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Thermodynamics, Heat Transfer, and Renewable Charging of Electric Vehicles

Efstathios E. (Stathis) Michaelides*

Department of Engineering, TCU, Fort Worth, Texas, USA
E.Michaelides@tcu.edu

Abstract

When all vehicles, including electric vehicles, complete a round trip and their tank or battery is charged to its initial state, the vehicles execute a thermodynamic cycle. This article uses a thermodynamic analysis to examine several characteristics and salient features of the energy consumed by electric vehicles. The computations on the convective heat transfer show that heat supply during cold days significantly affects the range of the vehicles and that the utilization of heat pumps with high coefficients of performance is of paramount importance in cold climates. The carbon dioxide emissions associated with the use of electric vehicles depend on how electricity is generated, and carbon dioxide emissions may increase, if the fuel mix of the electricity grid uses a high fraction of coal. The calculations also show that charging the vehicles during the working daytime hours entails large areas of photovoltaic panels, which are not available in typical metropolitan area garages. Also, that the fast-charging of large fleets of electric vehicles will cause spikes on the demand of electrical grids and demand-supply mismatches.

Keywords: electric vehicles; battery charging; electrcity grids; renewable charging; heat pumps; energy storage.

1. Introduction

The first electric vehicle (EV) was built in 1839 by sir William Grove who used a fuel cell to power a small tractor. However, the invention of the internal combustion (IC) engine delayed the widespread use of EVs for almost two centuries. Environmental concerns with CO_2 emissions in the 21st century in combination with new battery

* Corresponding author. Tel.: +1-817-257-6226; fax: +1-817-257-6226.
E-mail address: E.Michaelides@tcu.edu

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technologies and governmental incentives have ushered a new era for electric battery-powered vehicles. In parallel a network of publicly available EV charging stations is rapidly constructed in most countries: while in 2008 there were only 47 charging stations according to the Global EV Outlook (2019), the Globe News Wire (2022) estimates that in November 2022 this number mushroomed to more than 2.3 million, and is expected to reach 16.3 million by 2028.

The popular press has added to the acceptance of the EVs by portraying them as vehicles to alleviate the global dependence on fossil fuels; to halt the greenhouse gas (GHG) emissions; to reduce the energy used in transportation; and to usher the global sustainable development era. Among the scientific studies on the energy use of EVs Alves *et al.* (2016) presented a methodology to estimate the energy use in EVs, based on data measured with an on-board portable laboratory, and to establish needed benchmarks for the performance of EVs that are free of untested commercial hyperbolae. Wang *et al.* (2019) examined the effects of EVs on the use of electricity and the electric power grids and concluded that, if the EV charging is optimized to avoid fossil fuels, their proliferation will significantly benefit the capacity ratio of power plants and will even reduce the cost of fossil fuels. The pollution reduction benefits of EVs in urban settings were examined by van Wee (2012) while the ecological benefits of EVs were examined by Racz *et al.* (2015). Among other pertinent studies, the thermal management of EVs (heating and cooling) was the subject of a recent study by Iora *et al.* (2019) who suggested the adoption of *Tesla turbines*[*] replacing the expansion valve. The turbine recovers part of the exergy lost by the working fluid during the isenthalpic expansion process. Michaelides (2020) also examined the energy usage and cabin comfort of EVs using a heat transfer model.

This paper aims at a holistic analysis of the EV energy usage from a thermodynamics point of view. The rate of dissipation for EVs is calculated using an exergy analysis, which yields the minimum mechanical energy required for the operation of vehicles. The well-to-wheels efficiency of EVs is introduced as the figure of merit of EV efficiency, which is comparable to that of IC vehicles. The solar energy resources needed to charge the EVs are calculated for several cities. The paper also provides calculations and results for the effects of charging a large EV fleet by an electricity grid and the possible use of the batteries of an EV fleet for utility-level energy storage. Calculations are also presented for CO_2 avoidance in several countries.

