CESAR SCENARIOS

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THE POTENTIAL IMPACT OF ELECTRIC VEHICLES ON ALBERTA'S ENERGY SYSTEMS

David B. Layzell
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Canadian Energy Systems Analysis Research (CESAR) Initiative • www.cesarnet.ca

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David B. Layzell PhD, FRSC

Director, CESAR and Professor, University of Calgary

Bastiaan Straatman, PhD

Energy Systems Modeler, CESAR

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CESAR (Canada Energy Systems Analysis Research) is an initiative that was started at the University of Calgary in 2013 to understand and inform energy systems change in Canada. By building data resources and visualization tools, analyzing past and present energy systems and modeling energy futures, CESAR researchers work to inform policy and investment decisions regarding the transformation of Canada's energy systems towards sustainability. To carry out its work, CESAR brings researchers, disciplines and sectors together from across Canada.

Though its website (www.cesarnet.ca), CESAR provides visualizations that communicate a wealth of information on the energy systems of Canada, and it provinces. The data behind many of these visualizations have been made available through a cooperative agreement between CESAR and whatIf? Technologies Inc, an Ottawa, Ontario systems modeling company, and the owner and developer of the Canadian Energy Systems Simulator (CanESS) model.

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MAILING ADDRESS CESAR, 2603 7th Ave NW, Calgary AB T2N 1A6

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About the authors

David Layzell is a Professor at the University of Calgary and Director of the Canadian Energy Systems Analysis Research (CESAR) Initiative. From 2008 to 2012, he was the Executive Director of the Institute for Sustainable Energy, Environment and Economy (ISEEE), a cross-faculty, graduate research and training institute at the University of Calgary. Dr. Layzell began his academic career as a Professor of Biology (cross-appointments in the Schools of Environmental Studies and Public Policy) at Queen's University (Kingston) where he generated over 100 peer reviewed publications, 7 patents and a technology company (Qubit Systems Inc.) before being elected as a 'Fellow of the Royal Society of Canada' (FRSC) in 1998. In various roles, he has worked with hundreds of faculty at universities across Canada building multi-disciplinary research teams focused on energy and climate change solutions, including the launching of research networks such as the BIOCAP Canada Foundation, Fluxnet Canada, the Green Crop Network, Greenhouse Gas Management Canada Network and Carbon Management Canada.

Bastiaan Straatman has been modeling complex systems throughout his career, but since early 2012, he has been focused on developing and using the Canadian Energy Systems Simulation (CanESS) model to study the past, present and possible future energy systems of Canada. His past work has involved spatial decision support models, models of evolutionary dynamics in economics and models depicting greenhouse gas emissions in municipalities. Bastiaan holds a Master degree in Mathematics and a PhD in Geography.

Acknowledgments

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Table of contents

Executive Summary

To explore the implications for Alberta of plug-in electric vehicles (EVs) on energy and environmental factors (including oil and electricity demand and emissions of greenhouse gas and criteria air contaminants), three scenarios to 2040 were developed and compared to a fourth, 'reference' scenario.

The scenarios were developed using the Canadian Energy Systems Simulator (CanESS) from whatIf? Technologies Inc. (Ottawa, ON), following modifications and customizations by the research team. CanESS is a calibrated, internally-consistent model of the energy systems of Canada by province which incorporates 32 years of historical government data, and the potential to model future scenarios.

To project to the future, the reference scenario assumed a low oil sands growth (LOSG) rate[1], consistent with oil price at less than $50 per barrel, 'business-as-usual' human activity in terms of driving behaviour and vehicle preferences, as well as continuation of current policies[2] and existing technologies (See Straatman et al., 2016[3] for details).

The three EV scenarios were identical to the reference scenario but assumed rates of EV deployment based on 50 (slow), 30 (medium) or 20 (fast) years for EVs to saturate the share of personal light duty vehicles (LDV) sold. The rate of deployment was calculated to fit a standard 'S curve' for new household technology innovation. Given the fact that people keep vehicles for approximately 13 years, it takes many years for EVs to become the major stock of cars on the road.

The scenario models generated the following insights:

- Albertans travel about 88 billion kilometres per year, two-thirds of which is by light duty vehicles that have among the

1 The LOSG reference scenario was similar to that used by the Alberta Electrical System Operator (AESO).

2 All scenario models assumed deployment of Corporate Average Fuel Economy (CAFE) Standards to 2025 and existing coal power plant retirement policies.

3 Straatman B, Layzell DB & Lowey M. 2016. Alberta's Energy Systems from 2015 to 2040: Comparing High versus Low Oil Sands Growth. CESAR White Paper (http://www.cesarnet.ca/sites/default/files/HOSG_v_LOSG_backgrounder_Final.pdf)

highest per capita GHG emissions per kilometre. By 2040, personal travel is projected to increase to 110 billion km/yr.

- There are about 2.2 million personal use LDVs on the road in Alberta in 2015 and in recent years, light trucks have been outselling cars. By 2040, personal use LDV numbers were projected to increase to 2.5 million.
- The life cycle emissions (including fuel recovery and processing) for Alberta's public electrical grid is about 730 kilograms CO_2e per megawatt-hour in 2015 and this is projected to decline to 509 kg CO_2e/MWh by 2040 as a result of the 50 year, coal-fired power plant retirement policies in the province.
- However, if emissions from shale or tight gas production prove to be larger than currently estimated, the well-to-wheels footprint associated with electricity generation (and therefore EV use) could be much higher, and there may be less GHG benefits associated with the transformation to EVs in Alberta.
- In the fast EV scenario, 74% of the vehicles on the road were projected to be EVs by 2040. Since EVs are about 3 times more efficient than internal combustion engines (ICEs) vehicles, the total vehicle energy use was projected to be 48% of the reference scenario in 2040.
- Assuming 15,000 km/yr of city (60%) and highway (40%) driving, new 2015 ICE vehicles generate life cycle emissions of 3.3 to 4.4 t CO_2e/yr, about 1.24 t CO_2e/yr more than an EV. In 2040, a new ICE vehicle driving the same distance was projected to generate 2.3 to 3.2 t CO_2e/yr or about 1.48 tCO_2e/yr more than an EV.
- The greenhouse gas emissions associated with the construction and disposal of ICE and EVs were not included in this analysis. If the shift to electrification of personal transport coincides with a move to self-driving and car-sharing vehicles, the relative, per km contribution of vehicle construction and disposal should decrease dramatically.
- By 2040, the fast EV scenario projected about 31 Mt CO_2e emission reduction compared to the BAU reference scenario. The emission reductions would be greater than this if the GHG intensity of the Alberta grid were to be reduced more quickly.
- The emissions of criteria air contaminants were projected to decline over the study period, largely as a result of the imposition of the Corporate Average Fuel Economy (CAFE)

