger use (events/mo.)	−0.325	1.620	−0.102	0.843
Current DC fast charger use (events/mo.)	−7.715	14.863	−3.139	7.729
Currently use commercial chargers[b] (dummy)	9.855	6.576	−5.483	3.421
Currently have home renewable energy[c] (dummy)	2.397	5.369	4.422	2.791
Environmental reason primary or secondary[d] (dummy)	15.400**	7.094	4.055	3.691
Energy independence reason primary or secondary (dummy)	−3.136	6.834	4.096	3.555
Fuel cost savings reason primary or secondary (dummy)	−14.025**	6.777	−1.473	3.525
New technology reason primary or secondary (dummy)	−19.797**	7.645	0.670	3.972
Vehicles household owns (count)	1.218	2.728	−0.769	1.417
Household income (100,000 s)	0.674	4.904	−6.591***	2.550
Years of education	−1.690	1.400	0.065	0.728
Gender	−3.463	6.449	−2.415	3.355
Age (yr.)	−0.401*	0.237	0.106	0.123

[a] Given a value of 1 for owners of EVs and a value or 0 for owners PHEVs.

[b] Given a value of 1 for those that currently use public pay-per-use chargers, otherwise a value of 0.

[c] Given a value of 1 for those that currently charge their vehicle at with renewable energy at home, otherwise a value of 0.

[d] Given a value of 1 if respondents purchased a their vehicle for the stated reason, otherwise a value of 0.

* p < 0.1.

** p < 0.05.

*** p < 0.01.

renewable case. Only the optionally renewable case provided a statistically significant regression model for charger usage increase. At 6–22%, these models explain a minor fraction of the variability. Though, they do provide some trends.

For the likelihood of choosing a charger offering renewable over one that does not, regression indicates:

- 15% greater likelihood for those that purchased their vehicle for environmental reasons.
- 14% less for those that purchased for fuel cost savings.
- 20% less for those that purchased in interest of new technology.
- A weak correlation (with significance at the p = 0.1 level) of less likelihood with increasing age.

Regression of the indicated increase from current EVSE usage to usage if EVSE offered renewable energy shows that 6% of the variability can be attributed to a trend of a less usage increase for those with higher incomes.

5.3. Case study: Blink network

Our case study applies the knowledge gained from the survey to examine the economic and environmental benefits available to the electric vehicle charging industry by focusing on the Blink charging network as an example. The wind energy for this case study is sourced from U.S. wind farms through the purchase of RECs, which are the basis of grid-tied renewable energy trade in the U.S. See Section 2.2 for more information on RECs. The Blink public EVSE network was built by ECOtality, Inc. as part of The EV Project, which had a total of $230 million in support from the U.S. Department of Energy (DOE), Chevrolet, Nissan and other partners from 2009 to 2013. The EV Project was developed to build a significant charging infrastructure in 18 metropolitan areas across the U.S. and to collect and analyze data needed to learn from the first generation of PEVs in order to support the development of future vehicles and infrastructure. While our study focuses on the commercial EVSE, the project installed 6141 residential EVSE in addition to 2675 commercial AC Level 2 EVSE and 87 commercial DCFCs [21]. The collected charging data was summarized and published in numerous reports. This publicly available data, specifically the most recent quarterly report of second quarter 2013, are used in this study to calculate potential profitability and emissions reduction. The bankruptcy of ECOtality in September of 2013 led to the purchase of the Blink network by Car Charging Group, Inc.

5.3.1. Economic benefit

When combined with our survey results, The EV Project quarterly report provides enough information to determine the Blink network second quarter 2013 gross income and the increase in gross income and profit, if the offering of renewable energy leads to the usage and mean WTP found in the survey. This information will be annualized by simply multiplying quarterly values by four where appropriate, assuming no seasonal change or other source of increase or decrease in EVSE usage. Given that Blink's contracts with their EVSE host site owners are not public knowledge and that renewable energy profits may not be addressed in these contracts, it is unclear how the income and costs would be shared between these parties.

5.3.1.1. AC Level 2 EVSE price increase. Values used to calculate the income and profit for AC Level 2 EVSE are shown in Table 11. Since the WTP for renewable energy was surveyed with a base price of $1.00/h and because this was the price charged when the second quarter 2013 data were collected and at the time of survey administration, the case study uses the pre-September 2014 price.

