Energy Policy 102 (2017) 423–429

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Towards a meaningful metric for the quantification of GHG emissions of electric vehicles (EVs)

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ARTICLE INFO

Keywords:
Electric vehicles
Environmental impacts
Electric vehicle emissions index
Emissions

ABSTRACT

A key motivator for wider deployment of electric vehicles (*EV*s) – vehicles that are fully powered by battery charged from grid electricity – is to bring about environmental cleanliness. This goal is based on the fact that *EV*s produce zero tailpipe emissioon the associated carbon emissins. However, the generation and transmission of the charge electricity produce emissions that are not explicitly accounted by current measurement metrics for *EV* greenhouse gas (*GHG*) emissions and as such, the notion of environmental cleanliness of *EV*s becomes questionable. In this paper, we propose a comprehensive metric to quantify the actual environmental impacts of *EV*s. The new metric that we call the electric vehicle emissions index (*EVEI*) captures CO_2 emissions in the electricity production to consumption stages. Our metric is the first that provides transparency in the comparison of total emissions among various *EV* models, as well as in the side-by-side comparison of an *EV* with a gasoline vehicle (*GV*). Illustrative results indicate that the actual environmental impacts of an *EV* may show wide spatial variations and in some case, these impacts may be even greater than that of *GV*. Such insights that the *EVEI* provides may be useful in a wide range of applications, particularly in policy and incentive formulation.

1. Introduction

The past decade has seen a slow but steady rise in the sale of electric vehicles (*EV*s) – vehicles that are fully powered by batteries that are charged typically from the grid. A salient characteristic of *EV*s is their cleaner environmental impacts relative to conventional fuel vehicles, as they have either zero or lesser tailpipe greenhouse gas *(GHG)*/CO_2 emissions than conventional cars. Moreover, fuel economy, i.e., the distance travelled by a vehicle per unit of fuel consumed is also higher for an *EV* than for a conventional vehicle. As such, *EV*s are viewed as strong contributors to improve energy security and to reduce *GHG* emissions in the transportation sector. Therefore, there is a push to increase awareness about *EV*s and their environmental impacts and to promote more widely their deployment. A specific example is the revised Environmental Protection Agency (*EPA*) vehicle label (Revised EPA Label) to indicate the *GHG* rating of the vehicle based on its tailpipe emissions. All *EV*s are given the top *GHG* rating of 10 on a 10-point scale with 1 being the worst. However, neither fuel economy nor the *EPA* label presents a true picture of the environmental impacts of an *EV*. The *GHG* rating given by *EPA* is based on the tailpipe emissions of a vehicle, without accounting for emissions produced in the generation/transmission of the charge electricity. Fuel economy of *EV*s, measured in miles per gallon gasoline equivalent (MPGe) assumes that heat (energy) produced by burning one gallon of gasoline equals 33.7 kWh of electricity. This conversion factor holds only for an adiabatic process, which need not occur in an *EV*. Petroleum-equivalency factor (*PEF*) (Department of Energy, 2000) is a useful comparative measure of the *EV* energy consumption to that of a gasoline vehicle (*GV*) but fails to throw any light on the *GHG* emission impacts. Thus the notion of environmental cleanliness of *EV*s may be less than transparent and a deeper investigation is required to understand if a change of fuel from gasoline to electricity does indeed provide environmental benefits as claimed.

Several attempts have been made in the literature to assess the impacts of *EV*s on the environment. The work in Kotchen et al. (2014), Doucette and McCulloch (2011a), Yuksel and Michalek (2015) and McLaren et al. (2016) describe and are limited to the impact of resource mix and temperature respectively on the emissions of *EV*s excluding other considerations such as transmission and distribution (*T/D)* losses and charging equipment efficiency. McLaren et al. (2016) consider different charging scenarios and travel profiles of EVs and analyzes their impact on the associated carbon emissions. Hawkins et al. (2012), Elgowainy et al. (2009), EPRI and Group (2007), Archsmith et al. (2015), Abdul-Manan (2015) and Ma et al. (2012)

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http://dx.doi.org/10.1016/j.enpol.2016.12.003
Received 17 March 2016; Received in revised form 15 November 2016; Accepted 1 December 2016
Available online 03 January 2017
0301-4215/

have attempted to assess the true environmental impacts of *EV*s through the quantification of the total emissions associated with a vehicle from the fuel production to the energy consumption stages — the so-called well-to-wheel emissions, however, no metric has been proposed. The Argonne National Labs' *GREET* model (Argonne GREET Model) has comprehensively quantified well-to-wheel emissions of various advanced fuel vehicles, but the scope of Argonne GREET Model is limited to specific vehicle models. The work done in Lindly and Haskew (2002), Casals (2016) and Doucette and McCulloch (2011b) study the impact of *EV* penetration on global warming and thus, are relevant to our work, however, transmission losses have been ignored and neither has any metric been proposed. Other studies, such as those in Zhou et al. (2013), TIAX LLC (2007), Girardi et al. (2015) and Hooftman et al. (2016) compare of *EV*s and *GV*s in terms of life cycle and environmental impacts in a particular area/country of usage, however without proposing any metric either.

