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Authors

Taiebat, Morteza
Talebian, Hoda
Sassani, Farrokh
et al.

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Renewable Energy, Infrastructure and GHG Implication of Electrified Transportation: Metro Vancouver Case Study

Morteza Taiebat, Hoda Talebian, Farrokh Sassani, and Walter Mérida[†]

Clean Energy Research Centre (CERC), Department of Mechanical Engineering, University of British Columbia,
6250 Applied Science Lane, Vancouver, BC, Canada V6T 1Z4

ABSTRACT

This study is aimed to assess the fleet composition for the new portion of light and medium duty vehicles (LMDV) in Metro Vancouver forecasted for the year 2020. Accordingly, the analysis evaluates the sensitivity of the regional electricity demand on transportation electrification policies. Considering electricity and hydrogen as transportation infrastructures, sixteen scenarios of zero tailpipe emission Electric Vehicle (EV) penetration in the new fleet are investigated. The study assesses the efficiency of EV technologies, quantifies energy demand for the electric transportation, and summarizes the implications of using renewable electricity to power the transportation sector.

The analysis shows that wind energy is the superior resource in terms of life cycle Greenhouse Gases (GHGs). The life cycle GHGs of electricity production via wind turbines ranges from 390-3000 tonnes yr^{-1} and for photovoltaic cells from 1300-9900 tonnes yr^{-1} of CO_{2eq} across the scenarios. Furthermore, it is observed that 92% to 96% of life cycle greenhouse emissions could be reduced by deploying zero emission vehicles, which utilize solar or wind energy as a renewable resource. In this category, battery electric vehicles enable larger energy efficiency. Moreover, the results show that in order to respond to FCEV demand by 2020, the number of on-site hydrogen refueling stations should vary between 3 and 62, across different scenarios. The electricity demand to power these stations ranges from 32 to 248 GWh yr^{-1} which translates to annual production of 5 to 37 wind turbines with 2.24 MW of rated capacity, or alternatively 0.2 to 1.6 km^2 of photovoltaic cell surface.

1.1. Sustainable transportation

Electrified fleets represent a possible solution to mitigate Greenhouse Gas (GHG) emissions from cities and reduce tailpipe pollution. Two Zero Emission Vehicle (ZEV) technologies have emerged as replacements of the internal combustion engine: Battery Electric Vehicles (BEV) and Fuel Cell Electric Vehicles (FCEV). In of March 2015, the Government of British Columbia announced a new Clean Energy Vehicles (CEV) initiative, under the Climate Action Revenue Incentive Program (CARIP). To make CEVs more affordable and reduce greenhouse gas emissions, the Province offered incentives of up to CAD$5,000 for the purchase or lease of a new battery electric or plug-in hybrid electric vehicle, and up to CAD$6,000 for a hydrogen fuel cell vehicle [**1**]. This announcement follows a series of policy developments in the province to encourage consumers and establish behavioral changes towards green transportation.

The federal government expects 500,000 new electric and plug-in hybrid cars by 2018 across Canada [**2**]. Hyundai and Toyota have already started their FCEV leasing plans in North America and Mercedes-Benz will also commercialize its Fuel Cell B-class by 2018. Before widespread FCEV market deployment, hydrogen refueling stations must be available with adequate capacity and supply to maintain the service to the vehicles. Studies have addressed the regional renewable electricity requirement for

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[†] Corresponding author: walter.merida@ubc.ca

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charging stations for BEVs [**3**] [**4**]. The literature on hydrogen demand and refueling station availability with respect to penetration of FCEVs, is more limited. Alazemi et al. [**5**] have a survey on the status of existing hydrogen fuelling station worldwide to 2015.

In the present study, we consider the integration of renewable energy systems for light and medium duty transportation in Metro Vancouver, and quantify transportation energy and corresponding life cycle emission based on work from the government of British Columbia [**6**]. The reason for limiting the scope of this study to LMDV, is that they represent 82% of Metro Vancouver's passenger road vehicles, and are responsible for 85.8% of the GHG emissions (equal to 4.71 million tonnes CO_2 equivalent per year) and 86.36% of total consumed energy in transportation sector each year. Hence, policies or initiatives focused on LMDV can have the largest impact on GHG emissions.

1.2. Research Objective

This paper evaluates sixteen scenarios of electric vehicle penetration in the fleet of Metro Vancouver by 2020. It focuses on the effect of transportation electrification policies on the regional electricity demand outlook. If renewable-based energy (i.e., solar and wind) are used to power these new cars, how much energy should be integrated to the existing grid? Furthermore, if this energy demand is to be satisfied by renewable power plants, how many stations would be required? Additionally, based on the most recent data published by NREL [7] [**8**] [**9**] the life cycle GHG emissions of corresponding energy and infrastructure (i.e. photovoltaic cells or wind turbines) are estimated. The amount of hydrogen and the number of H_2 refueling stations are projected in order to accommodate FCEVs.