Gross annual income without renewable energy is calculated by multiplying together the number of charge events per year by the average number of hours per charge event by the price the customer paid for an hour of use.

$$Income_{L2} = 202,916\,\frac{events}{\mathrm{yr}} \times 4.5\,\frac{\mathrm{h}}{event} \times \$1.00/\mathrm{h} = \$913,122/\mathrm{yr}$$

Gross annual income from the sale of renewable energy is calculated similarly though with the mean WTP in place of the base price per hour.

$$Income_{L2,RE} = \$557,004/\mathrm{yr}$$

This represents a 61% increase in gross income from AC Level 2 charging. The profit without renewable energy cannot be determined as the costs of running the Blink network are not public information. However, the additional profit available through the sale of renewable energy can be calculated by subtracting the annual cost of RECs from the renewable energy gross income.

$$\begin{aligned} Cost_{L2,RE} &= 202,916\,\frac{events}{\mathrm{yr}} \times 8.6\,\frac{\mathrm{AC\ kW\ h}}{event} \times \$0.0012/\mathrm{AC\ kW\ h} \\ &= \$2094/\mathrm{yr} \end{aligned}$$

$$Profit_{L2,RE} = Income_{L2,RE} - Cost_{L2,RE} = \$554,910/\mathrm{yr}$$

This value indicates a 99.6% profit margin on the sale of renewable energy. Nationally sourced wind RECs sold on the voluntary, non-compliance market have traded below $0.002/kW h since 2010. The highest wind voluntary REC prices to date were observed for wind energy generated in the western U.S. during some price peaks between 2009 and 2012, with values topping out at $0.0086/kW h. While nationwide sourced wind was available at $0.001–$0.0015 during this period and there is no reason not to use the lower priced RECs, the effect of this higher price is noted as a point of profit sensitivity.

$$Cost_{L2,RE} \times \frac{\$0.0086}{\$0.0012} = \$15,007$$

The higher REC cost is clearly still well below $Income_{L2,RE}$, leaving a 97.3% profit margin, relative to the gross renewable energy income.

Table 11
Renewable energy profitability inputs.

Description	AC Level 2	DCFC	Source
Number of charge events	202,916 events/yr	107,644 events/yr	[21]
Average energy consumption	8.6 AC kW h/event	8.3 AC kW h/event	[21]
Average time connected	4.5 h/event	–	[21]
Price of charge	$1.00/h	$5.00/event	[21]
Wholesale cost of nationally sourced wind energy REC	$0.0012/AC kW h	$0.0012/AC kW h	[34]
Choice experiment mean stated renewable energy WTP	$0.61/h	$1.82/event	Survey from this study
Average stated usage increase with renewable energy	433%	433%	Survey from this study

5.3.1.2. DCFCs price increase. The needed inputs for the income and profit values from the sale of renewable energy on the DCFCs are also presented in Table 11. Following the same process, the DC fast charging gross annual income without renewable energy, the gross annual income from the sale of renewable energy, the cost of RECs and renewable energy profit is calculated as follows.

$$Income_{DC} = 107,644\frac{events}{\text{yr}} \times \$5.00/event = \$538,220/\text{yr}$$

$$Income_{DC,RE} = \$195,912/\text{yr}$$

$$Cost_{DC,RE} = 107,644\frac{events}{\text{yr}} \times 8.3\frac{ACkWh}{event} \times \$00012/\text{AC kW h}$$
$$= \$1072/\text{yr}$$

$$Profit_{DC,RE} = Income_{DC,RE} - Cost_{DC,RE} = \$194,840/\text{yr}$$

These values indicate a 36% increase in gross income and 99.4% profit margin from the sale of renewable energy on DCFCs.

