Analysis of Carbon Saving by the Adoption of Electric Vehicles in a Region Where Electricity Generation is Dominated by Thermal Power Plants

Parakram Pyakurel, Filipe Quintal*, James Auger and Julian Hanna

Madeira Interactive Technologies Institute, Funchal, Portugal
E-mail: filipe.quintal@m-iti.org
**Corresponding Author*

Received 25 February 2021; Accepted 25 February 2021;
Publication 30 March 2021

Abstract

One method of reducing atmospheric CO_2 emissions in the transportation sector is the replacement of conventional fossil fuel-based vehicles with Electric Vehicles (EVs). However, fossil fuels are still the primary source of electricity production in many regions and the utilization of EVs in such regions increases the electricity demand because of battery charging. This results in increased burning of fossil fuels by thermal power plants and therefore can offset savings in CO_2 emissions resulting from the adoption of EVs. In this paper, we consider a scenario where all fossil fuel-based conventional vehicles are replaced by EVs and then estimate the net CO_2 emission savings resulting from the adoption of EVs in a region where electricity is primarily supplied by thermal plants. Only emissions generated during the operational phase of vehicle use are considered; emissions during the production phase are not considered. The region under consideration is

Strategic Planning for Energy and the Environment, Vol. 39_1–4, 117–130.
doi: 10.13052/spee1048-4236.39146

Madeira, Portugal where thermal plants account for 80% of the total electricity produced. Our findings suggest that although EVs have huge potential to save CO_2 emissions, a substantial amount of the savings can be offset due to the increased burning of fossil fuels by thermal plants to meet the electrical demand of charging batteries.

Keywords: CO_2 emission, electric vehicles, renewable energy penetration, battery charging.

1 Introduction

Electric vehicles (EVs) have the potential to substantially reduce greenhouse gas emissions in the transportation sector [1] as these vehicles typically produce lower tailpipe emissions than conventional vehicles [2]. However, although the battery-powered electric car itself may not emit greenhouse gases, power plants that generate the electricity used to charge the batteries generally do [3]. As examples, the share of renewable energy in electricity production was 34.2% in Europe and 27.7% in North America in 2015 [4]. Therefore, EVs will indirectly contribute a certain amount of CO_2 emissions as long as the electricity grid is powered by fossil fuels. In order to estimate CO_2 emissions caused throughout the product cycle of EVs and other vehicles, several Life Cycle Assessments have been carried out [5–8].

The exact amount of CO_2 emissions indirectly caused by EVs depends upon various factors such as regional variability in electricity generation mix and battery charging time of EVs [5]. For instance, a study [6] in China has shown that CO_2 emissions from the production of EVs are about 59%–60% higher than from conventional fossil fuel-based cars with internal combustion engines. Even when entire life cycle assessments of electric, hybrid, plug-in and conventional fossil fuel vehicles were carried out for the U.S. [7], EVs were not ranked as the best vehicle option in any of the U.S. states under a state-based marginal electricity generation mix scenario. This scenario considered the generation mix of the incremental electricity demand (the marginal electricity) from EVs and plug-in hybrid electric vehicles for every U.S. state, since the greenhouse gas emission intensity of electricity generation is highly dependent on the energy source [7] and each state may have different source. Therefore, more studies are required to understand the CO_2 emission characteristics of EVs and devise policies that make optimal use of EVs to reduce emissions in the transportation sector.

In this paper, we compare CO_2 emissions from EVs and conventional fossil fuel-based vehicles during the use/operational phase. Other emissions from conventional fossil fuel vehicles that may indirectly or directly contribute to climate change are not taken into account. A scenario where all conventional fossil fuel-based vehicles are replaced by EVs is considered, and the net CO_2 emissions savings under such a scenario are estimated. The geographical region under consideration is Madeira, Portugal where thermal plants account for 80% of the total electricity produced [9]. The main objective of this study is to better understand the amount of CO_2 emissions that can be offset by the replacement of conventional vehicles with EVs in a case where thermal power plants are the predominant means of electricity production. Sensitivity of percentage share of renewable energy penetration on emission offset is examined and a planning approach to schedule the charging of EVs is presented.