2. The Metro Vancouver Area

2.1. Area and population

The region considered in this study is located in the southwest corner of the Province of British Columbia in Canada, officially known as Metro Vancouver, formerly identified as the Greater Vancouver Regional District (GVRD). This regional district comprises 21 municipalities. The official land area of the district is 2,877.36 square kilometers making it the third largest metropolitan area in Canada. According to a Statistics Canada report, [**10**] 2,476,700 inhabitants lived in this region in 2012.

Metro Vancouver Area	
Population (Official 2012)	2,476,700
Land Area	2,877.36 km^2
Total Registered Vehicles (2015)	1,559,691
LMDV (2010)	1,217,274
Total Transportation Fuel Consumed (2010)	2.33×10^9 Liters
Total Transportation Energy Consumed (2010)	84.92×10^{15} J

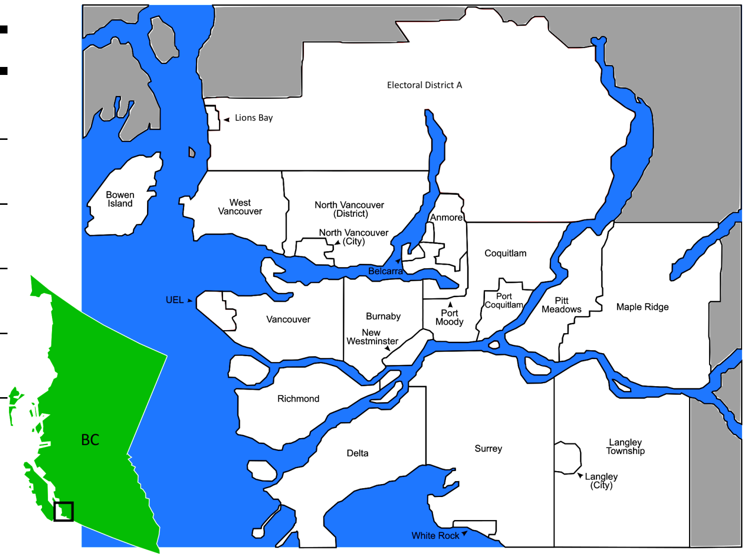
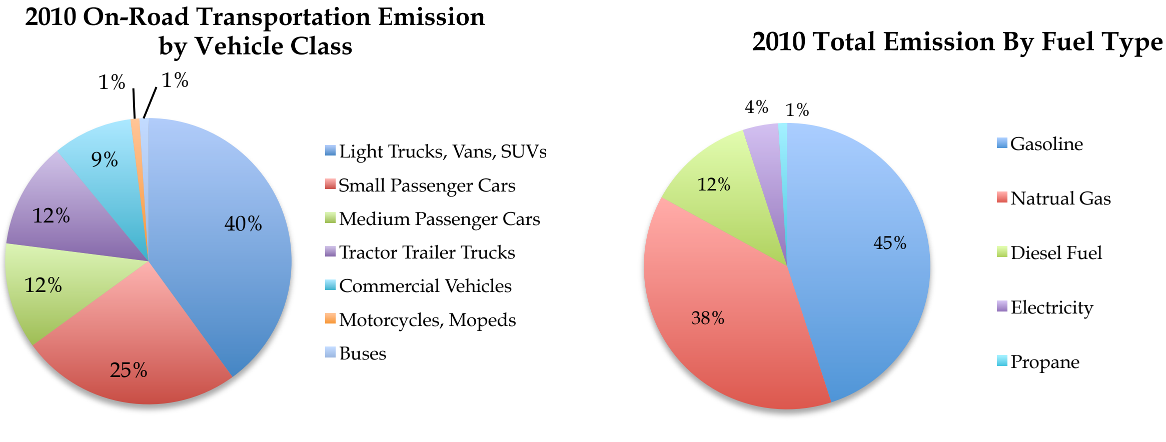


Figure 1. Metro Vancouver statistics

2.2. GHG and Emissions of Regional On-Road Transportation

GHG emissions from human activities are believed to be shifting the world's climate systems to wider extremes and have already warmed the Metro Vancouver's average temperature by 1 ^{o}C [**11**]. According to the latest report of Metro Vancouver Community Energy and Emission Inventory in 2010, published in February 2014 [**6**], Light and medium duty vehicles (LMDV) were responsible for 24% of the Metro-Vancouver's total greenhouse gas emissions and 85.8% of total transportation emissions. Figure 2.a represents the 2010 on-road transportation emissions by vehicle mode. The industry sector, transportation, residential and commercial buildings, and solid waste are the four main sources of GHG emissions in the region, in that order. Figure 2.b denotes the total emissions by fuel type in all sectors in 2010 inventory.