standards. The movement to EVs projected a further decrease in those emissions.

- With electrification of personal transportation comes a reduced demand for crude oil for up to 36,000 barrels per day for Alberta by 2040 for the fast EV scenario. Assuming the trend to electrification extends beyond Alberta, such a reduction is equivalent to 1.5 million bbl/d in lower demand across North America, and 6 million bbl/d globally. These calculations only consider personal light duty EVs, not the potential for EVs for use in taxis, trains, delivery vehicles, buses, etc. Since oil is 'traded-at-the margin', even a relatively small change in oil demand is likely to have a significant downward pressure on the price of oil and the economy of the province.

Policy-relevant insights and recommendations include:

1. Even in Alberta, with its high-carbon electricity, there are GHG benefits associated with fuel production and use in shifting from gasoline to electric-powered personal vehicles. For a typical personal-use vehicle driven 15,000 km/yr, the benefit is 1 to 1.5 t CO_2e per vehicle per year. For new vehicles in 2015, that represents approximately 33% reduction in emissions, but by 2040, the reduction is estimated to be 50%.
2. Most of the world's crude oil production is for transportation fuels, so Alberta, as a major oil-producing province, is clearly in the 'transportation business'. Hence, a global shift to plug-in electric vehicles (EVs), and away from oil, is a trend that is of critical importance to the province, its industries and communities.
3. Ignoring, resisting or fighting the trend to EVs (and the related technological shifts to car sharing and self-driving vehicles) will have little or no impact on whether or not they occur. Rather, the province, its industries and communities can only have an effect on how well prepared they are in responding to this change if it occurs. Will they be ready to 'ride the wave' of change, or be swamped by it?
4. It would be better to get in front of the pending EV / car sharing / self-driving 'tsunami,' by encouraging utilities, communities and companies to see it as an opportunity, positioning themselves to be a leader in the change and providing insights, services and technologies to others.

1. Introduction

The purpose of this study was to explore the potential GHG and air quality benefits of a transition to plug-in electric vehicles (EVs) in Alberta over the next 25 years, based on an analysis of Alberta's energy and transportation demand data.

To carry out this study, the Canadian Energy Systems Analysis Research (CESAR) Initiative at the University of Calgary partnered with whatIf? Technologies Inc., an Ottawa, Ontario software modeling company. whatIf? Technologies is the developer and owner of the Canadian Energy Systems Simulator (CanESS) model that CESAR researchers have both contributed to and used to explore past, present and possible future energy systems of Canada.

This report is organized into four sections:

First, **Reference Scenarios** were built to describe the energy systems for the province of Alberta from 2015 to 2040. These Business-As-Usual (BAU) scenarios take into account existing policies (e.g. Alberta coal retirement regulations[4], Corporate Average Fuel Economy (CAFE)[5] standard), as well as trends in economic and population growth, technologies, and human behaviour in energy systems projections from 2015 to 2040. The Low Oil Sands Growth (LOSG) scenario was chosen as the reference scenario for subsequent scenario models that vary in plug-in electric vehicles deployment. A description of a High Oil Sands Growth (HOSG) reference scenario and a LOSG reference scenario has been provided in a previous document[6].

Second, **Rates of Market Penetration for EVs** were assumed for three scenarios based on the demand for personal transportation as defined by the LOSG reference scenario; assumptions were identified by drawing on data for the rates of market share penetration for previous transformative household technologies.

Then, the results for three **EV Scenario models** were compared with the reference scenario and used to calculate changes in emissions

4 See http://www.aeso.ca/downloads/AESO_2014_Long-term_Outlook.pdf

5 See http://www.nhtsa.gov/fuel-economy/

6 Straatman B, Layzell DB & Lowey M. 2016. Alberta's Energy Systems from 2015 to 2040: Comparing High versus Low Oil Sands Growth. CESAR Scenarios (Jan 2016) Volume 1, Issue 1 (http://www.cesarnet.ca/sites/default/files/HOSG_v_LOSG_backgrounder_Final.pdf)

of greenhouse gases (GHGs), Criteria Air Contaminants (CAC[7]) and demand for oil.

Finally, based on the results, **Conclusions** and suggested relevance of this work for the province of Alberta were generated.

2. Reference Scenarios for Alberta's Personal Use of Light Duty Vehicles

A Reference Scenario of an energy system is a projection into the future that assumes a 'Business-As-Usual' (BAU) use of energy related technologies, policies and societal behaviours.

Such scenarios take into account ongoing trends in human behaviour that may be occurring (e.g. increase in dwelling size per capita, more per person kilometres travelled per year, etc.); existing policies that are in place (e.g. conditions on coal plant replacement following retirements, CAFE standards for personal vehicles); or identified trends in technology choices (e.g. more efficient furnaces, freight shift to trucks versus trains, or SUVs out-selling smaller cars). In some cases it makes sense to extrapolate trends into the future; in other cases, the trend is 'dampened' as it is clear that the existing trend cannot continue indefinitely.