2 Madeira Electrification and Transportation Status

Madeira is a Portuguese archipelago situated in the North Atlantic, southwest of Portugal. In this study we only consider the main island of the archipelago. The power plants on Madeira Island consist of thermal, hydro, solar PV and wind energy systems. In 2016, the share of renewable energy in the electricity grid was about 20% [9] and hence the electricity is predominantly supplied by thermal plants.

Gasoline (petrol) and diesel consumption by the road transportation sector in Madeira are 32,002 Tonnes of Oil Equivalent (TOE) and 73,898 TOE respectively [10]. Privately owned cars are the main mode of transportation in Madeira and here we assume that all gasoline consumption is due to conventional cars and taxis. There is also a small number of scooters and motorcycles that have a small percentage share in the total gasoline consumption but here we ignore these factors due to the lack of data availability on percentage share of gasoline consumption among different modes of transportation. Since the fuel economy of small cars is different from scooters or motorcycles, a margin of error is associated with our calculation, but this can be rectified if all the required data are available. The calculation approach utilized in this paper is generally valid; however, data unavailability may have some minor impact on the precise accuracy of the obtained results.

Diesel consumption is assumed to be shared by conventional private diesel cars, vans and public buses. The corresponding share of consumption of these conventional vehicles is assumed to be 45%, 40% and 15% respectively. There is no reliable data available on the exact percentage shares, so the above values are only educated guesses based on observations and opinions of local people.

3 Reference Conventional and Electric Vehicles

The conventional gasoline (petrol) car we have taken as a reference for the present study is a Renault Clio 0.9 L Limited TCe, which was the best selling car in Portugal in 2016 [11]. This car has a seating capacity of 5 people and can travel a distance of roughly 23.8 km/liter of gasoline [12]. Likewise, the conventional diesel car taken as a reference in this study is a Clio Energy dCi 90 Zen. This car also has a seating capacity of 5 people and has a fuel economy of 31.25 km/liter of diesel [13].

The conventional van used for reference is a Nissan NV200 EVALIA [14] with fuel economy of 20.41 km/liter. For the bus, the fuel economy used here is 1.57 km/liter as this is the average value of the largest local bus company in Madeira [15]. It is worthwhile to note that the system of testing cars to measure fuel economy in Europe has recently been somewhat discredited [16]. Nonetheless we are using the fuel economy values obtained from this testing system as a reference. If other realistic values are available in the future, the existing values can be substituted with realistic values in the methodology presented in this paper without the loss of general validity.

The electric car we use as a reference here is a Renault Zoe 40 (with a 41 kWh battery pack) [17]. This car can travel a distance of about 300 km when fully charged [17] before it is fully discharged. Likewise, the electric van we use for reference is a Nissan e-NV200 VAN [18] which can travel up to a distance of 280 km [18] from a fully charged state. The battery capacity is 40 kWh [18]. Similarly, the electric bus used as a reference is an e.City Gold CetanoBus [19] which can travel up to a distance of 200 km when fully charged and has a battery capacity of 150 kWh [19].

4 Estimation of CO_2 Emission Savings

In this section, the net CO_2 emission savings is calculated for a scenario where all existing fossil fuel vehicles are replaced by EVs. Expressions to calculate the additional electrical energy required to charge EVs that will replace conventional vehicles are presented. The expression to calculate net emission savings is also presented.

The fuel economy of a gasoline car is represented by $F_{g,c}$. The fuel economies of a diesel car, a diesel van and a diesel bus are represented by $F_{d,c}$, $F_{d,v}$ and $F_{d,b}$ respectively. All units of fuel economies for gasoline and diesel vehicles are km/liter. Likewise, the fuel economies of electric cars, electric vans and electric buses are represented by $F_{e,c}$, $F_{e,v}$ and $F_{e,b}$ respectively, where all the units are in km/kWh. Also, let E_g and E_d be the additional electrical energy in GWh required to be produced by the power plants to charge the EVs that replace gasoline and diesel vehicles respectively. The TOE of gasoline and diesel consumed are represented by T_g and T_d respectively. The total distances covered by electric vehicles have to be equal to their fossil fuel vehicles' counterparts to ensure full replacement of conventional vehicles by electric vehicles.