(a) (b)

Figure 2. 2010 Emission inventory distribution

2.3. Vehicle Fleet Outline

There were 1,559,691 registered vehicles in Metro Vancouver by January 2015. This number includes passenger vehicles, commercial vehicles, motorcycles, trailers, and commercial trailers with active insurance policy on January 30, 2015, within regional district [**12**].

The service provided by the region's main mobility modes was first quantified in terms of passenger-kilometer (pkm). The modes were then compared based on their energy efficiency, the amount of energy consumed per unit of travel (MJ km^{-1}), the emission efficiency, the equivalent amount of greenhouse gases emitted per unit of travel (CO$_2$-Equiv. gr km^{-1}).

Table 1 details the energy currency and corresponding amount of fuel, which is used for these modes of vehicles used in 2010 in the Metro Vancouver. These modes consumed a total of 84.92 PJ (10^{15} J), 86.36% of which was used in LMDVs including small and medium passenger vehicles, light trucks, vans and SUVs. The amount of consumed energy by LMDV was 73.338 PJ. The corresponding energy per capita consumption was 29.61 GJ yr^{-1} or 81 MJ day^{-1} for this transportation mode.

The total transportation service provided by LMDV amounted to 23.2 billion pkm, which is equivalent to a daily commute of 14.5 km each way every day of the year for each one of the 2.47 million inhabitants in the region. The total amount of fuel consumed by LMDV fleet is approximately 2.08×10^9 L (equivalent to 2.15 million cubic meters of gasoline), which is 89.2% of total amount of transportation fuel in the region.

Table 1. Inventory of vehicles in Metro Vancouver, type of fuel and consumed amount. Reproduced and customized based on [**6**]

Year 2010	Energy Currency	Number of Cars	Fuel Consumed (L)
Passenger Cars Small & Medium	Gasoline	672,989	901,956,168
	Diesel	10,290	11,707,394
	Hybrid**	7,461	10,468,948
	Other fuels*	262	854,298
Light Trucks, Vans, SUVs	Gasoline	448,483	919,145,379
	Diesel	7,335	19,705,471
	Hybrid	3,025	4,358,353
	Other fuels	1,196	2,282,740
Commercial Vehicles Light & Medium Duty	Gasoline	30,513	82,616,531
	Diesel	34,283	126,067,638
	Hybrid	120	302,514
	Other fuels	1,317	2,669,747

* Other fuels including natural gas, E85, propane, etc.

** In 2010, the technology of plug-in hybrid was not commercialized. This data only encompass regular hybrid cars.

2.4. Vehicle Fleet Energy and Emission Efficiency

Table 2 highlights several differences between modes of transportation in terms of energy and emission efficiency. LMDVs are responsible for 85.8% of the 5.52 million tonnes of transportation greenhouse gas emissions (equivalent to 2.24 tonnes yr^{-1} $capita^{-1}$ or 6.12 kg day^{-1} $capita^{-1}$). Among LMDVs, the second category (Light Trucks, Vans, SUVs) and third category (Commercial Vehicles) are on average 55% and 105% less efficient (both in energy and GHG emissions) than small passenger cars, respectively. Considering the passenger occupancy, buses are the most efficient in terms of emission efficiency per passenger kilometer.

Table 2. Comparison of energy and emission o2qf transportation modes in Metro Vancouver. Reproduced and customized based on [**6**]

Year 2010	Passenger Cars Small & Medium	Light Trucks, Vans, SUVs	Commercial Vehicles Light & Medium Duty
Average Vehicle Km travel	15,300	14,920	18,200
Total Vehicle travel (1000 Km)	10,572,331	6,863,782	1,205,441
Operating Emissions* (tonnes of CO_2 Equiv.)**	2,077,003	2,144,760	518,748
Emission Efficiency per km travel (CO_2 Equiv. gr km^{-1})	196.46	312.47	430.34
Emission Efficiency per passenger-Km (CO_2 Equiv. gr p^{-1} km-1)	151.12	240.37	331.03
Total Energy (GJ)	32,404,885	33,135,103	7,798,102
Energy Efficiency per Km travel (MJ km^{-1})	3.07	4.83	6.47

* Operating emission only accounts for emissions occurring during vehicle normal operation and does not include life cycle emissions that occurred during the vehicle manufacturing stage or the fuel production stage.

** GHGs are stated in terms of CO_2 equivalent, which is summation of amount of each emission component multiplied by corresponding global warming potential (GWP) coefficients.