Nomenclature

A	Area
C_D	Coefficient of aerodynamic friction
C_R	Friction coefficient
F	Force
g	Gravitational acceleration
h	Heat transfer coefficient (inside and outside)
k	Conductivity
m	Mass
Q	Heat ($\dot{Q}$ is power)
T	Temperature
V	Velocity
W	Work ($\dot{W}$ is power)
Δx	Thickness (glass, metal, composite, etc.)
ρ	Air density
Subscripts	
F	Total Friction
R	Ground Friction
D	Aerodynamic Drag

[*] A centripetal flow turbine without blades that was patented by Nikola Tesla in 1913. The patent has expired and the design of this turbine is now in the public domain.

2. Power Requirement for Road Transport

A vehicle in motion needs power to overcome the effect of two types of dissipative forces, friction with the ground and friction with the surrounding air (aerodynamic drag). In addition, it needs power to accelerate and to climb road gradients. The last two types of power are spent to elevate the vehicle in conservative energy (kinetic and potential) fields and are, in principle, recoverable. The two dissipative forces are given by the equation:

$$F_F = F_R + F_D = C_R mg + \frac{1}{2} C_D \rho A V^2 \ , \tag{1}$$

where the first term represents ground friction and the second term is the aerodynamic force. Consequently, the power required for the two irreversible fields when the vehicle cruises with velocity V is (Michaelides, 2020):

$$\dot{W} = V\left(C_R mg + \frac{1}{2} C_D \rho A V^2 \right) . \tag{2}$$

It is this power that is dissipated during the cruising of a vehicle and cannot be recovered. It is also the minimum power that needs to be continuously supplied by the battery.

3. Heating and Air-Conditioning

Other power expenditures for all vehicles are: a) the power for instruments, lights, and other equipment, such as air-circulation fans, which are typically very low and b) power for heating and air-conditioning, which can be very high depending on the temperature and the vehicle speed. While heating is readily provided by the exhaust gases in IC-engine vehicles, in EVs the power for both heating and air-conditioning must come from the battery. The most efficient method to supply the needed heat for the cabin is with the use of a heat pump, which doubles as air-conditioner in the summer. Hence, the minimum rate of the necessary power for the operation of the EV, that cruises with velocity V is:

$$\dot{E} = V\left(C_R mg + \frac{1}{2} C_D \rho A V^2 \right) + \dot{W}_{eq} + \frac{\dot{Q}}{\beta} \ , \tag{3}$$

When the ambient temperature is low, the rate of heat transfer and the additional power required for the heating of the vehicle are significant. The absolute value of the rate of heat that enters or leaves any segment of the vehicle may be calculated from the following equation (Incropera and DeWitt, 2002):

$$\dot{Q}_i = UA_i \left| T_{in} - T_0 \right| \tag{4}$$

where A_i is the area of the i^{th} segment of the vehicle (glass, composite, metal, etc.); T_{in} is the desired cabin temperature T_0 is the ambient temperature; and the overall heat transfer coefficient, U, is given by an expression of the form:

$$\frac{1}{U} = \frac{1}{h_{in}} + \frac{\Delta x}{k} + \frac{1}{h_{out}} \ , \tag{5}$$

The convective heat transfer coefficients, h_{in} and h_{out} are functions of the velocity V. The total rate of heat that enters or leaves the EV is obtained by summing the rate of heat over all the segments of the vehicle, which are exposed to the ambient air.

Calculations were performed for the power requirements of a typical sedan-style EV when the difference between the interior cabin and the ambient is 0, 20 K and 50 K (the latter applies to very cold days, e.g. when the outside temperature is -25 ºC and the cabin temperature is maintained at 25 ºC) and when the coefficient of performance of the heat pump is $\beta=3$. The results are shown in Figure 1, where one may see that during extreme weather conditions the EV requires significantly higher power – 25% higher at a cruising speed of 100 km/hr.