The situation presents need for a metric that provides a more meaningful quantification of the actual *EV* environmental impacts by the comparison of emissions from the fuel pathway of electricity and gasoline. The metric needs to account for all the factors that contribute to the emissions associated with the usage of an *EV* from generation of electricity to its consumption in the *EV*. Furthermore, the metric must encompass the wide spatial variations in emissions that occur in the generation of electricity. Additionally, the metric should be generic to be applicable to all *EV* models.

In this paper, we address directly the need for a meaningful metric to quantify such impacts for *EV*s. Specifically, we propose a metric called the Electric Vehicle emission index (*EVEI*) for the quantification of CO_2 emissions of *EV*s and describe the methodology for its evaluation. The *EVEI* provides transparency in the evaluation of environmental impacts of the *EV* through the explicit consideration of factors that contribute to emissions in the fuel pathway of electricity, i.e., resource mix, loss components and fuel economy. Additionally, the quantification of the cleanliness/dirtiness of an *EV* with respect to a reference *GV* in the *EVEI* lends to the ease of interpretation of the metric and can be a particularly useful feature of the metric.

In the paper, we limit our studies to comparison of fuel life cycle assessment of EVs and GVs which excludes emissions associated with manufacturing of EVs and GVs. Regardless, we do present a literature review of the cradle to grave emissions of EVs compared to GVs as it is important for the reader to understand the impact of EV manufacturing emissions on the total emissions of associated with the vehicle. The emissions associated with manufacturing of vehicles account for a substantial portion of the total emissions associated with the vehicle, particularly for EVs (Kim et al., 2016; Dunn et al., 2012; Majeau-Bettez et al., 2011). However, estimates of the emissions generated from EV manufacturing vary widely in literature. On one hand Shen et al. (2015) attribute emissions from the EV production process to account for about 17% of the total emissions from the EV with CO2 emissions being approximately 3460 kg, whereas on the other hand, Kim et al. (2016) account that share to be almost 50% of the total life time emissions of the EV. One such study on cradle-to-grid analysis of vehicles, presents lifetime CO2 emissions for an EV to be 47.8 g/km, with production alone accounting for 45% of the emissions. In contrast, for a GV these values were 30.7 g/km, with production only contributing a mere 15% (Baptista et al., 2009). Argonne GREET Model presents a simulation software (GREET) which has been used by several other studies to effectively calculate the energy required and the emissions produced in the manufacturing process of the vehicles. Although they don't provide any data for BEVs as such, the emissions from the battery production comes around 20% of the total emissions from the production phase for Hybrid Electric Vehicles (HEVs). The work published by Hawkins et al. (2013) concludes that the GHG emissions from the production of an EV is almost double the emissions from the production of a GV remarking that battery production contributes somewhere between 35% and 41% to the production phase emissions. The inconsistencies can be attributed a variety of factors. One is that emissions from an EV vary widely based on battery technology and power train of the vehicle. Another is the lack of data (collected directly from industrial operations) for emission and energy consumption, thus requiring authors to use secondary data such as literature values, databases, engineering modeling, or proxy data. Additionally, some studies (Kim et al., 2016; Dunn et al., 2012) partially double count material production impacts. It may be noted here that the studies done in this paper focus extensively on the emissions that are produced along the fuel pathways of electricity and gasoline and factors that such as manufacturing and disposal of *EV*s/*GV*s have not been included in the scope of the paper due to numerous reasons. As such, the results in this study would have been distorted by the study used to calculate emissions from manufacturing. Furthermore, some studies (Dunn et al., 2015; Ellingsen et al., 2014) have revealed that GHG emissions depend on production volume with emissions, which may be difficult to estimate for a particular automobile.

The paper is organized as follows. In Section II, we discuss the key factors of the *EVEI* metric – the resource mix, loss components and fuel economy and describe their contribution to the emissions associated with an *EV*. We then provide the definition of our metric and discuss its mathematical formulation. In Section III, we discuss the salient characteristics of the *EVEI* and the usefulness of the metric in terms of applications to policy and incentive formulation. In Section IV, we evaluate the *EVEI* of Nissan leaf across the different states of *US* and provide results obtained and their implications. In Section V, we summarize our key findings and conclusions and discuss directions for future work.

2. The *EVEI* metric: key factors and mathematical formulation

An *EV* is powered by a battery that is electrically charged, typically from the grid, and therefore, the CO_2 emissions from an *EV* are based on the fuel pathway of electricity. Thus, the explicit considerations in the formulation of the *EVEI* must include emissions associated electricity generation and its transmission and distribution to finally charge the EV. In this section, we discuss in detail each of these factors and describe the mathematical formulation of the metric with the inclusion of these factors.

A mixture of fuels generates the electricity used to charge the EV. This mixture is known as the generation resource mix or simply, the resource mix. Power plants that use fuels such as coal, natural gas and petroleum emit significantly higher emissions than other energy generation technologies such as wind, solar, hydro and nuclear that emit low or near zero emissions. Thus, the CO_2 emissions associated with the generation of electricity depend on the resource mix used for generation.