5.3.1.3. Totaling and usage increase. Summing the AC Level 2 and DCFC pre-renewable energy gross annual income provides the total pre-renewable energy EVSE income

$$Income_{EVSE} = Income_{L2} + Income_{DC} = \$913,122/\text{yr} + \$538,220/\text{yr}$$
$$= \$1.45 \text{ mill}$$

and the total gross annual income from renewable energy is

$$Income_{EVSE,RE} = Income_{L2,RE} + Income_{DC,RE} = \$0.75 \text{ mill}$$

This represents a 52% increase in gross income. Due to the low cost of REC's the total annual profit increase from the addition of renewable energy WTP is quite similar and is calculated simply the sum of

$$Profit_{EVSE,RE} = Profit_{L2,RE} + Profit_{DC,RE} = \$0.75 \text{ mill/yr}$$

Averaging the stated usage increase from the every charge renewable case and the optional renewable case from the survey results of this study provides a stated usage with renewable energy increase of 433%. The impact this rise in usage has on gross annual income and profit increase can be calculated as follows.

$$Income_{EVSE,Tot} = Usage \times (Income_{EVSE} + Income_{EVSE,RE})$$
$$= 433\% \times (\$1.45 \text{ mill} + \$0.75 \text{ mill}) = \$9.5 \text{ mill}$$

$$Profit_{RE,Tot} = Usage \times Profit_{EVSE,RE} = 433\% \times \$0.75 \text{ mill}$$
$$= 3.2 \text{ mill/yr}$$

Combined with the renewable energy price premium, such a rise in usage would bring the total gross annual income increase to 655% from the original $1.45 million to $9.5 million. At this usage rate, the cost of RECs would rise to $13,700. Regardless of the direct recipient, such increases in income and profits would provide some needed financial support to this industry experiencing low usage rates and bankruptcies.

These income and profit calculations are obviously based significantly on survey provided stated WTP and stated charger usage. While the findings of this and past studies show the drivers of PEV's have a strong interest in renewable energy with being 50–150 times more likely to power their home with PV energy than the general population, future study in the form of regional or small scale trails with customers actually making purchases are recommended to improve these estimates.

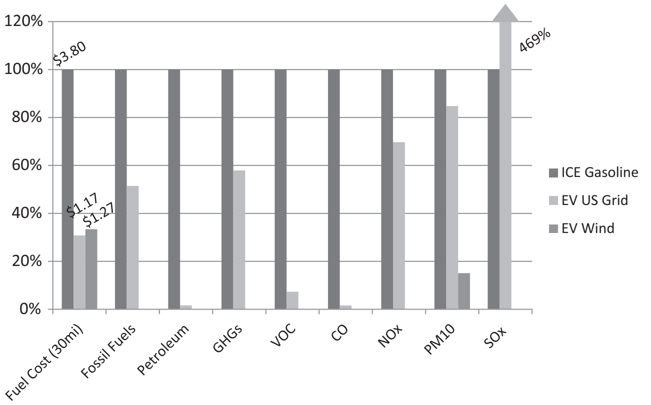

Fig. 3. Normalized fuel well-to-wheels life cycle emissions mass and consumer costs.

5.3.2. Emissions reduction simulation

A fuel well-to-wheels life cycle impact assessment comparison of powering vehicles with three different energy sources was simulated using the GREET model produced by Argonne National Laboratory [4]. Fig. 3 compares the consumer energy costs and life cycle emissions mass for a vehicle powered with gasoline, average U.S. power grid electricity mix and wind generated electricity, based on U.S. average residential electric utility pricing and U.S. average gasoline cost September 2013 – August 2014 [1,35].

These results show energy costs for 30 miles of travel in a U.S. passenger vehicle at $3.80 for gasoline, $1.17 for residential grid electricity and $1.27 for residential wind energy. Switching from gasoline to average U.S. mix electricity reduces every modeled emission type with the exception of SO_x. Switching from gasoline to wind power reduces emissions of every modeled type by more than 4 orders of magnitude, with the exception of PM10. Relative to gasoline, GHGs are 42% less for grid electricity and 99.997% less for wind energy.