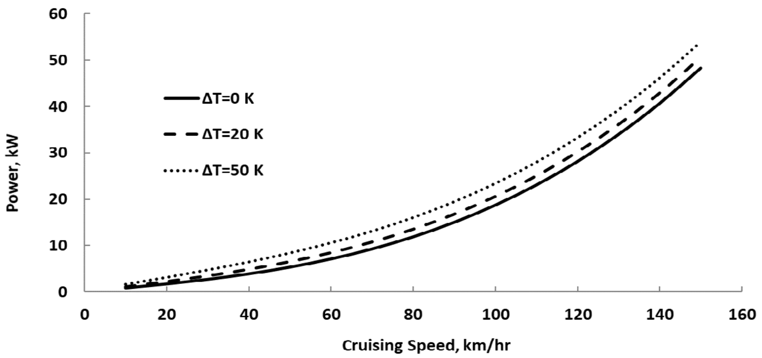

Figure 1. Effect of cruising speed and temperature on the power requirements of an EV

Given the higher power requirements, the importance of an efficient heat pump to maintain a comfortable cabin temperature and vehicle range (mileage) becomes apparent. Figure 2 depicts the power requirements of an EV when no heating is needed ($Q=0$) as well as when heat is supplied by resistance heating ($\beta=1$) and by a heat pump with coefficient of performance $\beta=2$ or $\beta=4$.

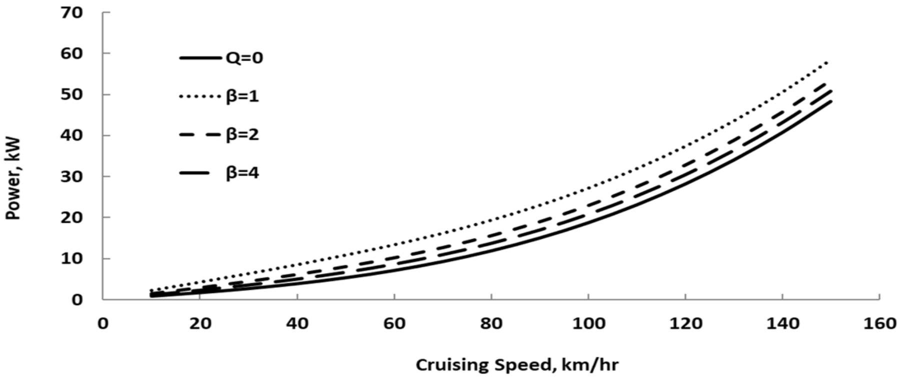

Figure 2. The importance of an efficient heat pump in a cruising EV.

4. Charging with Renewable Energy

In the United Nations document *Our Common Future* (2020) and several reports by the Intergovernmental Panel on Climate Change (Pachauri and Meyer, 2014) it is strongly recommended that CO_2 emissions from the electricity generation sector be reduced by 90% or more from the 2010 levels. Several planners envision that, in a future where EVs are the most common vehicles, it will be possible to equip the vehicles or the garages with solar panels (wind is intermittent and not reliable for commuter vehicle charging) to charge the EV batteries. Table 2 shows the results of computations on the needed surface area of photovoltaics that might supply with 25 kWh electricity the batteries of a single EV as well as of 800 EVs (typical of a medium-size garage) when they are left for nine hours (8:00 am to 5:00 pm) in four metropolitan areas of the USA – New York, Boston, Kansas City, and Miami.

Data for the solar irradiance in the computations of Table 1 have been obtained from the NREL's National Solar Radiation Data Base (Wilcox, 2012). In order to avoid the weather-related fluctuations of irradiance, ten-day averages (in January for winter and July for summer) were used. The PV panels are stationary facing south at the optimum angle for each location (Michaelides, 2018). The rated efficiency of the commercial PV panels is 20% and the battery charging efficiency is 88%. It is apparent in Table 1 that the surface area of a single vehicle is insufficient to generate daily 25 kWh using roof-embedded PV cells. Multilevel garages in cities, where thousands of vehicles are parked, also do not have sufficient roof and side areas to charge all the EVs. If the EVs are to be charged by solar energy, the electricity must be generated in solar farms outside the urban areas, where land may be plentiful and cheaper.

Table 1. PV area required for the charging of EVs by 25 kWh in several US cities.