However, there arise many complications in the incorporation of the resource mix in the metric. One reason is that there is significant variation in the types of electric power plants across the United States, and the emission rates differ greatly among them. Furthermore, the emission rates also vary with the unit commitment and dispatch of various power plants to meet the load (Siler-Evans, 2012). These dispatch patterns vary with season and also with time of the day. For example, low load periods during the night can be met mostly by fossil fired base load power plants but a more diverse mixture of power plants with a higher proportion of renewables/storage meets off – peak loads. A second reason is that adds to the complexity is the considerably lengthy charging process of an *EV* (6–8 h) (Forward et al., 2013) during which resource mix may change. Furthermore, the charging of an *EV* need not occur at the same time each day, and therefore, the resource mix that is used to charge the *EV* cannot be forecasted. Lastly, it is also difficult to ascertain the source of generation of the energy used by an *EV* since the gigantic *US* electricity system is comprised of smaller interconnected networks and electricity is traded among these networks.

Once the electricity is generated at the source, it is delivered for usage to the *EV* battery through the *T/D* network. However, the output energy at the point of consumption is not equal to the energy input at the source due to various system losses. Each loss component is associated with additional energy that must be produced and its attendant emissions, and thus must be accounted for the determination of the overall emissions involved. Consequently, the loss components must be explicitly accounted for in the formulation of *EVEI*.

There are two major loss components in the path from the source of generation to the point of consumption, i.e., at wheels of the *EV*. One is the portion of energy is lost in the process of *T/D*. The grid *T/D* efficiency dictates this loss. *T/D* efficiencies of *US* states lie in the range of 92–98% and are fairly uniform across the *US* subcontinent. Therefore, a fair approximation of the *T/D* losses can be made even if the exact pathway of the electricity from the generation to the *EV* may be difficult to be ascertained accurately. We refer to the second loss component as the wall-to-wheel losses. This loss component includes the losses that are unique to an *EV* and occur from the point of distribution – the power outlet on the wall to the point of usage – the wheels of the *EV*. The wall-to wheel losses may include the losses associated with the climate-related effects on the efficiency of the *EV* (Kotchen et al., 2014) and the losses that may occur during the considerably lengthy charging process of an *EV*, for ex. losses in conversion of *AC/DC* power and losses associated with charging equipment efficiency (Forward et al., 2013).

A final factor to be accounted for in the formulation of the metric is the fuel economy of the *EV*. The fuel economy of any vehicle is the energy it consumes to travel a specified distance. Fuel economy reflects the efficiency of the vehicle powertrain. The fuel economy of an *EV* is expressed as the energy consumed by the *EV* in kWh to travel a distance of 100 mile. Thus, the lower the kWh/100 mile travelled for the EV, the lesser environmental impacts it has. In contrast, the fuel economy of a conventional *GV*, has an inverse measure for the measurement of fuel economy – miles per gallon (*MPG*), i.e., the distance travelled by the *GV* for a gallon of gasoline consumed. Thus, the higher the *MPG* of a *GV*, the lesser fuel it consumes and the lesser emissions it emits.

We now proceed to define our metric, the *EVEI* and describe its mathematical formulation to include the effects of key factors discussed above.

Definition:. The EVEI is defined as the ratio of the total GHG emissions of an EV to the total GHG emissions of a GV for the same distance with the total GHG emissions of the vehicle considered including the emissions due to production, transportation and consumption of the energy.

The *EVEI* metric explicitly accounts for the emissions associated with the generation of electricity, the losses in *T/D* and the losses in the *EV* to compute the total emissions that are associated with the usage of an *EV*. However, these emissions are evaluated with respect to emissions of a *GV* – the most commonly used light duty vehicle in the *US*. Thus, an *EVEI* greater (lesser) than one indicates that the *EV* under consideration is more (less) polluting than the reference *GV*. The use of *GV* environmental impacts as a reference for the evaluation of the *EV* environmental impacts allows for an intuitive interpretation of the metric and provides useful information to the user.

The first step towards the mathematical formulation of *EVEI* involves the computation of the total emissions of an $EV\varepsilon_{EV}$ associated with a travel of a distance d. For this purpose, we require the knowledge of the four parameters – the carbon intensity of electricity γ_E, i.e., the emissions associated with the generation of each unit of electrical energy used to charge the *EV*, the efficiency of the network used to transmit the electricity to the $EV\eta_{T/D}$, the wall-to-wheel efficiency of the $EV\eta_w$ and the fuel economy of the $EV\rho_{EV}$. We use the fuel economy to compute the energy that is consumed by the *EV* for travelling a distance of d and use the $\eta_{T/D}$andη_w to compute the total energy E that is required to be generated at the source to supply the energy to the *EV* and the associated losses. E can be expressed as:

$$E = \frac{d\ \rho_{EV}}{\eta_{T/D}\ \ \eta_w} \tag{1}$$

For the computation of the emissions, we ignore the temporal variation of the resource mix and assume the γ_E to represent the average value of the emissions over time. We note that such averaging makes sense, as over the long run, the *EV* is likely to charge at different times in the day, and thus the emissions associated with the charging process with will tend to the average value of emissions associated with production of each unit of electricity from the resource mix. We then multiply this energy by γ_E, to obtain the total emissions ε_{EV} that are associated with the *EV* usage.