For this study, two reference scenarios for the province of Alberta were developed: one based on High Oil Sands Growth (HOSG) and one based on Low Oil Sands Growth (LOSG). Details on these reference scenarios are provided elsewhere[8], and only highlights will be summarized here:

- The HOSG scenario assumed a high (>$80/bbl) oil price over the next 15 to 20 years and few, if any constraints on growth. Consequently, oil production in Alberta was assumed to grow from approximately 3 million barrels per day in 2015 to 5.4 million bbl/day in 2040. Alberta's population was assumed to increase from about 4.1 million today to 6.2 million in 2040, and the province's GDP was assumed to increase from $215 billion (in -2002 dollars) per year today to $380 billion ($2002)/yr by 2040.

7 Includes Non-Methane Hydrocarbons (NMHC), Carbon Monoxide (CO), Nitrous Oxides (NOx) and Particulate Matter (PM)

8 Straatman B, Layzell DB & Lowey M. 2016. Alberta's Energy Systems from 2015 to 2040: Comparing High versus Low Oil Sands Growth. CESAR Scenarios (Jan 2016) Volume 1, Issue 1 (http://www.cesarnet.ca/sites/default/files/HOSG_v_LOSG_backgrounder_Final.pdf)

- The LOSG scenario assumed a continuing low (<$50/bbl) oil price over the next 15 to 20 years and /or constraints on growth. Consequently, oil production in Alberta was assumed to grow from approximately 3 million bbl/day in 2015 to 3.8 million bbl/day in 2040. In effect, only the oil sands projects already under construction will be completed and go into production, and no new projects will be initiated. Consequently, the Alberta population will only increase from 4.1 million today to 5 million in 2040, and the GDP will only grow from $210 billion ($2002)/yr today to $270 billion ($2002)/yr by 2040.
- Total energy use in Alberta in the HOSG was projected to rise from 3200 to 5800 petajoules (PJ) in 2040. The LOSG scenario on the other hand showed a more moderate increase to 4300 PJ in 2040. In 2015, the energy use for personal transport accounted for 180 petajoules per year or about 5.5% of total energy use.
- Total greenhouse gas (GHG) emissions in Alberta in the HOSG were projected to rise from about 270 megatonnes (Mt) CO_2e in 2014 to 409 Mt CO_2e /yr in 2040, whereas in the LOSG scenario, 2040 emissions were projected to be 318 Mt CO_2e /yr. The emissions from personal transportation averaged 3.6% of total emissions in the HOSG scenario and 3.4% of total emissions in the LOSG scenario.
- In 2015, the person-kilometers travelled in Alberta totaled 88 billion for all trip types and modes. In the HOSG scenario, this number is projected to rise to 138 billion person-km, while in the LOSG scenario this number increases to 111 billion person-km.
- Given the different population projections for the two scenarios, the number of vehicles in Alberta was projected to differ considerably. The total light duty vehicle stock for personal use in the HOSG scenario was projected to grow from 2.2 million vehicles in 2015 to 3.1 million vehicles in 2040 for the HOSG scenario, but ‘only’ to 2.5 million vehicles for the LOSG scenario.

In this study, a **LOSG scenario** was assumed as the reference scenario for all subsequent modeling. The LOSG scenario was assumed to more accurately reflect Alberta today, since many analysts now suggest that a low-oil price scenario may continue well into the future. Consequently, the Albertan demand for person-km travelled depicted in Figure 1 provides the reference point for all electric vehicle (EV) scenarios explored in this report.

Most of the projected increase in person-km travelled per year can be attributed to population growth. Note that two-thirds of these personal kilometres travelled were calculated to be via light duty vehicles (LDVs). They have the highest carbon footprint per person-km of all modes of personal transport, and they are the mode that is most likely to be transformed by EVs. Hence the remainder of this document will be focused on the personal use of LDVs.

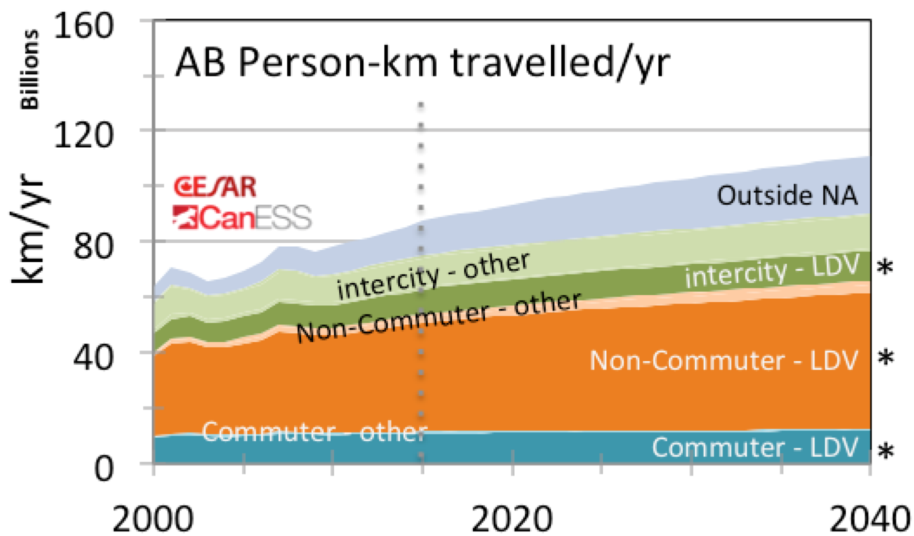

Figure 1. A comparison of person-km travelled per year by Albertans, by purpose and mode of personal travel for the Low Oil Sands Growth reference scenario. Historical (2000-2015) and projected (2015 to 2040) values are provided. Note that light duty vehicles associated with commuter, non-commuter and intercity travel accounts for 64 to 68% of all personal travel.

3. Assumed Rates of Market Penetration

In the household sector of the economy, market penetration of a technology is defined as the percentage of households within a jurisdiction that have bought into the technology in question. Typically, adopters are classified as innovators, early adopters, early majority, late majority and laggards (Grubler 1990)[9]. The associated

9 Grubler A 1990. The Rise and Fall of Infrastructures: Dynamics of Evolution and Technological Change in Transport, Physica- Verlag Heidelberg

transition follows a logistic or 'S'-curve that can be separated into three phases:[10,11].