City	Power, per m^2, kW	PV area for one EV, m^2	PV area for 800 EVs, m^2
Boston, winter	0.52	56.6	45,249
Boston, summer	0.92	32.0	25,575
Kansas City, winter	0.60	49.0	39,216
Kansas City, summer	1.14	25.8	20,640
Miami, winter	1.08	27.2	21,786
Miami, summer	1.20	24.5	19,608
New York, winter	0.60	49.0	39,216
New York, summer	0.94	31.3	25,031

5. Carbon Dioxide Avoidance

Two of the principal enticements for the higher market penetration of EVs is the perception of zero pollutant emissions, and the associated subsidies of the vehicles. While it is correct that the actual vehicles do not emit any pollution, the electricity generation that supplies the motive power for EVs is laden with significant pollutant production. Fossil fuel combustion (and the associated CO_2 emissions) is still the predominant primary energy source for electricity generation: 38.4% of the global electricity was generated by coal, 23.7% by natural gas, and 4.8% by liquid hydrocarbons and waste (United Nations, 2022). It becomes apparent that the primary energy source used for the generation of electricity determines whether or not the substitution of IC-powered cars with EVs results in any environmental benefits. If the electricity supplied to EVs is generated by non-carbon energy sources – nuclear, hydroelectric, solar, wind and biomass – there is CO_2 avoidance by switching to EVs. On the other hand, if a high fraction of the electricity is supplied by fossil fuels (especially coal and heavy liquid fuels) the substitution of IC-powered vehicles with EVs entails little CO_2 avoidance – and in some cases a net increase of CO_2 emissions.

A holistic method for the determination of the environmental impact of engineering systems is the Life Cycle Assessment (LCA). According to this method, the pollutants associated with the manufacture, operation (during its useful life) and disposal of the systems are determined (Meyer et al, 2015, Michaelides, 2021). In the case of EVs, which consume a great deal of energy and are expected to operate for ten years or more, the LCA of CO_2 emissions is close to the emissions of the power units that generate the needed electricity for their operation plus the LCA emissions associated with the manufacture of their components, in particular of the battery.

Calculations were performed for the CO_2 emissions avoidance resulting from the substitution of IC-engine vehicles with EVs in countries that generate electricity by a different mix of primary energy sources, using the concept of well-to-wheels efficiency. The latter accounts for the energy dissipation in the entire chain of processes, from the primary energy source to the vehicle powertrain (Ramachandran and Stiming, 2015; Michaelides, 2018). Results of the calculations for several countries are depicted in Table 2. The first five columns of Table 2 show the country and the fraction of electric energy generated by coal, natural gas, petroleum, and non-carbon sources – primarily nuclear, hydroelectric, and other renewables (Enerdata, 2022; United Nations, 2022). Biofuels, which utilize CO_2 from the atmosphere and wastes are included in the non-carbon emitting sources (they are carbon-neutral). The low heating value (LHV) of gasoline was used in the calculations for the IC-powered vehicles because the vehicles do not utilize the latent heat of water vapor in their exhausts (Fuels 2020). Also, since a fraction of the modern gas turbines that operate with natural gas and petroleum increasingly use combined cycles with preheaters, the average of the low- and high- heating values (HHV) was used for the natural gas and liquid hydrocarbons (petroleum) consumed for the generation of electricity (Fuels 2020). The sixth column of Table 2 depicts the CO_2 avoidance under the current electricity generation mix, when IC-powered vehicles are substituted with EVs. The last column in Table 2 indicates the CO_2 avoidance when the well-to-wheels efficiencies associated with EVs improve by a factor 1.2. This efficiency improvement is expected to be caused by the following trends in the manufacturing of EVs and electricity generation:

1. Lower vehicle weight.
2. More efficient battery charging and discharging.
3. On the electricity generation side, thermal cycle efficiency improvements – e.g. with the further dissemination of combined cycle units.
4. Further decarbonization of the electricity generation sector.

Table 2. Electricity generation and CO_2 avoidance for several countries. Negative values in the last two columns signify CO_2 emission increases.