$$\varepsilon_{EV} = \frac{\gamma_E\ \ d\rho_{EV}}{\eta_{T/D}\ \ \eta_w} \tag{2}$$

The next step involves the computation of the emissions from a reference *GV*. For this purpose, we require the knowledge of the fuel economy of the $GV\rho_{GV}$, the upstream emissions factor, k and the carbon intensity of gasoline γ_G, i.e., the CO_2 emissions produced per unit of gasoline burnt. ρ_{GV} allows us to calculate the quantity of gasoline that needs to be combusted for the *GV* to travel d. The resulting quantity of gasoline, multiplied by the carbon intensity of gasoline provides us the emissions emitted at the tailpipe of the *GV*. However, the well-to-wheel emissions, i.e., the total emissions associated with the *GV* are different from the tailpipe emissions due to the additional emissions that are produced during the production, transportation, storage and refining processes of gasoline. We make use of the upstream emissions factor to capture these additional emissions associated with a *GV*. The multiplication of the tailpipe emissions of the *GV* with the upstream emissions factor gives us the total well-to-wheel emissions associated with the usage of the reference $GV\varepsilon_{GV}$ for travelling an equal distance as the *EV*.

$$\varepsilon_{GV} = \frac{\gamma_G\ k\ d}{\rho_{GV}} \tag{3}$$

The final step in the computation of the *EVEI* is the division of the total emissions of the *EV* by the emissions from the *EV*. The expression for *EVEI* ϕ can be then written as given in Eq. (4).

$$\phi = \frac{\rho EV\ \ \rho GV\ \ \gamma E}{\eta T/D\ \ \eta w\ \ k\ \ \gamma G} \tag{4}$$

3. *EVEI*: salient characteristics and policy implications

The *EVEI* provides a useful merit order for evaluation of the emissions of from *EV*s and allows the side-by-side comparison of the environmental impacts of *EV*s. An *EV* with a higher *EVEI* is more polluting than an *EV* with a lower *EVEI* with respect to the same reference *GV*. As such, the *EVEI* overcomes the limitation of the current metrics that regard all *EV*s as equally clean and gives valuable insights into the true environmental impacts of *EV*s. This feature of can play an important role in policy and incentive formulation. One example is the application of *EVEI* in the formulation of carbon tax for *EV*s. Another example is the *CARB* zero emission vehicles mandate (California Air Resources Board, 2015) imposed on automobile manufacturers in *CA* that requires the manufacturers to earn a certain percentage of credits from the sale of vehicles that emit zero tailpipe emissions – *EVs*, hybrid electric vehicles (*HEV*s), plug-in hybrid electric vehicles (*PHEV*s) and hydrogen fuel vehicles. These credits are based on tailpipe emissions of a vehicle and thus consider all the *EV*s to be equally and therefore are not fairly awarded to the *EV*s. The

Table 1
Data used for the computation of *EVEI and results* $\gamma_G = 8,887$ g/gallon, $\rho_{EV} = 30$ kWh/100 mi, $\rho_{GV} = 35.5$ MPG, $\eta_w = 0.95$.

State	γ_E (g/kWh)	$\eta^s_{T/D}$ (%)	ϕ
AL	511.0684113	96.78534519	0.540
AK	493.2056409	94.64145015	0.533
AZ	495.6037818	96.26242154	0.527
AR	537.8768325	95.90685703	0.574
CA	231.9192763	92.43081308	0.257
CO	824.708546	94.37101503	0.894
CT	278.9110446	95.40446867	0.299
DE	697.5024344	91.97164336	0.776
FL	557.1363942	94.37143369	0.604
GA	583.0982766	93.85537652	0.636
HI	699.6135423	94.72865738	0.756
ID	59.85336949	91.24356523	0.067
IL	486.5340283	95.92505723	0.519
IN	907.7348421	94.55569503	0.982
IA	736.990521	95.35238027	0.791
KS	754.4156205	94.99909586	0.813
KY	939.8347769	94.53340835	1.017
LA	507.6593046	94.36185896	0.551
ME	219.0981809	94.50039687	0.237
MD	612.3589976	90.82783029	0.690
MA	481.746909	91.16249588	0.541
MI	636.7932275	97.76094785	0.667
MN	590.9173862	92.68516312	0.652
MS	509.7393414	94.94555874	0.549
MO	831.8602403	95.04418447	0.896
MT	678.340395	97.25415486	0.714
NE	659.9283246	94.97516741	0.711
NV	478.3548573	94.48075052	0.518
NH	252.5271402	96.87810072	0.267
NJ	280.0958269	93.55215893	0.306
NM	820.5597214	96.50457723	0.870
NY	286.6180263	94.12143464	0.312
NC	535.719685	93.84261703	0.584
ND	886.8335042	97.74685584	0.928
OH	799.842814	93.45775488	0.876
OK	670.8043268	95.75774456	0.717
OR	182.8715569	95.73737578	0.195
PA	531.8390694	96.37420755	0.565
RI	413.1829856	94.85735427	0.446
SC	397.1857483	95.4662612	0.426
SD	351.6805824	94.63172836	0.380
TN	518.3446167	92.94961815	0.571
TX	577.361744	94.91744987	0.622
UT	830.2022255	95.7258563	0.888
VT	1.303305894	95.37936016	0.001
VA	470.8514478	91.3565851	0.527
WA	136.2931016	95.61842684	0.146
WV	892.7520633	97.6733203	0.935
WI	706.7012348	93.84314508	0.771
WY	947.5856209	98.06583713	0.989
AL	511.0684113	96.78534519	0.540
AK	493.2056409	94.64145015	0.533
AZ	495.6037818	96.26242154	0.527
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Table 1 *(continued)*