- Traction phase (0%-10% market penetration), typically by technology enthusiasts and the visionaries (innovators and early adopters);
- Maturity phase (10%-40% market penetration), represented by the pragmatists (early majority adopters); and
- Saturation phase (40%-75% market penetration), represented by the skeptics (late majority adopters).

It is rarely possible to predict with confidence and precision the rate of emergence of any new technology. Certainly, electric vehicles are not an exception to this rule. Ford et al. (2011)[12] provided an overview of a large number of EV studies and concluded that 65% of the studies assume an EV market penetration between 0% and 20% by 2050; 20% of the studies envisioned a 2050 EV market penetration between 21% and 50%; and 15% assume market penetration of above 50% by 2050.

In 2015, many technology specialists would consider the Ford et al. (2011) study as dated and overly conservative, especially given recent developments in battery technologies[13], and the huge investments that are being made in electric vehicles by companies with proven track records in transformative technological and market change. Nevertheless, it is clear that there are widely divergent opinions on the rate of market penetration by EVs in the coming decades. Figure 2A shows the market penetration rates for a wide range of household technologies that were introduced throughout the 20th century.

For the current analysis, four scenarios were identified and modeled, reflecting different rates of EV market penetration:

- **Reference scenario** (LOSG, described in Appendix A) in which EVs accounted for only about 1% of the vehicles on the road by 2040;
- **Slow EV scenario**, in which it takes 50 years for EVs to be effectively 100% of light duty vehicle sales (plus an additional 13 or so years [average lifetime of a car] before the entire LDV

10 Geoffrey M 1991. Crossing the Chasm: Marketing and Selling High-Tech Products to Mainstream Customers, New York, HarperBusiness.

11 DeGusta 2012. Are smart phones spreading faster than any technology in human history. (http://www.technologyreview.com/news/427787/are-smart-phones-spreading-faster-than-any-technology-in-human-history/)

12 Ford J et al. 2011. A comparative study on Emerging Vehicle Technology Assessments, US Department of Energy Technical Report (http://www.osti.gov/scitech/biblio/1008834)

13 Yong et al. 2015. A review on the state-of-the-art technologies of electric vehicle, its impacts and prospects, Renewable and Sustainable Energy Reviews 49 p.365-385

stock is electrified). This rate of market penetration would be similar to that for clothes washers in the 1960s (Figure 2A);

- **Medium EV scenario**, in which it takes 30 years for EVs to be effectively 100% of light duty vehicle sales. This rate of market penetration would be similar to that for refrigerators in the 1940's and 50's (Figure 2A);
- **Fast EV scenario**, in which it takes 20 years for EVs to be effectively 100% of light duty vehicle sales. This rate of market penetration would be similar to that for colour TVs in the 1970s and 80s. (Figure 2A).