One ton of gasoline is taken as equivalent to 1.05 TOE of gasoline [20] and the density of gasoline is considered to be 0.75 kg/liter [21]. Likewise, one ton of diesel fuel is taken to be 1.01 tons of diesel [20] and the density of diesel is taken as 0.85 kg/liter [22]. For gasoline cars:

$$\begin{aligned}
&\text{total distance covered by gasoline cars}\\
&\quad = \text{total distance covered by electric cars},\\
&\quad \Rightarrow \frac{F_{g,c} \times T_g}{\text{gasoline density } \times \text{TOE per ton of gasoline } \times\ 10^6} = F_{e,c} \times E_g,\\
&\quad \Rightarrow E_g = \frac{F_{g,c} \times T_g}{F_{e,c} \times\ 787500}. \qquad (1)
\end{aligned}$$

Similarly, for diesel vehicles:

$$\Rightarrow \frac{F_{d,i} \times T_g}{\text{disel density } \times \text{TOE per ton of diesel } \times 10^6} = F_{e,i} \times E_d,$$

where the subscript i can represent car (c), van (v) or bus (b),

$$\Rightarrow E_d = \frac{F_{d,i} \times T_d}{F_{e,i} \times 858500}. \qquad (2)$$

Let p be the renewable energy penetration in the electricity grid in fraction. We assume that the share of renewable energy in supplying the additional demand caused by EVs charging shall be the same as the existing share of renewable energy penetration, i.e., 20%. Also, let N_t be tons of CO_2 emission per GWh from thermal plants, N_g be tons of CO_2 emission per TOE of gasoline and be N_d be tons of CO_2 emission per TOE of diesel. The net emission saving by the adoption of electric vehicles can be calculated as:

$$\text{Net saving} = N_g \times T_g + N_d \times T_d - N_t \times (1 - p) \times (E_g + E_g). \qquad (3)$$

4.1 Electrical Energy Required to Replace Gasoline Vehicles

The total gasoline consumption is assumed to be solely by reference conventional gasoline cars (see Section 3) as vans and buses are all diesel-based in Madeira. Therefore, in the scenario we are considering, the reference electric car shall replace every reference gasoline car.

Assuming battery charging efficiency of 89% [23], the energy required to charge 41 kWh battery of the reference electric car is approximately 45.55 kWh. This gives a fuel economy ($F_{e,c}$) of 6.59 km/kWh for the electric car. By substituting $F_{g,c} = 23.8$ km/ltr and $T_g = 32,002$ in Equation (1), the total electrical energy required to charge the electric cars that will replace gasoline fuel is found to be 146.52 GWh.

4.2 Electrical Energy Required to Replace Diesel Vehicles

An approach similar to the one carried out above for gasoline is utilized for diesel. The total diesel consumption is assumed to be shared among diesel cars, vans and buses with percentage share of 45%, 40% and 15% respectively. The total electrical energy required to charge EVs that shall replace diesel fuel is found to be 310.35 GWh.

4.3 Net Carbon Saving

The amount of CO2 emission per TOE of gasoline consumed is taken as 3.0 tons [24]. Likewise, the amount of CO2 emission per TOE of diesel consumed is taken as 3.2 tons [25]. Also, the amount of CO2 emission per GWh of energy generated is 622.37 tons/GWh for thermal power plants in Madeira [9]. By substituting $N_g = 3, N_d = 3.2, N_d = 73,898, T_d = 32,002, p = 0.20, E_g = 146.52$ GWh and $E_d = 310.35$ GWh in Equation (3), the net emission savings is found to be 106.55 kilo tons (kT). The total potential emission savings from EVs is 332.48 kT but there are additional emissions from fossil fuel-based power plants as more electricity has to be generated to charge EVs. If the renewable energy penetration in the electrical grid is assumed to remain 20% under the considered scenario where all conventional vehicles are replaced by EVs, the additional emission from power plants is 228.47 kT and thus the net savings is 104.01 kT. Therefore, the emission from power plants causes an offset of 68.72% of the potential savings that could be achieved from EVs.