The total annual energy distributed by the Blink network can be calculated by summing the total annualized second quarter 2013 AC Level 2 and DCFC energy consumption as follows, using the values from Table 11.

$$202,916\frac{events}{\text{yr}} \times 8.6\frac{\text{AC kW h}}{event} + 107,644\frac{events}{\text{yr}} \times 8.3\frac{\text{AC kW h}}{event}$$
$$= 2639 \text{ MW h/yr}$$

Using an average U.S. electricity mix carbon dioxide intensity factor [36] the total annual grid electricity carbon dioxide emissions for the Blink network are

$$2639 \text{ MW h/yr} \times 602 \text{ kg } CO_2/\text{MW h} = 1589 \text{ metric tons } CO_2/\text{yr}$$

Using the GREET model wind energy carbon dioxide intensity factor, powering every charge with wind energy would reduce emissions to

$$2639 \text{ MW h/yr} \times 0.0476 \text{ kg } CO_2/\text{MW h} = 126 \text{ kg } CO_2/\text{yr}$$

This equates to the prevention of 1589 metric tons CO_2 per year or the removal of 334 U.S. gasoline passenger cars from the road [36]. At the increased survey stated usage rate, these figures increase to 6880 metric tons CO_2 prevented per year and the elimination of 1446 passenger cars.[2]

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[2] Our calculations summing emissions mitigated only include emissions that would be saved relative to powering the electric vehicles with grid electricity, based on a fuel life cycle analysis.

Expanding these calculations to all PEV's in the U.S., the US Energy Information Administration [37] estimates the number of PEV's on the road in 2015 at 340,000 vehicles. Our respondents indicate 58 commercial charge events per vehicle per year with renewable energy. Applying the calculations used above, it can be estimated that 167 GW h of renewable energy would be required to meet the demand if every commercial charge were powered renewably. This electricity demand represents 0.07% of the 2015 U.S. annual wind and solar energy production of 230,000 GW h [38]. This amount of wind powered PEV charging would prevent 98,700 metric tons CO_2/yr, equivalent to the elimination of 20,800 gasoline passenger cars.

6. Conclusions and implications

Previous studies and the survey findings of this study show PEV drivers have a higher- than-average interest in renewable energy and in protecting the environment, with currently 50% powering their home with renewable energy and 60% having purchasing their PEV for environmental reasons. These findings show a will to take action and pay for reducing their environmental impact. The survey and choice experiment results in this study indicate a 433% increase in the usage of the EVSE if renewable energy was offered and a mean WTP to upgrade to renewable energy of $0.61 per hour for AC Level 2 EVSE and $1.82 per charge for DCFCs. Using data from the 2013 second quarter report of Blink, a public charging station company, this WTP and usage translates directly to an annual gross income increase of 655% from the original $1.45 million to $9.5 million, with a cost of $13,700 to purchase RECs. Excluding any profit seen purely from the rise in usage, $3.2 million in profits would be gained directly from the renewable energy price premium.

Looking at residential and retail energy pricing, the energy cost for 30 miles of travel in a U.S. passenger vehicle is $3.80 for gasoline, $1.17 for residential grid electricity and $1.27 for residential wind energy. Switching from gasoline to wind power reduces emissions of GHGs, VOCs, CO, NO_x, and SO_x by more than 4 orders of magnitude. Relative to gasoline, GHGs are 42% less for U.S. average blend grid electricity and 99.997% less for wind energy. Powering all Blink network charge events with wind energy would reduce the annualized 2Q 2013 GHG emissions of 1589 metric tons CO_2/yr to 126 kg CO_2/yr the equivalent of removing 334 U.S. gasoline passenger cars from the road. At the 433% survey stated increased usage, 6880 metric tons CO_2/yr would be prevented per year or the equivalent of the elimination of 1446 passenger cars. These economic and environmental benefit values will increase with the usage of commercial chargers, which is expected as PEV ownership increases with time.

Our results provide a promising new charging strategy for companies that offer public EV charging stations such as utility companies, charging companies, and EV manufacturers to increase their profits through offering renewable energy charging sources. Given the current lack of EV charging infrastructure, which is one of the biggest challenges for the development of EV industry, our study demonstrates prominent financial benefit to encourage private sectors to invest in such charging stations with the option of providing renewable energy. In addition, this strategy is associated with significant environmental benefit.

A logical next step in future work for evaluating the potential presented by this study would be to perform regional or small scale customer trials with actual purchases to improve estimates of WTP for renewable energy and charger usage if renewable energy were offered, both of which significantly impact the findings.