Country	Coal	Natural Gas	Petroleum	Non-carbon	CO_2 avoidance, %	Avoid. at 20% improvement
Australia	0.6271	0.196	0.0204	0.1565	-17.32	2.28
Brazil	0.045	0.098	0.026	0.831	81.97	84.98
Canada	0.091	0.087	0.011	0.811	77.26	81.05
Estonia	0.836	0.005	0.009	0.15	-33.20	-10.95
European Union	0.226	0.188	0.018	0.568	46.85	55.72
France	0.026	0.072	0.013	0.889	88.53	90.45
Germany	0.372	0.131	0.008	0.489	29.63	41.38
India	0.748	0.048	0.016	0.188	-23.64	-2.99
Japan	0.329	0.373	0.0654	0.2326	10.15	25.16
Norway	0.00127	0.017	0	0.98173	98.39	98.66
P.R. China	0.682	0.027	0.034	0.257	-13.44	5.50
Russian Fed.	0.157	0.478	0.01	0.355	34.57	45.49
South Korea	0.451	0.222	0.02	0.307	8.34	23.65
UK	0.0689	0.404	0.005	0.5221	55.13	62.62
USA	0.308	0.312	0.008	0.372	24.73	37.30
World Average	0.384	0.232	0.037	0.347	16.24	30.22

It is observed in Table 2 that the IC with EV substitution reduces (on the average) the CO_2 global emissions by 16.24% and the improvement may reach 30% with significant well-to-wheels efficiency improvements on the EV side. This effect is local and depends on the primary energy sources used for electricity generation. Countries, such as Norway, Brazil and Canada that generate a high fraction of their electricity with renewables as well as countries, such as France and the UK that use a high fraction of nuclear energy, achieve high CO_2 avoidances. On the contrary, in countries such as P.R. China, India and Australia, which primarily use coal for electricity generation, substituting IC-engine vehicles with EVs results in an increase of CO_2 emissions. It is also observed in Table 2 that the CO_2 avoidance will improve as the well-to-wheels efficiency of EVs improves and as the decarbonization of the electricity sector progresses, a trend that is apparent in the so-called *TRIZ -based guidelines,*(Russo and Spreafico, 2020).

6. Effect on Grid Capacity and Stability

The global transportation sector consumed 98.3 HJ (excluding bunker oils) in 2019 of which approximately 60% (59.0 HJ) was consumed by IC-powered cars, small trucks, vans, sport utility vehicles, and motorcycles (United Nations, 2022). If all these vehicles were to be substituted by EVs, there would be an additional need for 4,680 TWh/year electric energy generation globally. This quantity of electricity may be generated by the spare capacity of the electricity generation units during hours of low consumer demand, which usually occurs at nighttime. For example, in the USA, the transportation sector consumed 28.4 HJ in 2022, with 15.4 HJ going to the light road vehicles that can be electrified (US-DOE, 2023). Assuming that all these eligible road vehicles are converted to EVs with equivalent well-to-wheel efficiency, the all-electric fleet in the USA would require an additional 1,126 TWh annually. This quantity of electricity could have been easily generated by the spare capacity of the USA electricity grids during periods of lower electricity demand (e.g. during the nighttime).