5 Sensitivity Analysis of Renewable Energy Penetration

This section examines the effects that the renewable energy penetration in the electricity grid will have on the net CO_2 emission savings in a scenario where all conventional vehicles are replaced by EVs. The renewable energy penetration in the electrical grid is varied from 0% to 100% and the net CO_2 emission savings for different percentage shares of renewable energy penetration is calculated.

It can be seen in Figure 1 that the net CO_2 emission savings increases linearly with the increase in the percentage share of renewable energy in the electrical grid. Therefore, the higher the percentage share of renewable energy in the electrical grid, the higher also will be the potential of CO_2 emission savings by the adoption of EVs.

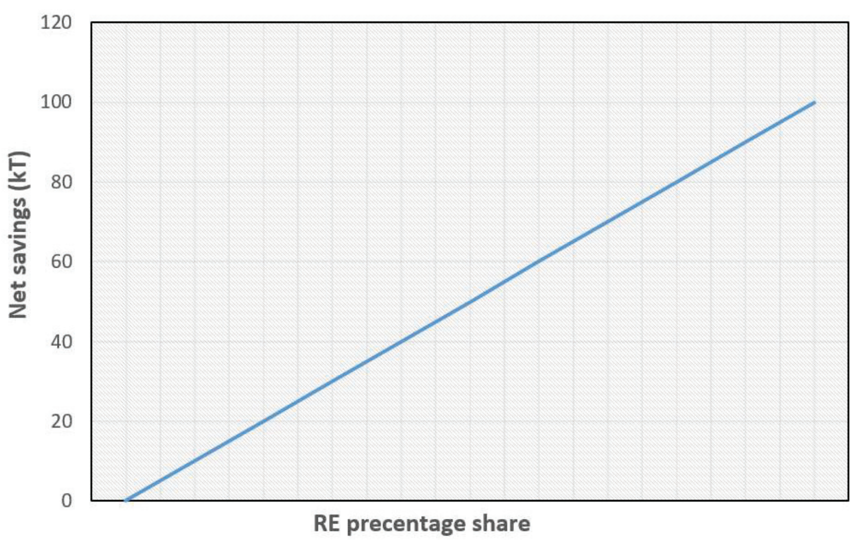


Figure 1 Relationship between Renewable Energy (RE) penetration and net CO_2 savings.

6 Approaches for Planning the Charging Schedule

It is noted that greater the percentage share of renewable energy penetration in the grid, the higher is the amount of CO_2 emission offset by the adoption of EVs. Therefore, charging EVs at the time of the day when renewable energy penetration is relatively high can help increase the amount of CO_2 emission offset. In this section, strategies to plan the charging schedules of EVs that result in relatively higher CO_2 emission offset are discussed based on dispatchability of renewable energy sources. Technical challenges that constrain the charging schedules are also discussed.

Average daily renewable energy penetration profile in the Madeira grid is shown in Figure 2 at the temporal resolution of 1 hour. It is noted that the penetration is relatively high during the period of 10:00 hours to 14:00

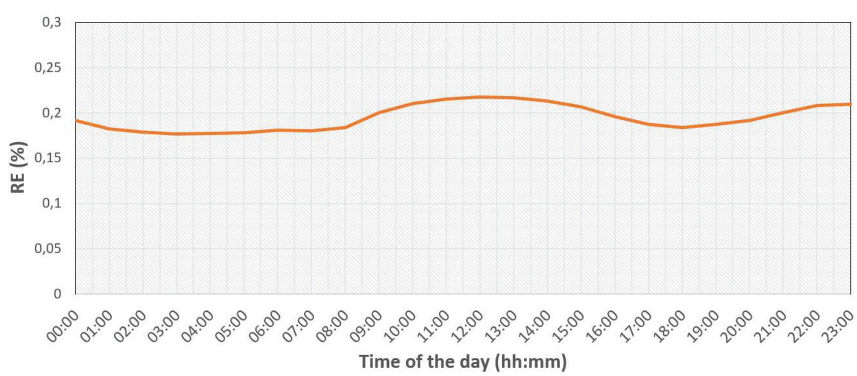


Figure 2 Average daily share of renewable energy in electricity grid.