This comparison masks significant differences between modes. Quantifiable elements such as the average speed and qualitative factors such as perceived service are not identical among these three categories and it may be argued that higher amount of service in commercial vehicles requires higher energy consumption. In 2013 the average rush-hour commute by LMDV was estimated at 32 km h^{-1} in the Metro Vancouver and at less than 20 km h^{-1} within the city of Vancouver [**13**].

The main gases in greenhouse emissions are CO_2, CH_4, N_2O and sulfur hexafluoride (SF_6), with different GHG impact weighting coefficients, as well as the principal airborne pollutants: CO, NO_x and SO_x.

The impact weighting of GHGs are usually stated as Global Warming Potential (GWP) coefficients. Relative to CO_2, the GWP of these gases are 1, 21, 310 and 24,900 respectively [**14**]. Sulfur hexafluoride is used as a cover gas in the process of magnesium casting. Due to its large GWP, the GHG effect of SF_6 is considerable in life cycle analysis, even though its mass amount is significantly less than other GHGs. Similarly, for considerations of air pollution, the airborne pollutants CO, NO_x, SO_x and volatile organic compounds (VOCs) are characterized by the following weighting coefficients relative to NO_x: 0.017, 1, 1.3 and 0.64, respectively, according to Intergovernmental Panel on Climate Change (IPCC) assessment report [**14**].

3. Methodology

3.1. Life Cycle Assessment

For the investigation of environmental impacts of the potential energies, a Life Cycle Assessment (LCA) was conducted. LCA can be defined as a tool for a robust and comprehensive understanding of environmental impacts throughout different stages of implementing a new sustainable energy over its whole life cycle [**15**]. A Well-to-Wheel (WTW) analysis is a type of LCA, which focuses on energy pathways between the original source of energy ((in this case, wind or solar) and the wheels of a vehicle. The components of the pathways are the energy conversion, distribution, and storage stages required to transport and convert the energy that eventually moves the car. WTW analysis can be furthermore split into Well-to-Pump (WTP) and Pump-to-Wheel (PTW) sections. WTP corresponds to generation of energy from renewable resource, integration to grid, transmission to the charging station or hydrogen fuelling station. PTW, which sometimes is also referred as Tank-to-Wheel pathway, is analogous to vehicle level pathway. In the present work, the GREET model developed by the Argonne National Laboratory [**16**] was used for analysis of on-board vehicle energy consumption.

3.2. Scenario Definition and Planning Horizon

The present work considers fleet composition to the year 2020. It assumes that by the end of this planning horizon, 30, 20, 10 or 5 percent of new vehicles will be electric. In each case, 40, 30, 20 or 10 percent of the total electric vehicles are proton exchange membrane (PEM) FCEV and the rest are BEVs. With these assumptions, sixteen different scenarios can be defined. Figure 3 illustrates these scenarios graphically.

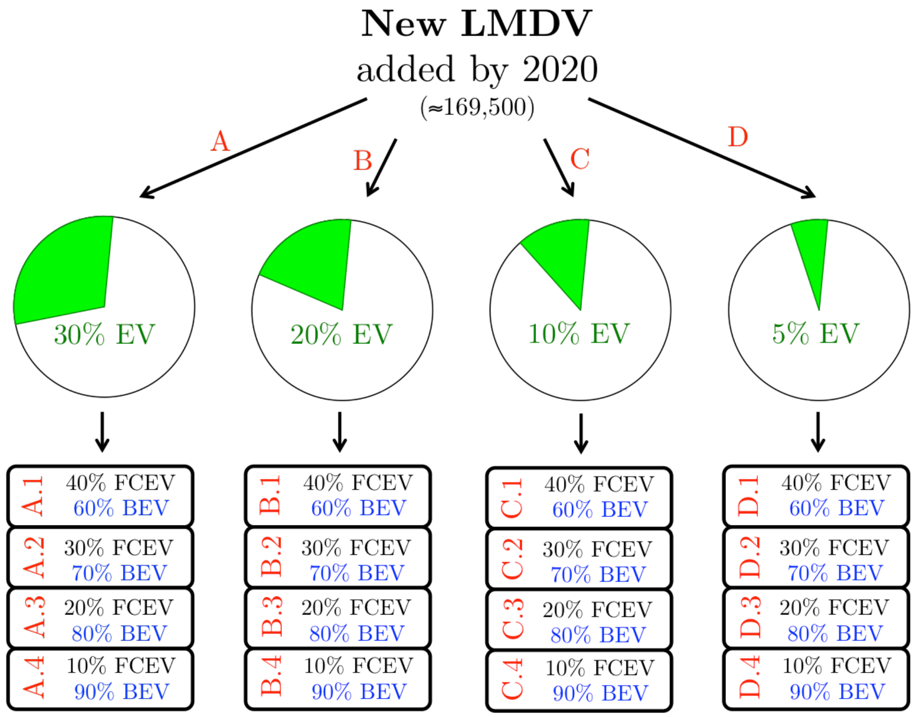


Figure 3. Scenarios investigated

3.3. Analysis Assumptions

The assumptions and references associated with each part of the analysis are cited throughout the paper. A summary of assumptions is given in

Table 3. The energy conversion efficiency of all the modules (e.g. transmission lines, battery chargers, electrolysers, compressors, vehicles components) is used to determine how much renewable electricity would be required to power these new electrified vehicles, either to directly charge BEVs or produce hydrogen for FCEVs. These vehicles are assumed to be similar in size, occupancy, and passenger-km traveled.