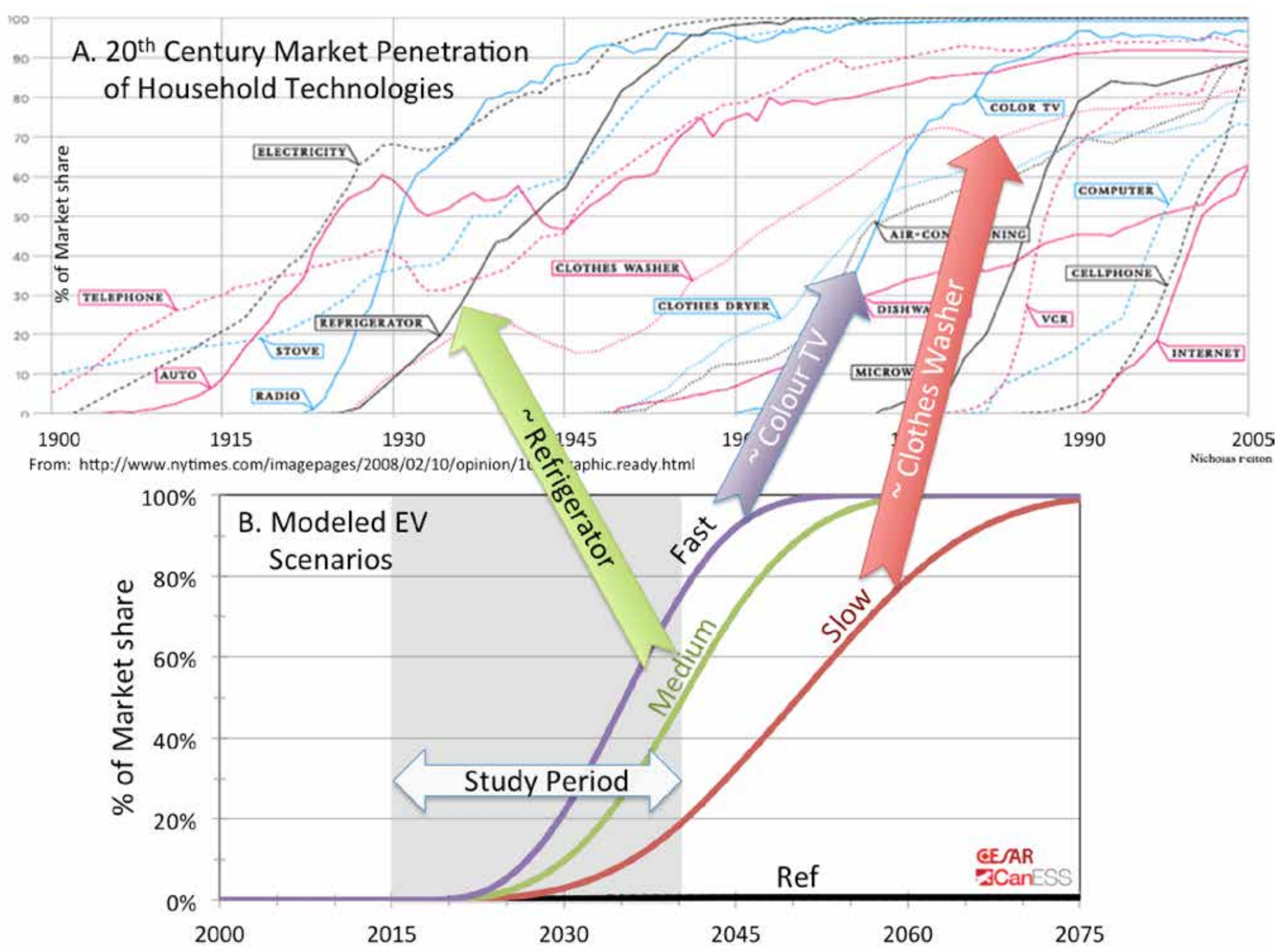

Figure 2. A. The percent of U.S. households that own a range of new technologies over the 20th Century. **B.** The percentage of market share of EVs (as a percentage of total number of cars on the road) for the four EV Scenarios carried out in this study. The EV share of new cars sold was defined such that full market share was gained in 20, 30 and 50 years for the fast, medium and slow scenarios, respectively. The arrows show the technology from the 20th century that had comparative rates of market penetration. Source of data for panel A: Felton N 2008 New York Times (http://www.nytimes.com/imagepages/2008/02/10/opinion/10op.graphic.ready.html)

The Fast EV scenario also approximates what Elon Musk, president and CEO of Tesla Motors, has targeted to sell as part of his effort to transform personal transportation to EVs[14]. By 2020, he has a target of 500,000 Tesla vehicles sold worldwide, including 250,000 in North America. If the Canadian portion of the Tesla target is approximately 32,000 vehicles, and Tesla accounts for half the market (Tesla has about 17% market share now), an estimated 60,000 EVs would be sold across Canada in 2020.

The Fast EV Scenario projects 36,000 EVs sold in Canada in 2020, or 3,500 EVs sold in Alberta so it is perhaps one or two years slower than the 'Tesla target'. To put the Alberta number in perspective, there are currently about 2.2 million personal use light duty vehicles (not counting 725,000 commercial LDV) on the road in Alberta (Figure 3A).

4. Scenarios for Personal Use of Light Duty Vehicles

4.1. The Number and Types of Vehicles on the Road in Alberta

When the reference scenario and the three EV scenarios summarized in Figure 2B were entered into the stock roll-over model within CanESS, calculations were made of the numbers of vehicles on the road projected to 2040 (Figure 3).

The stock roll-over calculation took into account:

- The demand for personal vehicles,
- A vintaged base stock of vehicles,
- Survival rates of vehicles before retirement / recycling, and
- The market share of new vehicle types.

In addition, the demand for vehicles depended on the composition of Alberta's population and families, as well as the number of vehicles per family. It is worth noting that the number of vehicles per family has been declining gradually since 1980 for all family compositions, sizes and age structure; in the CanESS model, this was projected to continue into the future. None of the scenarios considered the

14 http://www.autonews.com/article/20140113/OEM/301139981/audacious-growth-plans-will-stretch-tesla-beyond-its-comfort-zone

impact of car sharing. If there was a major movement towards car sharing, the total number of vehicles on the road would be expected to decline rapidly, but the number of kilometres travelled by each vehicle would be expected to rise.

The age-dependent survival rates in the model was set for an average of 13 years, so new vehicles were only added to the existing stock to meet demand in response to a growing population and the aging and removal of cars.

Consequently, all scenarios projected a gradual growth from 2.2 (today) to 2.5 million cars on the road in Alberta in 2040 – the result of population growth and slightly fewer vehicles per family. The projections in Figure 3 also reflect the shift in customer preference from car to light truck (including SUV and minivan) that has been observed over the past decade.