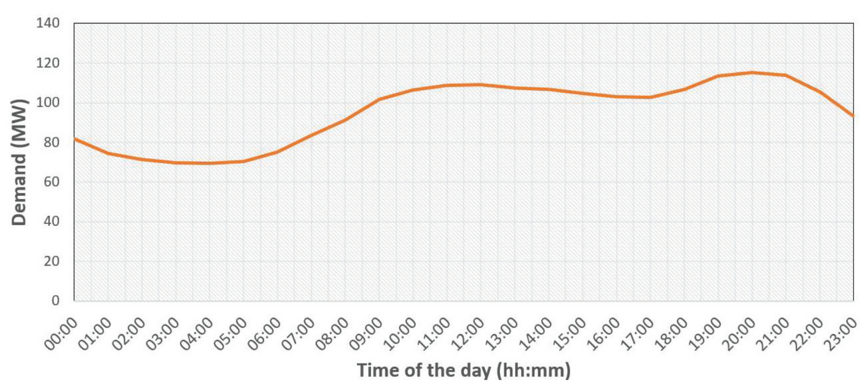


Figure 3 Average daily load consumption pattern of Madeira.

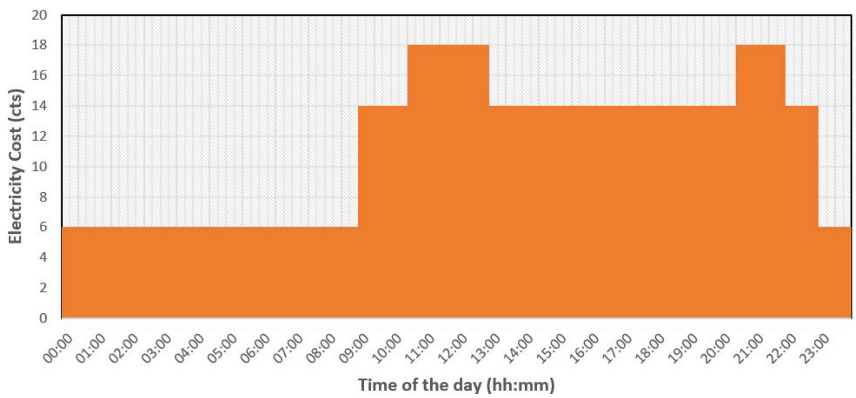


Figure 4 Daily electricity tariff structure of Madeira.

hours. The average penetration over this period is 21.46% whereas the average penetration over the remaining hours is 18.95%. We assume that the additional amount of renewable energy can be generated during the period of 10:00 hours to 16:00 hours so that the percentage share of renewable energy penetration remains the same as Figure 2 in a scenario where all EVs are charged during this period. The high renewable energy penetration during the period of 10:00 hours to 14:00 hours is due to electricity from solar PV systems; Madeira is sunny and the potential for electricity generation from PV is not yet saturated, therefore the assumption is reasonable. Theoretically, the annual savings of 7 kT (6.6% of the total) of CO_2 could be achieved if all the charging can be done during the period of 10:00 hours to 14:00 hours based on the sensitivity analysis (See Section 5) under the prevailing assumption. However, this leads to an increase in daily variability of power consumption, and in turn to an increase in variability of power generation from renewable energy sources. This variability of power generation from renewable energy systems such as solar PV can cause swinging of power factor value of the electrical grid as well as causing an imbalanced load [26]. Therefore, distributed PV systems that bypass the main electricity grid of Madeira designed only for EV charging purposes could be required in order to achieve charging of all EVs during the period of 10:00 hours to 14:00 hours.

In a situation where EVs are charged at private houses, the electricity for charging will be transmitted via the electrical grid, and in such cases the matching of demand and supply is important for load balancing. The average daily electricity consumption pattern of Madeira is shown in Figure 3 at the temporal resolution of 1 hour. From the perspective of smoothing out fluctuation in electricity consumption, the charging of EVs between 0:00 hours and 9:00 hours is ideal. This is also true from the perspective of economics and can be noted from the electricity tariff structure of Madeira (Figure 4). It is noted that the tariff is at a minimum when the electricity demand is minimum.