Besides quantifying energy consumption and greenhouse gas emissions for the year 2020 in each scenario, the required amount and type of renewable resources are identified. For the case of fuel cell vehicles, the required amount of hydrogen for service, and the minimum number of hydrogen production fuelling stations are calculated (based on the documented capacity of a single station [**5**].

Table 3. List of assumptions

Targeted Fleet	New LMDVs added to the Metro Vancouver fleet from 2010 to 2020 Ratio of LMDV to all vehicles remains constant [**6**] Estimation of vehicles by 2020: Geometric extrapolation with growth rate=0.01311
Wind Turbine	Average capacity factor=40% [**9**] Average capacity rating=2.24 MW, and identical turbines) Life-cycle electricity generation emission= 12 CO_2-Equiv. gr kWh^{-1} [**17**] [**18**]
Photovoltaic Cells	Regional average solar irradiation=1400 kWh m^{-2} yr^{-1} [**19**] Module efficiency=14% [**8**] Performance ratio=0.8 Life-cycle electricity generation emission= 40 CO_2-Equiv. gr kWh^{-1} [**7**] [**8**]
On-site Hydrogen Production-Refueling Station	Overall efficiency=69% (Electrolysis=82%; Hydrogen compression=85%) [**20**] [**21**] Single station Hydrogen production capacity=130 kg day^{-1} [**5**] Conservative coefficient for estimation of required stations=1.2 Hydrogen mass energy density=142 MJ kg^{-1} [**22**]
BEV	Overall on-board vehicle efficiency=64% (Charger=89%; Li-ion battery=90%; E-drivetrain =80%) [**23**] [**24**] On-board energy requirement=0.2125 kWh km^{-1}
FCEV	Overall on-board vehicle efficiency=45% (Hydrogen tank + PEM FC system=56%; E-drivetrain= 80%) [**25**] [**23**] On-board energy requirement=0.3035 kWh km^{-1}
Network Grid	Electricity transmission and distribution losses=7% [**26**]

The scenarios are solely defined based on the contribution of new LMDVs from 2010 to 2020 in Metro Vancouver. In order to forecast the number of vehicles by 2020, a geometric extrapolation was used:

$$\text{population by the year } N = (\text{initial population}) \times (1 + X)^N \qquad \text{(eq. 1)}$$

Where X is the constant annual growth rate. The advantages of geometric over linear extrapolations for forecasting the car ownership are given in the literature [**27**].

This analysis has its limitations: the projection may underestimate the total number of new vehicles; and the energy efficiency was calculated using the upper limits of current technologies. Clearly, as the technology improves, future energy efficiencies will likely be higher which means that the energy demand figures used in this analysis may be overestimated.

4. Provincial Electricity Production and GHG Intensity

Since the late 1980s, British Columbia (BC) Hydro has depended on electricity imports and purchasing to meet the demand for power [**28**]. BC Hydro, the Province's main utility company produces more than 45,000 GWh a year, while the demand is around 55,000 GWh. This shows that the Province has not yet achieved self-sufficiency in electricity generation through domestic power sources [**29**].

The long-term electricity load forecast indicates a 1.7% annual average growth rate in domestic electricity demand [**29**], while the possible load from transportation electrification is overlooked in the published outlook. Hence, for policy development on meeting the demand, it is required to estimate the transportation load, based on the different scenarios of EV penetration in the fleet.

BC Hydro reports that direct emission factor for electricity generation is 12 tonne GWh^{-1} (3.33 gr MJ^{-1}) CO_2 equivalent GHGs [**30**]. Approximately 110 tonnes per GWh CO_2 equivalent GHGs is estimated as the indirect emission of BC's electricity production, due to infrastructure and pre-processing materials. Meanwhile, based on the GREET model, using the U.S. national average grid mix (including fossil-based and renewable resources), producing 1 GWh of electricity results in 720 tonnes of CO_2 equivalent life cycle GHGs [**16**]. This shows that BC Hydro's electricity production corresponds to some of the lowest life cycle emissions in North America. The reason is that about 90% of total electricity is produced by hydroelectric generation and the rest is mainly produced from natural gas-fired power plants, landfill gas, wood-based biomass and run-of-river [**30**] [**28**].