State	γ_E (g/kWh)	$\eta^s_{T/D}$ (%)	ϕ
MS	509.7393414	94.94555874	0.549
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ND	886.8335042	97.74685584	0.928
OH	799.842814	93.45775488	0.876
OK	670.8043268	95.75774456	0.717
OR	182.8715569	95.73737578	0.195
PA	531.8390694	96.37420755	0.565
RI	413.1829856	94.85735427	0.446
SC	397.1857483	95.4662612	0.426
SD	351.6805824	94.63172836	0.380
TN	518.3446167	92.94961815	0.571
TX	577.361744	94.91744987	0.622
UT	830.2022255	95.7258563	0.888
VT	1.303305894	95.37936016	0.001
VA	470.8514478	91.3565851	0.527
WA	136.2931016	95.61842684	0.146
WV	892.7520633	97.6733203	0.935
WI	706.7012348	93.84314508	0.771
WY	947.5856209	98.06583713	0.989

EVEI can provide a meaningful basis for awarding these credits to the *EV*s as well as for the formulation of carbon taxes for *EV*s.

The *CA* trend to reduce *GHG* emissions through increased sale of *EV*s is expected to spread to other states. *CT*, *MA*, *ME*, *NJ*, *NY*, *OR*, *RI* and *VT*, and *D.C.* have followed the *CA* suit and have imposed similar mandates on the sale of *EV*s. However, such mandates need to consider the spatial variation of the environmental impacts of an *EV* arising from the variation in the resource mix of across different regions. These variations are captured by the *EVEI* as the emissions from the resource mix have been explicitly accounted in the *EVEI*. Thus, the *EVEI* provides a valuable means of quantification of the variation of environmental impacts of an *EV* across the regions of its usage. As such, the *EVEI* may provide a useful measure in the formulation of region specific *EV* policies and incentives.

A third valuable characteristic of the *EVEI* is that it allows for the comparison of the emissions from an *EV* to that of a conventional *GV*. An *EVEI* greater (lesser) than one indicates that the *EV* under consideration has higher (lower) emissions than the reference *GV*. The high *EVEI* in such cases can be typically attributed to a dirty resource mix. As such, in areas where the *EVEI* of *EV*s is greater than one, the efforts to transition to *EV*s may be inadequate to reduce the *GHG* emissions from the transportation sector unless accompanied by simultaneous efforts to transition to a cleaner generation resource mix. Thus, the *EVEI* of *EV*s in a region may be a useful basis for the determination of the necessary renewable portfolio standards (*RPS)* required for achieving the *GHG* reduction goals in the transportation sector.

Additionally, the multiplication of the percentage increase (decrease) in *EVEI* with the emissions of the *GV* – the denominator of the *EVEI* – allows us to compute the increase (decrease) in the emissions from the electrification of each vehicle. As such, the *EVEI* provides as an easy means to quantify the reductions/increment in *GHG* emissions achieved from the electrification of a fleet of vehicles.

Furthermore, the *EVEI* can be indicated on the *EPA* sticker or included in the specifications given by the manufacturer to increase consumer awareness of the environmental impacts of the *EV* in the area of usage. A survey conducted by the California center for sustainable energy states that 22% of the participants who took the survey cited environmental considerations as the primary motivator for