7 Conclusions

Potential CO_2 emission savings in the transportation sector during the operational phase of vehicles is estimated for a scenario where conventional fossil fuel vehicles are fully replaced by EVs. The geographical location under consideration is Madeira, Portugal where electricity is mainly supplied by the burning of fossil fuels. Although this study presents a case of Madeira as an example, the presented approach can be utilized for any other location without the loss of generality.

The relationship between renewable energy penetration in the electricity grid and potential CO_2 emission savings from EVs is examined. Furthermore, approaches to schedule the charging of EVs are presented. The results from this study can provide inputs for comparative life cycle assessments of conventional fossil fuel vehicles and EVs. In addition, the obtained results can provide information on scheduling the charging time of EVs.

Acknowledgements

We would like to thank the Fundação da Ciência e Tecnologia (grant number UID/EEA/50009/2013) and ENERMAC - Renewable Energy and Energy Efficiency for the Sustainable Development of Western Africa and Macaronesian islands, for funding this research.

References

[1] W. J. Smith, "Can EV (electric vehicles) address Ireland's CO_2 emissions from transport?," *Energy*, vol. 35, no. 12, pp. 4514–4521, Dec. 2010.

[2] "EERE: Alternative Fuels Data Center Home Page." [Online]. Available: https://www.afdc.energy.gov/. [Accessed: 02-Mar-2018].

[3] D. Biello and D. Biello, "Electric Cars Are Not Necessarily Clean," *Scientific American*. [Online]. Available: https://www.scientificamerican.com/article/electric-cars-are-not-necessarily-clean/. [Accessed: 02-Mar-2018].
[4] World Energy Council, "World Energy Resources 2016," 2016.
[5] M.-A. M. Tamayao, J. J. Michalek, C. Hendrickson, and I. M. L. Azevedo, "Regional Variability and Uncertainty of Electric Vehicle Life Cycle CO2 Emissions across the United States," *Environ. Sci. Technol.*, vol. 49, no. 14, pp. 8844–8855, Jul. 2015.
[6] Q. Qiao, F. Zhao, Z. Liu, S. Jiang, and H. Hao, "Comparative Study on Life Cycle CO_2 Emissions from the Production of Electric and Conventional Vehicles in China," *Energy Procedia*, vol. 105, pp. 3584–3595, May 2017.
[7] N. C. Onat, M. Kucukvar, and O. Tatari, "Conventional, hybrid, plug-in hybrid or electric vehicles? State-based comparative carbon and energy footprint analysis in the United States," *Appl. Energy*, vol. 150, pp. 36–49, Jul. 2015.
[8] H. Huo, H. Cai, Q. Zhang, F. Liu, and K. He, "Life-cycle assessment of greenhouse gas and air emissions of electric vehicles: A comparison between China and the U.S.," *Atmos. Environ.*, vol. 108, pp. 107–116, May 2015.
[9] Empresa da Electricidade da Madeira, "Relatório e Contas 2015."
[10] Direção Regional de Estatística da Madeira, "Energy Balance of the Autonomous Region of Madeira," 2018.
[11] "Os 10 carros mais vendidos em Portugal em 2016," *Razão Automóvel*, 12-Jan-2017. [Online]. Available: https://www.razaoautomovel.com/2017/01/os-10-carros-vendidos-portugal-2016. [Accessed: 02-Mar-2018].
[12] "Renault Clio TCe 90 Energy Life, Manual, 2016 - 2018, 90 Hp, 5 doors Technical Specifications," *Cars-Data.com*. [Online]. Available: http://www.cars-data.com/en/renault-clio-tce-90-energy-life-specs/78448. [Accessed: 24-Jan-2018].
[13] "Renault Clio DCi 90 Energy Zen, Manual, 2016–2018, 90 Hp, 5 doors Technical Specifications," *Cars-Data.com*. [Online]. Available: http://www.cars-data.com/en/renault-clio-dci-90-energy-zen-specs/78460. [Accessed: 24-Jan-2018].
[14] "Nissan NV200 EVALIA – Carros 7 lugares |Nissan." [Online]. Available: https://www.nissan.pt/veiculos/novos-veiculos/nv200-evalia.html. [Accessed: 21-Feb-2018].