By December 2014, the total number of wind turbines installed in BC was 217, and the total installed capacity was 488.7 MW [**31**]. This translates to an average capacity rating of 2.24 MW for each wind turbine. The solar electricity generation in the Province is limited to small-scale residential purposes.

5. Energy Conversion Efficiency and Life-Cycle Environmental Impacts

Analyzing the efficiency of each vehicle's WTW pathway allows us to determine the total energy consumption and environmental impacts of entire fleet. The assumptions for this analysis are summarized in section 4.3. Based on the long-run development of the partially electrified transportation infrastructure, the cumulative energy demand and produced GHGs in each section was included. Figure 4 shows the WTW efficiency pathways for BEV and FCEV technologies.

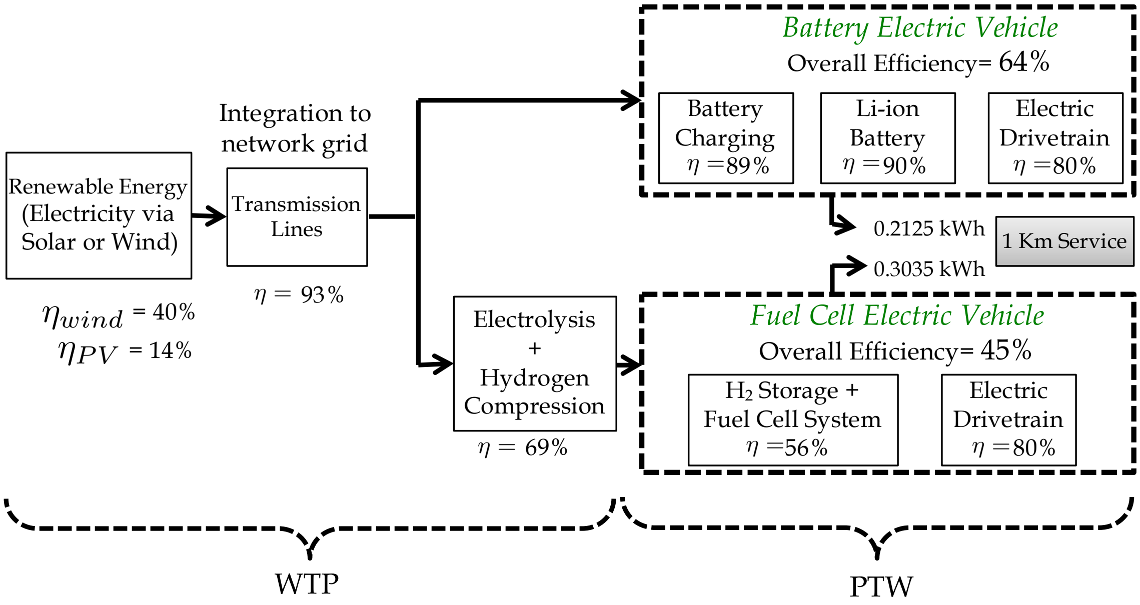


Figure 4. Well-to-Wheel pathway and energy conversion efficiencies [**9**] [**20**] [**20**]

5.1. Integrated Renewable Energy Resources

We assume that solar and wind sources can produce electricity as the output, either for direct charging or for the production of electrolytic hydrogen, for EVs and FCEVs, respectively. We further assumed that the renewable power plants can be integrated to the existing network grid.

The International Energy Agency reports that wind energy has had the fastest growth among renewable energy sources [**32**]. In parallel, and taking advantage of low maintenance requirements, and economies of scale in mass production, solar energy is now competitive with established technologies in several jurisdictions [**7**].

In this study, we consider solar and wind energies, as the renewable resources to produce electricity via photovoltaic cells and offshore or onshore wind turbines, respectively. These sources cannot produce energy continuously. However they could produce electrolytic hydrogen, which can be stored until it is needed. Furthermore, the excess solar and wind energy that would normally be lost can be stored as hydrogen fuel.

For hydrogen production only water electrolysis is considered in the present work. In this case, only the indirect energy for implementing infrastructure is responsible for the environmental impact [**16**]. There is no *direct* fossil fuel energy consumption, thus there is no *direct* emission associated with the hydrogen production level.

6. Results and Discussion

The Insurance Corporation of British Columbia (ICBC) has a database of registered vehicles in Metro Vancouver, which is updated each January [**12**]. We have used the data from 1999 to 2015, to find the average annual growth rate. Using the value of 1.311% for growth rate and (eq. 1, the total number of vehicles by 2020 is estimated. Assuming that the reported portion of LMDV to total cars in the reference [**6**] remains constant from 2010 to 2020, the projected number of new LMDV, added to the Metro Vancouver's fleet, will be approximately 169,500 vehicles by 2020. The linear and geometric extrapolations have less than 2% difference. A linear extrapolation gives a conservative number, while a geometric extrapolation is more realistic, due to the population growth and the fact that the number of passengers per vehicle is declining.