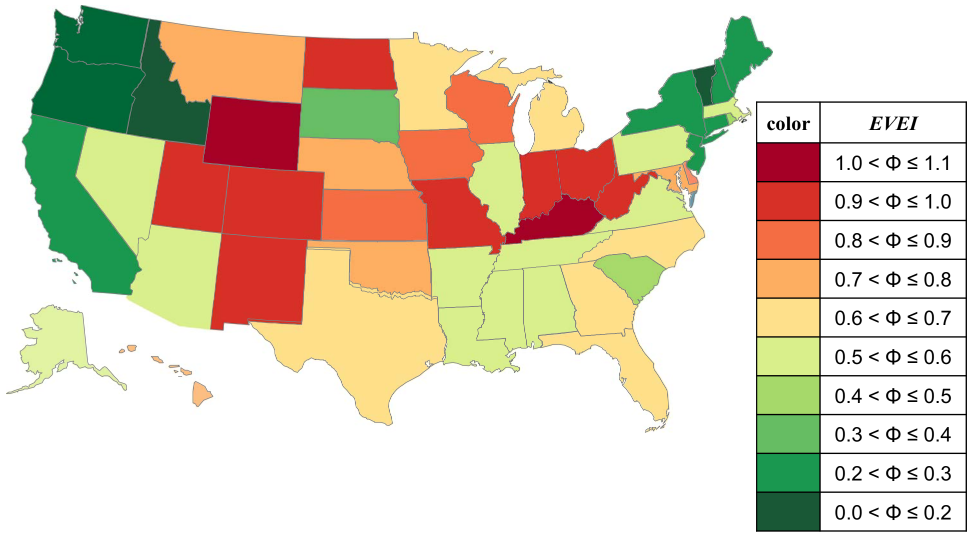

Fig. 1. The variation in *EVEI* values of Nissan Leaf *EV* on a state-by-state basis in the *US*.

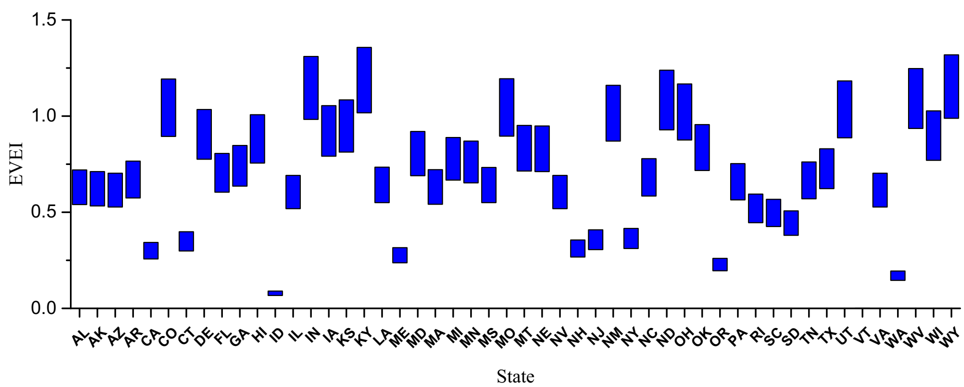

Fig. 2. Variation of the EVEI with EV fuel econom y; the min(max) for each state corresponds to a fuel economy of 30 kW h/100 mi(40 kW h/100 mi).

purchasing *EV*s (C.C.f.S. Energy, 2014). As such, the display of *EVEI* on the *EPA* stickers can be useful to *EV* owners as well.

The framework provided for computation of the CO_2 emissions in the *EVEI* can be easily extended to other *GHG* gases such as NO_x, SO_x etc. For instance, diesel vehicles have gained popularity in the recent times due to their higher fuel economy and lower CO_2 emissions. However, they emit more NO_x emissions as compared to other vehicles. As such, the *EVEI* of *EV*s with respect to diesel-fueled vehicles may be desired with NO_x being the *GHG* of interest. In such scenarios, the *EVEI* may be obtained by replacing the carbon intensities of electricity and gasoline with the nitrogen intensities of electricity and diesel respectively.

4. Illustrative results and discussions

In this section, we evaluate the *EVEI* of a widely used *EV*- the Nissan Leaf with a fuel economy of 30 *kWh*/100 *mile*. As the *EVEI* is resource mix specific, we evaluate its value in the various regions of *US*. We also investigate the effect of parameter uncertainty in the wall-to-wheel efficiency on the *EVEI* values in these regions.

For the purpose of evaluation, we use the yearly average values of the γ_E available in the eGrid database (U.S. Environmental Protection Agency, 2014). Specifically, we use the values of given for each state in the eGrid for the year 2010. We convert the values specified in eGrid from lb/MWh to g/kWh using the conversion factors of 453.592 g/lb and 1000 kWh/MWh. The wall-to-wheel efficiency is assumed to be 95%. We then proceed to compute the *T*/*D* efficiency for each *US* state $\eta^s_{T/D}$ and for this purpose, we used the state electricity profiles available in (State Electricity Profiles). These profiles contain the estimates for losses, state generation, direct usage.[1] The *T*/*D* efficiency for each state is computed from this data as follows:

$$\eta^s_{T/D} = \left(1 - \frac{losses}{generation - direct\ \ use}\right) \times 100 \tag{5}$$

The reference case for *GV* is a fuel economy of 35.5 MPG – the average fuel economy of a light duty passenger vehicle in *US* (U.S. Department of Transportation). We use the value of 8887 g/gallon for the carbon intensity of gasoline and the value of 1.25 for the upstream emissions factor (U.S E.P.A) in the calculation of well-to-wheel emissions of the *GV*.

The tabular data and computed values of *EVEI* of the Leaf across the various states of *US* have been presented in Table 1 and Fig. 1 respectively.