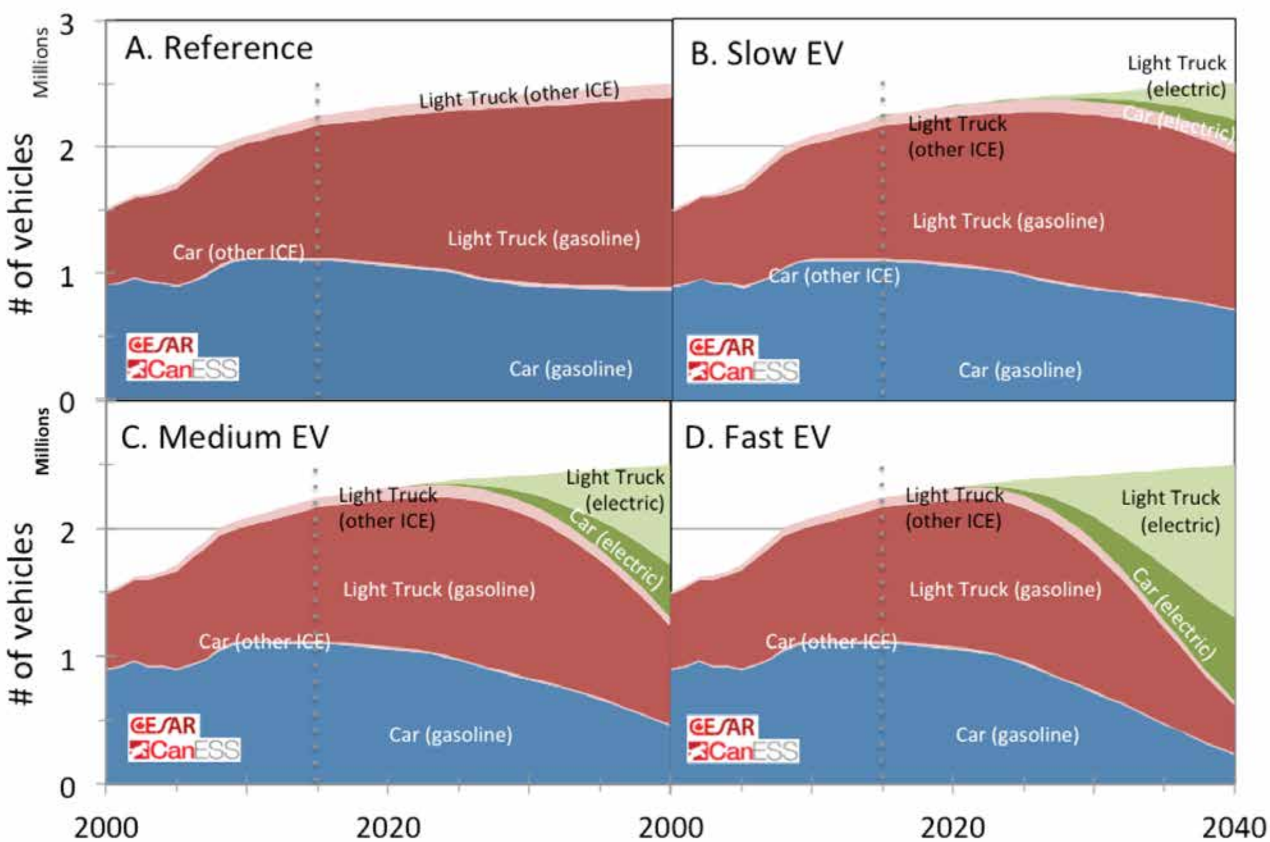

Figure 3. The number and types of personal use, light duty vehicles projected to be on the road in Alberta under the reference scenario and three different scenarios for EV deployment. See Figure 2B for scenario assumptions. The 'other ICE' categories account for hybrid, natural gas and propane vehicles. ICE, internal combustion engine.

In the three EV scenarios (Fig 3B,C,D), a shift was projected to occur in the proportion of EVs on the road. By 2040, 18%, 48% and 74% of the vehicles on the road were projected to be EVs in the slow, medium and fast EV scenarios, respectively.

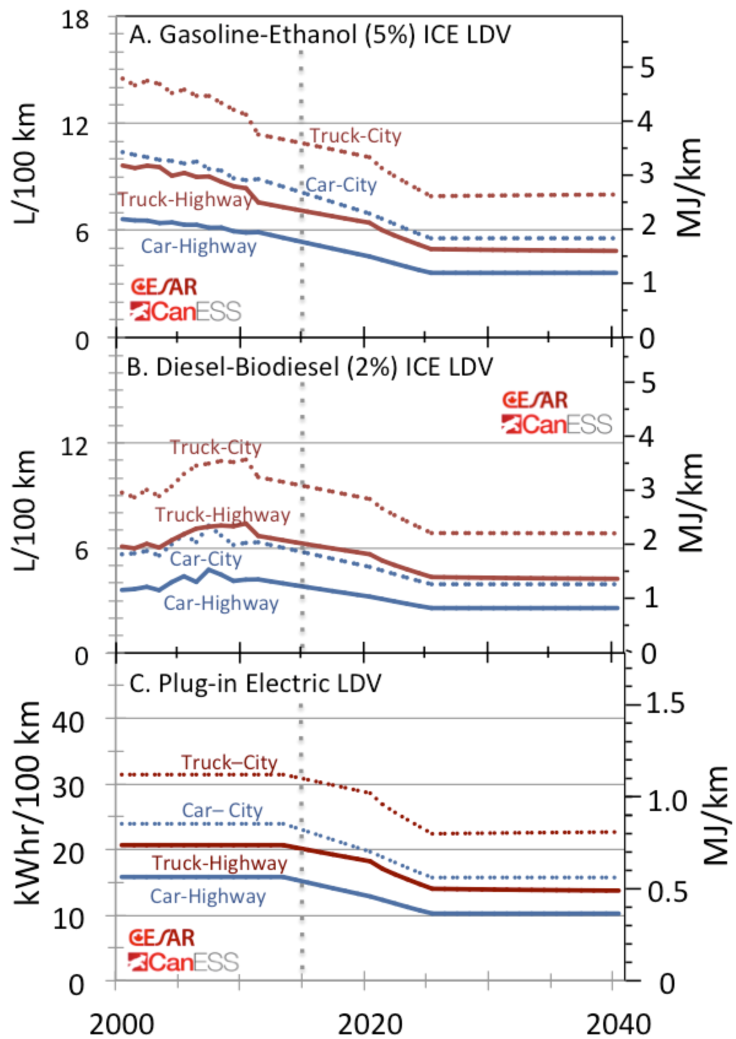

Figure 4. The past and projected future fuel (Panel A and B) or grid electricity (Panel C) use per distance traveled for light duty vehicles (LDV).

4.2. Energy Demand by Light Duty Vehicles for Personal Transport

Historical data for the efficiency of Light Duty Vehicles fueled with gasoline-ethanol or Diesel-biodiesel (Figure 4A and B) were obtained from Transportation Canada[15] while future projection assumed the Corporate Average Fuel Economy (CAFE[16]) standard policy. CAFE is a U.S. government policy that is driving improvements in the fuel efficiency of cars and trucks until 2025, and – given the integration of the US and Canadian auto industry – a standard that will define the market in Canada. For example, the fuel consumption for a typical 2015 model, city driven, gasoline-powered car must be reduced from about 8 litres per 100 kilometres to 5.6 L/100km by 2025. No additional CAFE standards were assumed to exist beyond 2025 in any of the scenarios.

15 Sales-weighted fuel consumption rates, 2000-2011, Canada from Source: Vehicle Fuel Economy Information System, 2012, Transport Canada

16 See http://www.nhtsa.gov/fuel-economy/

Expressed in units of MJ fuel energy per km travelled, the internal combustion engine (ICE) LDV of today were estimated to be 1.2 to 3.6 MJ/km but with the CAFE standard they range from 0.8 to 2.7 MJ/km by 2025.