Since the EVs portion of new LMDV is zero emission, the PTW GHG reduction in each primary scenario is 4.18%, 2.78%, 1.39% and 0.7% compared to the entire LMDV fleet by 2020.

Figure 5 depicts the required amount of electricity from renewable resources, with respect to each scenario. The amount is calculated based on the description in the previous section. Accounting for energy requirement of a single BEV (3.187 MWh yr^{-1}) and a single FCEV (6.598 MWh yr^{-1}), assuming 7% losses in electricity transmission and distribution, the amount of electricity required from the resource is quantifiable based on each scenario.

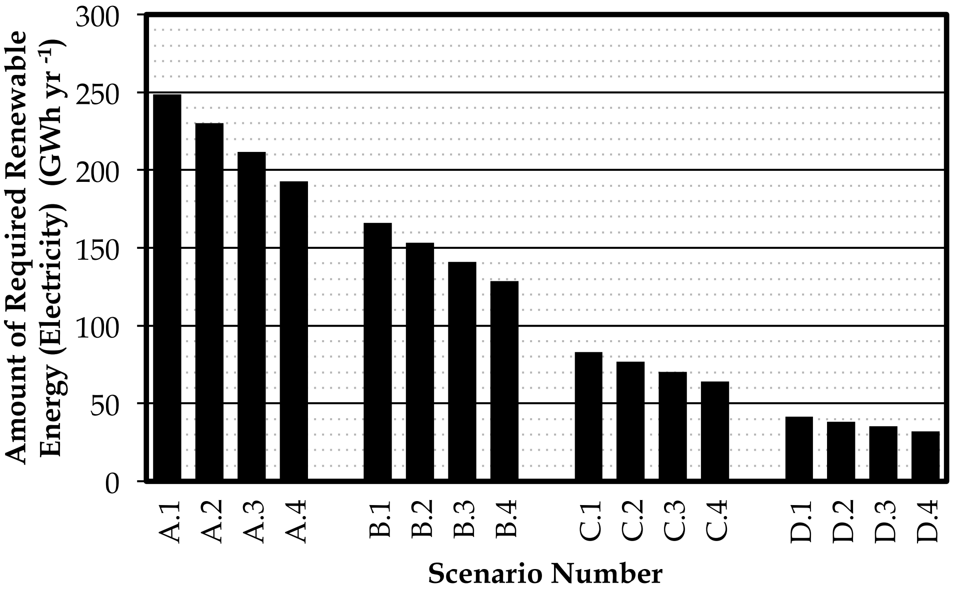


Figure 5. The amount of required renewable electricity for each scenario.

It is clear that the higher portion of FCEV in the share of EV requires more energy, due to the lower energy efficiency of FCEV and the losses in the process of electrolysis and hydrogen compression. Table 4 represents the corresponding infrastructure for generating required renewable electricity in the scenarios. According to the efficiency, specification and life cycle emissions described in section 6, the area that should be covered by photovoltaic cells or the number of wind turbines, which can deliver same amount of electricity, are calculated

It should be noted that the turbines are identical and have the same capacity rating of 2.24 MW. However, in some cases, implementing larger or smaller wind farms might be more economical, but the non-linearity trends are out of scope from this study. Table 4 also displays the life cycle GHGs of electricity generation via PV or wind turbines in terms of CO_2 equiv. tonne yr^{-1}. It is apparent that PV technology is associated with larger life cycle emissions for electricity generation.

Table 4. Infrastructure requirement of electricity generation via wind turbines and photovoltaic cells in each scenario and corresponding life-cycle emissions.

Scenario #	Area Required for Photovoltaic Cells (m^2)	Life-Cycle GHGs of Electricity Generation via PV (CO_2-Equiv. tonne yr^{-1})	Number of Required Wind Turbines	Life-Cycle GHGs of Electricity Generation via Wind Turbines (CO_2-Equiv. tonne yr^{-1})
A.1	1,587,190	9,955	37	2,986
A.2	1,468,269	9,209	34	2,763
A.3	1,349,348	8,463	31	2,539
A.4	1,230,428	7,717	28	2,315
B.1	1,058,127	6,637	24	1,991
B.2	978,846	6,139	23	1,842
B.3	899,566	5,642	21	1,693
B.4	820,285	5,145	19	1,543
C.1	529,063	3,318	12	995
C.2	489,423	3,070	11	921
C.3	449,783	2,821	10	846
C.4	410,143	2,572	9	772
D.1	264,532	1,659	6	498
D.2	244,712	1,535	6	460
D.3	224,891	1,411	5	423
D.4	205,071	1,286	5	386