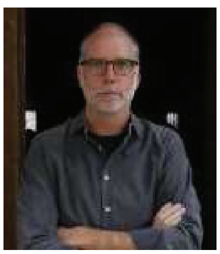
[15] Horarios Do Funchal, "Horarios Do Funchal - Relatório e Contas."
[16] "Mind the Gap 2015: Closing the chasm between test and real-world car CO2 emissions |Transport & Environment." [Online]. Available: https://www.transportenvironment.org/publications/mind-gap-2015-closing-chasm-between-test-and-real-world-car-co2-emissions. [Accessed: 02-Mar-2018].
[17] "2017 Renault ZOE: full prices, specs and battery details |Carbuyer." [Online]. Available: http://www.carbuyer.co.uk/news/154974/2017-renault-zoe-full-prices-specs-and-battery-details. [Accessed: 02-Mar-2018].
[18] "Nissan e-NV200 VAN - Veículo elétrico - Van," *Nissan*. [Online]. Available: https://www.nissan.pt/veiculos/novos-veiculos/e-nv200-van.html. [Accessed: 24-Jan-2018].
[19] "e.City Gold," *Caetanobus*, 11-Mar-2016. [Online]. Available: http://caetanobus.pt/en/buses/e-city-gold/. [Accessed: 02-Mar-2018].
[20] "Glossary:Tonnes of oil equivalent (toe) - Statistics Explained." [Online]. Available: http://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Tonnes_of_oil_equivalent_(toe). [Accessed: 02-Mar-2018].
[21] "Gasoline density." [Online]. Available: https://www.aqua-calc.com/page/density-table/substance/gasoline. [Accessed: 02-Mar-2018].
[22] "Diesel density." [Online]. Available: https://www.aqua-calc.com/page/density-table/substance/diesel. [Accessed: 02-Mar-2018].
[23] J. Sears, D. Roberts, and K. Glitman, "A comparison of electric vehicle Level 1 and Level 2 charging efficiency," in *2014 IEEE Conference on Technologies for Sustainability (SusTech)*, 2014, pp. 255–258.
[24] O. US EPA, "Greenhouse Gases Equivalencies Calculator - Calculations and References," *US EPA*, 10-Aug-2015. [Online]. Available: https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references. [Accessed: 02-Mar-2018].
[25] "How much carbon dioxide is produced from burning gasoline and diesel fuel? – FAQ – U.S. Energy Information Administration (EIA)." [Online]. Available: https://www.eia.gov/tools/faqs/faq.php?id=307&t=11. [Accessed: 02-Mar-2018].
[26] D. Al-Baik and V. Khadkikar, "Effect of variable PV power on the grid power factor under different load conditions," in *2011 2nd International Conference on Electric Power and Energy Conversion Systems (EPECS)*, 2011, pp. 1–5.

Biographies

Parakram Pyakurel is currently a researcher at Solent University, UK. His research is on a broad topic of sustainable infrastructure design. His recent works explore complex interactions among energy, environment and society in order to plan for energy justice and sustainability. He has extensively published his research in peer reviewed journals, conferences and digital media.

Filipe Quintal is an assistant professor at the Faculty of Exact Sciences and Engineering at University of Madeira. He is also a researcher and a post-doc at the Interactive Technologies Institute. Most of his research are focused on energy and sustainability, especially how IT can help the overall global sustainability effort.

James Auger is an "enseignant chercheur" (teacher and a researcher) at ENS Paris Saclay. His work explores ways through which practice-based design research can lead to more considered and democratic technological futures. James was part of the critically acclaimed Design Interactions department at the Royal College of Arts in London.



Julian Hanna is an Assistant Professor and a researcher. His work focuses on critical intersections between culture, politics and technology. After completing his PhD at the University of Glasgow, he has taught at several institutions including the University of British Columbia and the University of Lisbon.