As with internal combustion engine (ICE) LDVs, the energy consumption of plug-in electric vehicles (EVs) were assumed to differ between city and highway use. In alignment with other reports for EV's[17], we assume current highway electricity demand of 15 to 20 kWh/100km (= 0.5 to 0.7 MJe/km), and city demand ranging from 22 to 31 kWh/100km (= 0.8 to 1.1 MJe/km) (Figure 4C). With implementation of the CAFE standards between 2015 and 2025, the electricity consumption improvements are assumed to keep up with the improvements required of that industry overall. This results in

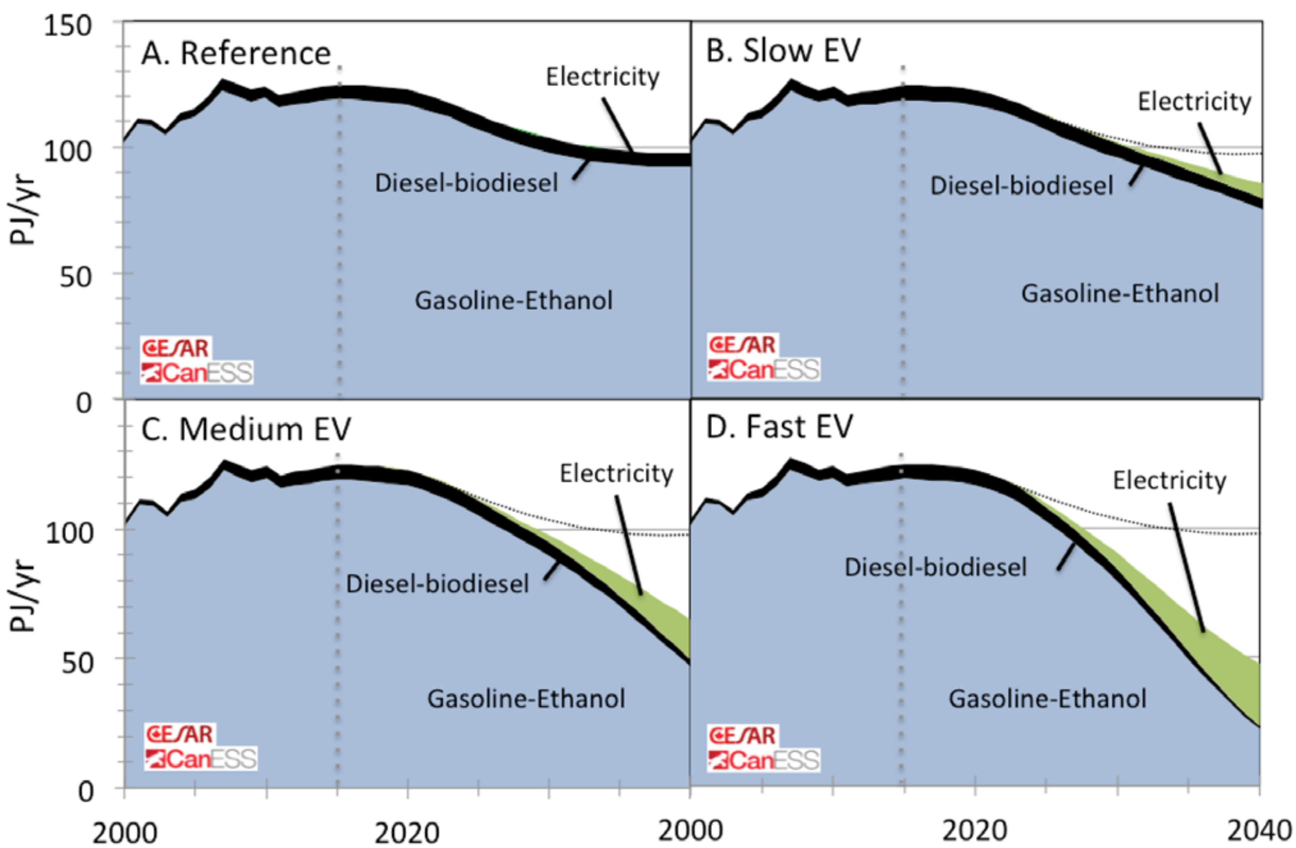

Figure 5. Vehicle energy use associated with the projected personal vehicle numbers (Figure 3) for the reference scenario and three different scenarios for EV deployment (Panels A to D). See Figure 2 for scenario assumptions. The dashed lines in panels B to D show the total energy use in the reference scenario (Panel A) to illustrate the magnitude of the reduction for each scenario.

17 TU Vienna, 2012. BatterieElektrische Fahrzeuge in der Praxis (http://www.övk.at/aktuelles/2012/Batterieelektrische_Fahrzeuge_in_der_Praxis_2.pdf). See also Wikipedia (https://en.wikipedia.org/wiki/Electric_car) for an overview of current electric vehicles showing energy consumption ranges of between 15 and 34 kWh/100km.

electricity consumption dropping to a range of 10 to 23 kWh/100 km (0.4 to 0.8 MJe/km) by 2025 (Figure 4C), values that are in line with other future projections of energy efficiency for personal vehicles in the next 15 years[18].

Note from Figure 4 that the energy needed to travel a kilometer using an EV is about one third of that required to travel the same distance using an ICE (Figure 4C vs. 4A and 4B).

When the data summarized in Figure 4 are combined with the projected gradual increase in both personal vehicle numbers in Alberta (Figure 3) and vehicle kilometres travelled per year (Figure 1), it is possible to calculate total energy use associated with personal vehicle use in the province of Alberta (Figure 5). In the reference scenario (Figure 5A), total energy use was projected to decline, reflecting the importance of the CAFE standards (Figure 4) in the energy efficiency of this sector. Note that electricity use for vehicles in the reference scenario accounted for only 0.8 petajoules per year in 2040, so it cannot be seen easily in Figure 5A.