We find that the *EVEI* of the Nissan Leaf lies in the range of [0.067, 1.017] for the year 2010. The spatial differences in the *EVEI* of the Leaf arise due to a change in the resource mix across the various states. We observe that in the states of *CO*, *IN*, *KS*, *KY*, *MO*, *NM*, *ND*, *OH*, *UT*, *WV* and *WY*, the CO_2 emissions of the Leaf are comparable to or higher than the emissions of the reference *GV*. The high *EVEI* can be attributed to the fossil-intensive resource mix of these regions. However, in the states of *CA*, *CT*, *NH*, *NJ*, *NY*, *ME*, *OR*, *VT* and *WA,* the emissions of the same *EV* are about one third of the reference *GV*.

[1] Direct use electricity is the electricity that is generated at facilities and that is not put into the electricity *T*/*D* grid, and therefore does not contribute to *T*/*D* losses.

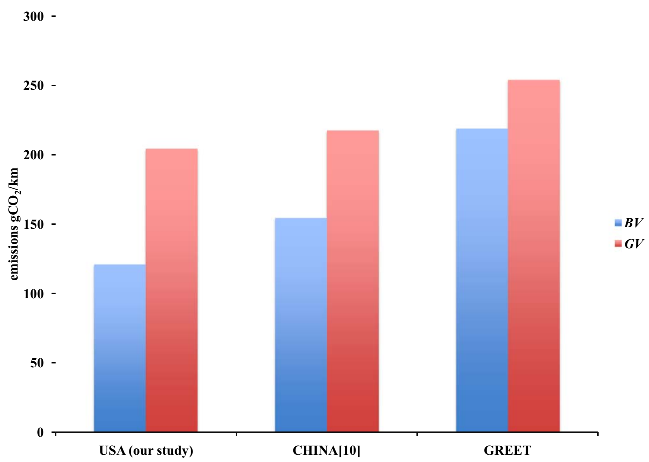

Fig. 3. Comparison of results in the paper with that given in literature.

The low *EVEI* in these states can be attributed to the deeper penetrations of integrated renewable resources in their grids The wide variation of *EVEI* for the year 2010 clearly indicates that zero tailpipe emissions of the Nissan Leaf fails to capture the actual emissions associated with electricity production, transmission and distribution. As such, an *EV* may have a wide variation in emissions across different locations and the formulation of *EV* policies and incentives need to take this reality into account.

We then study the impact of the fuel economy of the Leaf to observe sensitivity of the *EVEI* to the fuel economy of the *EV*. We vary the fuel economy from 30 kWh/100 mile to 40 kWh/100 mile since this range captures the fuel economy of most of the *EV* models available in the market for the years 2012–2016. The sensitivity of the *EVEI* with respect to *EV* fuel economy can be expressed as:

$$\frac{d\phi}{d\rho_{EV}} = \frac{\rho GV \quad \gamma E}{\eta T/D \quad \eta w \quad k \quad \gamma G} \tag{6}$$

As can be seen from Eq. (6), the *EVEI* increases proportionally to the increase in fuel economy of the *EV*. As such, for the range of *EV* fuel economies selected, the Leaf, with the best fuel economy of 30 kWh/100 mile results in the lowest *EVEI* while an *EV* with a fuel economy of 40 kWh/100 mile has the highest *EVEI* in each of the states. The results of the sensitivity analysis are shown in Fig. 2. We see that in many states, the fuel economy of the *EV* may be the key determinant in the breakeven of emissions of the *EV* with respect to the *GV*.

The *EVEI* formulation also indicates that each percent improvement in fuel economy of the reference *GV* brings an equal percentage increase in the *EVEI* of the *EV*. In certain regions, such fuel economy improvements can make the *GV* emissions comparable to those of an *EV*, thereby rendering the claim that *EV*s are environmentally cleaner than *GV*s questionable. The insight is particularly valuable in light of the tightening corporate average fuel economy standards (CAFE Standards) that have to be met by the automobile manufacturers. In such scenarios, each percentage fuel economy improvement in the *GV* fleet has to be met by either by an improvement in the fuel economy of the *EV* or by a marginal decrease in emissions of the resource mix to ensure that the *EVEI* of the *EV* does not increase.

Furthermore, our results indicate that for a decrease in *EVEI* by 0.1, the electrification of a fleet of hundred thousand vehicles decreases the CO_2 emissions by 312.92 kg. Such a result can provide a meaningful means to evaluate the impacts of fleet electrification.

We also present the comparison of our results, with that given in the literature is in Fig. 3. With the exception of (Argonne GREET Model), the results presented in the paper concur with those of existing studies. The figures presented for EV/GV emissions in (Argonne GREET Model) are higher than ours as (Argonne GREET Model) considers the emissions associated with the manufacturing of vehicles as well, which are unaccounted in our paper.

Table 2
Impact of renewable penetration on the *EVEI* of Nissan Leaf.