Since the hydrogen mass energy density is 142 MJ kg^{-1} [**22**], from the FCEV equivalent energy demand of each scenario, the amount of required hydrogen can be calculated. Additionally, a typical single unit station can produce 130 kg hydrogen fuel per day [**5**], which translates to 42.47 tonnes yr^{-1}. Figure 6 shows the amount of required hydrogen and the number of H_2 refueling station in each development scenario. It should be noted that for covering the fuelling station requirement of an urban area, typically the number of stations should be considered conservatively. Here, a coefficient of 1.2 is multiplied to the minimum number of stations (based on hydrogen demand) to have a realistic estimation for the required stations.

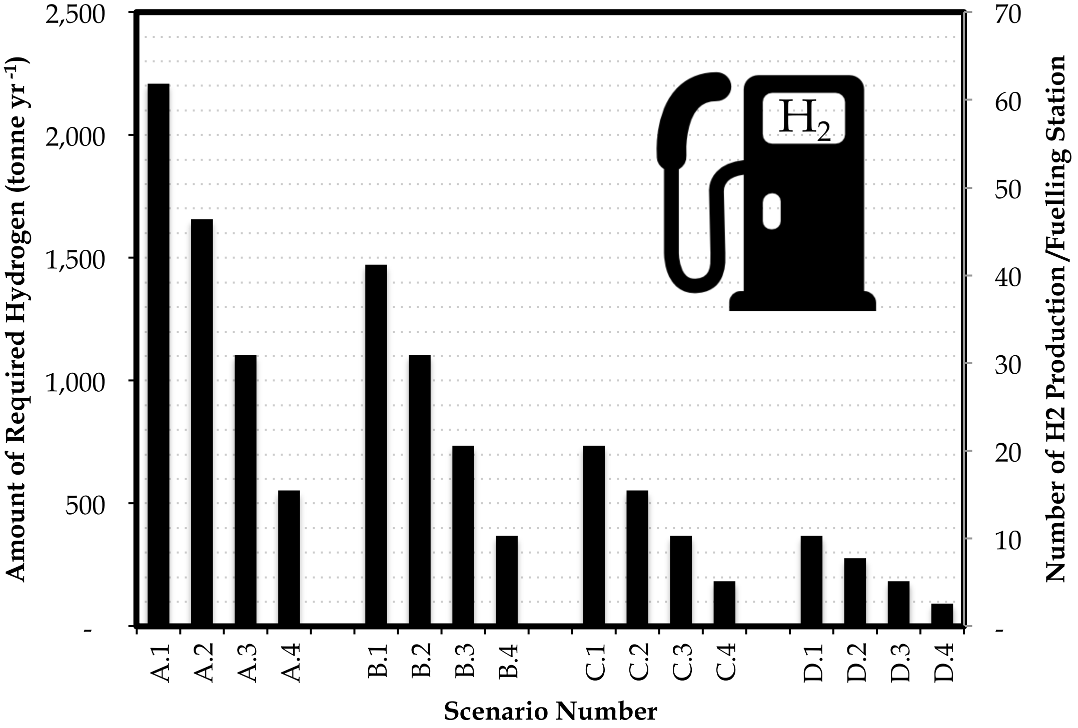


Figure 6. Amount of required hydrogen and the number of H_2 refueling station in each scenario.

7. Conclusions

The main contribution of this paper was to demonstrate that even if a small fraction of urban transportation is electrified, the implications for the regional electricity generation and transmission network would be significant. This issue is more prevalent in the case of Metro Vancouver, where the Province is not self-sufficient for electricity generation.

Our results indicate that, if one percent of the fleet is converted to EVs, more than 100 GWh per year of electricity will be required.

The analysis shows that zero emission vehicles, which utilize energy from renewable resources, i.e. solar or wind, can eliminate 92% to 96% of the life cycle greenhouse emissions, depending on the energy pathway. This can contribute to a substantial shift in reducing urban emissions and mitigate environmental impacts.

The on-board efficiency of BEV and FCEV were calculated at 64% and 45%, which is two to three times higher than the best internal combustion engines. The differences are particularly drastic since we assume that the energy is derived from renewable resources. While BEV technology is more energy efficient than FCEV, the FCEV should be considered as a complementary technology, due to the qualitative factors such as the size of vehicle, range of travel and large capability of the Province to complement renewable hydrogen production with production from regional natural gas resources. The storage capability of hydrogen, which is produced during off-times from these intermittent renewable resources, can be also considered as a complementary energy storage technology for the transportation sector.

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