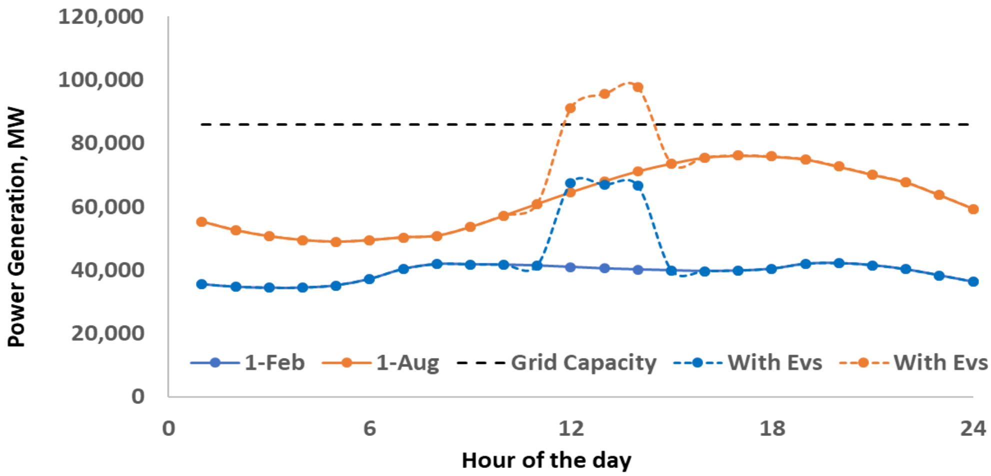

Figure 3. The effect of EV charging in the ERCOT grid between noon and 2:00 pm on two days of the year.

The electricity grids of most countries are capable of supporting the charging process of large fleets of EVs during the nighttime, when demand is typically low. Significant problems are foreseen if large EV fleets are charged during peak demand hours and, especially, if charging takes place during short periods of time. It is often taught in the popular press that EVs on long trips may be charged in stations along the highways, while the owners have a meal. This notion was tested with reference to the ERCOT grid, which supplies with electricity 92% of the population in Texas (approximately 26 million people). The area has approximately 21 million vehicles that may be converted to EVs. Let us assume that 5% of these vehicles (1.05 million vehicles) are on trips longer than their ranges and their drivers stop at lunch time (between noon and 2:00 pm) to charge each one with 40 kWh energy and the charging efficiency is 80% (this includes the transmission-transformer-inverter efficiencies). Calculations show that the grid will need to generate at least 26.25 GW of power between noon and 2:00 pm in addition to the usual electricity demand. This would represent a spike on the demand side that will be difficult for the grid to always meet. Figure 3 shows the demand on the ERCOT grid on two days of the year – the 1st of February, which is typical of days with no air-conditioning need and the 1st of August, which is typical of days with significant air-conditioning need (ERCOT, 2023). Figure 3 shows that the charging of EVs may be accommodated in the late fall, winter and early spring days. However, the grid will not be able to meet the additional demand for the fast charging of EVs during the high afternoon demand days, which abound in the months of May through early October. A careful look at the 2022 electricity demand data shows that the demand would have exceeded the dispatchable capacity of the ERCOT grid for 138 days of the year if 5% of the vehicles in the region served by the grid were to be charged with 40 kWh between noon and 2:00 pm. It is apparent that additional power and the associated infrastructure needs to be developed, before the daytime fast-charging of EVs becomes feasible. Additional research and development efforts in the area of EV fast-charging may address this problem of supply-demand mismatch, which threatens the stability and reliability of grids (ten Have *et al.*, 2020, Mandrile *et al.*, 2021).

7. Conclusions

Using a thermodynamic analysis, this paper determines the power needs of EVs when they are cruising and determines the heat transfer to and from the cabin. During very cold periods of time, the battery needs to supply substantial power to maintain a comfortable cabin temperature for the driver and this cuts into the mileage/range of the vehicles. It is important for vehicles in colder regions to be equipped with heating/cooling systems with high coefficients of performance. Calculations were performed for the charging of EVs during the daytime for four metropolitan areas at different geographic latitudes. It was determined that, while the charging of the vehicles can be achieved during the typical working hours, significant power is needed, and this cannot be simply provided by placing photovoltaics on the roof of in-city garages. Solar farms will be needed for this purpose, outside the large metropolitan areas. Regarding the CO_2 emissions avoidance, the study of the electricity generation mix in several countries shows that the substitution of IC engines with EVs only has beneficial impact on CO_2 avoidance in countries where a high fraction of electricity is generated by renewables or nuclear. For grid stability and avoidance of electric power demand-supply mismatch, it is best to slowly charge the EVs during the nighttime, when electricity demand is low. The computations with the actual demand in the ERCOT electricity grid show that fast-charging during the early afternoon hours will result in significant demand spikes that affect the stability of the grid in its current capacity.

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