For policy makers to help develop the charging infrastructure for the EV industry, in addition to providing direct subsidies for charging companies, they should also help these companies to adopt new business strategies to grow more sustainably. Our results show that policy makers can educate and incentivize these companies to provide renewable energy option for their EV charging customers to increase company profits, given the elicited WTP for renewable energy of the PEV drivers. In addition, policy makers can educate PEV drivers as well as the general public of such renewable charging programs through information and education programs. Our results are based on the premise that the REC market can be operated efficiently. Thus policy makers and regulators should be aware of any potential issues in operating the REC market such as lack of uniformity in REC rules across regional markets and REC ownership uncertainty, which can be barriers for expanding REC to larger markets.

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Appendix A. Direct ask WTP

WTP was assessed for AC Level 2 and DCFCs using the choice experiment and direct ask methods. The choice experiment WTP values are estimated with several models. For this comparison to the direct ask WTP findings we will focus on the WTP values from model one, which incorporates only parameters presented in the choice sets and provides one of the lower valued choice experiment WTP estimates.

At $0.61 per hour to upgrade to 100% renewable energy using AC Level 2 EVSE and $1.82 per 30 min charge event for the DCFC, the mean WTP collected through the choice experiment method are substantially higher than those from the direct ask method, as shown in A-1. In the calculation of the direct ask mean WTP and the 95% confidence interval, a value of $0.35 was used for those that selected "more than $0.30," assuming an additional increment of $0.05 for the AC Level 2 and a value of $1.00 was used in place of "more than $0.80," an additional increment of $0.20 for the DCFC. The bootstrap method was used to calculate the confidence intervals. As discussed, the choice experiment results are less prone to bias and are expected to be a closer approximation to actual WTP.

The direct ask WTP distributions are given in Table A.2. We see a bimodal distribution with $0.00 WTP for 16% of participants for Level 2 EVSE and 20% for DCFC. The other 84% for Level 2 and other 80% for DCFC of respondents broadly showing interest increasing with increasing WTP. The most popular option for both was the highest WTP option, "more than $0.30" per hour for Level 2 and "more than $0.80" per charge for DCFC. There is little difference in the direct ask WTP results between renewable energy being provided with every charge and with it being offered as an option, as seen in the mean values in Table A.1.

Table A.1
AC Level 2 renewable energy upgrade WTP statistics.

Survey method	Mean WTP ($/h)	95% confidence interval ($/h)
AC Level 2		
Direct Ask – Every Charge	$0.20	$0.19–$0.23
Direct Ask - Optional	$0.21	$0.19–$0.23
Choice Experiment	$0.61	$0.51–$0.70
30 min DCFC		
Direct Ask – Every Charge	$0.54	$0.49–$0.61
Direct Ask - Optional	$0.54	$0.49–$0.61
Choice Experiment	$1.82	$1.51–$2.14

Table A.2
Distribution of direct ask WTP for renewable energy on a commercial EVSE with every charge renewable.

AC Level 2		DCFC	
WTP ($/h)	Participant fraction (%)	WTP ($/Charge)	Participant fraction (%)
More	28	More	33
$0.30	11	$0.80	9
$0.25	12	$0.60	9
$0.20	10	$0.40	9
$0.15	6	$0.30	10
$0.10	10	$0.20	6
$0.05	4	$0.15	1
$0.02	2	$0.10	1
$0.00	16	$0.05	1
		$0.00	20

Appendix B. Choice experiment – Supporting findings

See Table B.1.

Table B.1
Conditional choice models.

Mean and standard errors of coefficients	Level 2	DC Fast
Price	-4.464^{***} (0.514)	-1.397^{***} (0.202)
Renewable fraction	4.820^{***} (0.161)	4.565^{***} (0.158)
Renewable fraction * Charge at this type of commercial charging station	0.856^{***} (0.159)	1.610^{***} (0.386)
N	6090	6090
LR chi2(2)	2103.78	1474.48
Log likelihood	−2824.4816	−3139.1294
Willingness to pay estimate		
Mean	1.080	3.269
Lower bound for the 95% interval	0.863	2.433
Upper bound for the 95% interval	1.296	4.105

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