% Renewables in resource mix	***EVEI***	**Decrease in emissions from base case of 100,000 Leafs (kg of CO_2)**
28.75 (base case)	0.257	–
33.33	0.241	4.79
50.00	0.180	23.97

Additionally, we study the impact of the deeper penetration of renewables in the resource mix on the *EVEI*. For illustration, we perform our studies for the state of *CA*. We assume that in the year 2010, the carbon intensity of electricity generation (GWh) can be attributed solely to the electricity generation from non-renewable resources. We keep the energy generated unchanged and increase the percentage of electricity generated from renewables. We then, decrease the γ_E of the electricity by a proportional amount. We realize that our results may suffer from a small loss in accuracy from these simplifications, however, the goal of our assumptions is to obtain valuable insights from the resulting approximation of *EVEI*s regarding the reductions in emissions that can be achieved from the vehicle fleet electrification accompanied by the transition to a cleaner generation mix. The results obtained are presented in Table 1.

We infer that while fuel economy improvements in both, *EV*s and *GV*s may decrease the *EVEI,* transition to cleaner resource mix may be a much stronger means to reduce emissions from electric vehicle fleet due to two reasons. One is that the marginal improvements in fuel economy become increasingly difficult to attain for both, *EV*s and *GV*s. The other reason is that fuel economy improvements in newer model(s) may reduce emissions in a fraction of the fleet comprising of that(-ose) model(s), while the transition to a renewable-intensive resource mix will decrease the emissions from the entire electrified fleet of vehicle in that area.

Since the wall-to-wheel efficiency can vary with climate, we evaluate the effect of parameter uncertainty on the *EVEI* using a sensitivity analysis. The sensitivity of the *EVEI* with respect to wall-to-wheel efficiency can be analytically expressed as:

$$\frac{d\phi}{d\eta_w} = -\frac{\phi}{\eta_w^2} \tag{7}$$

In our work, we evaluate the sensitivity for a wall-to-wheel efficiency of 0.95 and with a value of *EVEI* equal to 1.017 – the maximum *EVEI* obtained across *US*. As such, a change in wall-to-wheel efficiency of 0.05 can affect the *EVEI* by a maximum of 0.055.

The sensitivity of the EVEI with respect to the upstream emissions factor *k* is also of interest as in the event of a change in manufacturing and/or transportation process(es) of gasoline may increase/decrease the total emissions associated with it. The sensitivity of EVEI w.r.t *k* is given by (8)

$$\frac{d\phi}{dk} = -\frac{\phi}{k^2} \tag{8}$$

From (8), we infer that for a value of EVEI equal to 1.017, the effect of a 0.01 decrease in k from1.25 to 1.24, is to increase the EVEI by 0.007, which is about 21.9 kg of increase in CO_2 emissions from a fleet of 100,000 vehicles.

Through such a sensitivity analysis, the impacts of climate and battery degradation on the *EVEI* can be quantified.

5. Conclusion and policy implications

The perception of environmental cleanliness of *EV*s is associated with their zero tailpipe emissions and consequently, does not provide a true picture of the actual environmental impacts. The paper proposes an innovative metric that is the first that challenges the notion that all *EV*s are equally clean by the computation of the emissions associated with the fuel pathway of electricity and gasoline. The metric explicitly considers the emissions associated with the generation of electricity, *T/D* losses and wall-to-wheel losses and computes the true environmental impacts of *EV*s *i*n the area they are adopted. Furthermore, our metric provides transparency in the assessment of environmental cleanliness of *EV*s and provides a meaningful basis for the comparison of different *EV*s.

The current policies and incentives regard all *EV*s as equally clean and as such may not be appropriately formulated. The *EVEI* may be particularly useful in the re-design of policies and incentives to reflect the actual environmental impacts of *EV*s. Furthermore, the EVEI indicates the *EV* environmental impacts in an area of usage, and as such, also helps policy makers in the design of policies on an area-specific basis (Table 2).

The illustrative results of the *EVEI* evaluation of Nissan Lean across the different states of *US* show that if the resource mix is fossil intensive, the Leaf may emit higher emissions than a conventional *GV*. These results are still optimistic, as they do not take into account the emissions associated with the manufacturing and disposal of EVs, which may be up to 40% higher than GVs (Kim et al., 2016). Thus, the notion of environmental cleanliness of EVs may completely fail in such scenarios. However, as the *RPS* achieves deeper penetrations, it significantly decreases the *EVEI* of all *EV*s in the area of usage. Thus, to meet the objective of reduction of *GHG* emissions, a symbiosis of vehicle fleet electrification and the transition to a cleaner generation mix is required.

As evident in the results, the fuel economy of the *EV* is a major contributor to *EV* emissions in the transportation sector. As such, *EV* manufacturers must place an increased emphasis in the improvement of fuel economy along with the range of *EV*s as well.

To this end, our work can be highly useful in policy formulation and analysis discussions to environmentalists, policy makers and *EV* owners. The work may be extended to account for emissions produced in the manufacturing, use and disposal of both, *EV*s and *GV*s. Furthermore, as the growth of *HEV*s and *PHEV*s may be the first most realistic implementation of battery vehicles comes to market, the work may be extended to include such mix fueled – electricity and gas fueled vehicles.

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