In the EV scenarios, the energy demands for personal transport were much less than that in the reference scenario (Figure 5 B, C and D). This difference was attributed to the fact that EVs are about three times more efficient than ICEs in converting fuels/ electricity into motion.

The implementation of the CAFE standards may play out very differently from that assumed in Figure 4. For example, fuel efficiency gains that originate from the inclusion of more electric vehicles in the fleet may reduce the pressure on manufacturers to achieve the energy efficiency improvements in their ICE vehicles. In that case, overall energy use may be higher than that projected here (Figure 5), but then similar or even larger differences would be expected between the EVs and the vehicles powered by internal combustion engines.

4.3. 'Well-to-Wheels' GHG Emissions for Light Duty Vehicles used in Personal Transport

It is important to note that the energy use reported in Figure 4 and 5 represented only the energy use that occurred within the vehicles (i.e. 'Tank to Wheels'); none of the upstream energy use, either for

18 Bosch targets 12kWh/100km by 2020 (http://www.egvi.eu/uploads/1-3_BOSCH_EV2_Battery-ICT4FEV_2010_11_30.pdf), a number that is reused by others (http://e-mobility-nsr.eu/fileadmin/user_upload/events/2013_Hoje_Taastrup/3._Beate_Mueller__Roadmaps__Projects_And_Future_Plans.pdf). Others have projected even higher efficiency (8-10kWh/100km) by 2030 (http://www.transport2020.org/file/prof-jiang-kejun-nrdc-transport-day.pdf)..

producing gasoline or producing electricity, has been accounted for in these Figures. Estimates of the 'Well to Wheels' emissions add to the carbon footprint for both ICE Vehicles and EVs as described here:

For gasoline and diesel fuels. Combustion of gasoline and diesel fuels (i.e. 'tank-to-wheels' emissions) are known to release about 76 and 80 gCO_2e per megajoule (MJ) of fuel[19], respectively. However, there are also energy costs associated with recovering the oil, converting it to the refined petroleum products and delivering it to the vehicle where it will be consumed. When all these additional emissions are summed, and assuming Alberta's oil sands operations provide the feedstock, the resulting 'well-to-wheels' life cycle emissions have been estimated to range from 98 to 123 gCO_2e/MJ[20]. If we assume well-to-wheels greenhouse gas (GHG) emissions of 107 grams of CO_2e per megajoule (gCO_2e/MJ), the upstream emissions are about 34 to 41% higher than only those emissions associated with the combustion of the fuels.

For electricity generation in Alberta. For electricity generation from surface-mined coal, combustion emissions are approximately 1000 kg CO_2e per megawatt-hour (MWh) were assumed, and to these emissions were added an additional 2% to account for those emissions associated with recovery and processing[21]. In the case of natural gas used for power generation, Life Cycle Analysis (LCA) emission

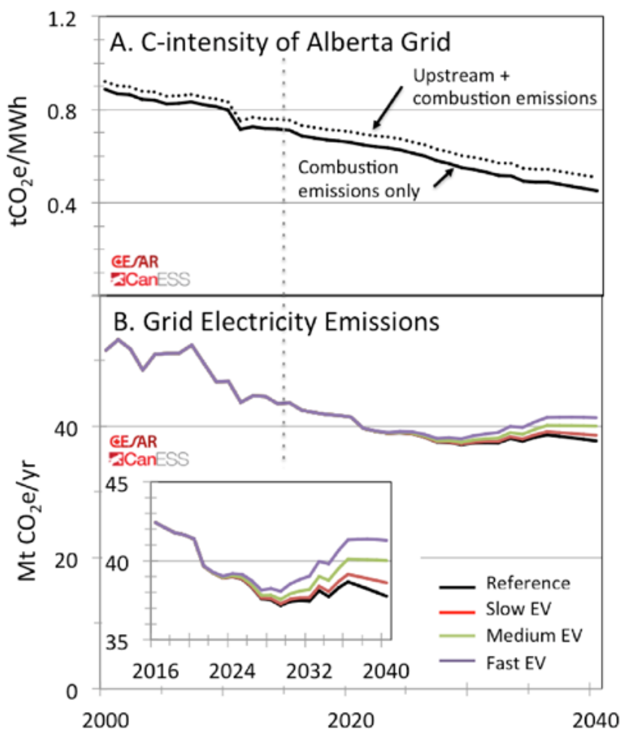

Figure 6. A. The carbon intensity of the Alberta electrical grid, which includes (dashed line) or does not include (solid line), the 'upstream emissions' associated with the recovery and processing of the coal or natural gas used for power generation. **B.** The GHG emissions from the 'public grid' in Alberta (not counting 'behind-the-fence' generation), including the upstream and combustion emissions associated with power generation. Values are provided for the reference scenario and three different scenarios for EV deployment. See Figure 2 for scenario assumptions.

19 From Table A2.6 in Environment Canada 2013. Canada's Emissions Trends (https://www.ec.gc.ca/ges-ghg/985F05FB-4744-4269-8C1A-D443F8A86814/1001-Canada's%20Emissions%20Trends%202013_e.pdf), then converted to Lower heating value (LHV)

20 Brandt, A 2011. Upstream greenhouse gas (GHG) emissions from Canadian oil sands as a feedstock for European refineries, Table 6 p 37.

21 Howarth, R et al, 2011. Supplementary material to Methane and the greenhouse-gas footprint of natural gas from shale formations. Climatic Change 2011, vol 106, p 679-690

were estimated to be 16% higher than the direct combustion emissions using either single cycle gas turbines (500 kg CO_2e/MWh) or combined cycle gas turbines (390 kg CO_2e/MWh)[22], resulting in life cycle emission intensities of 580 and 452 kg CO_2e/MWh, respectively.

There are numerous reports in the literature[23] providing evidence for much higher upstream GHG emissions associated with unconventional natural gas extraction processes, while others[24] suggest values closer to those assumed in the present study. If upstream emissions from shale gas production do prove to be much higher than currently estimated, and if gas does replace coal on the Alberta grid, the system level benefits of a switch to EVs may be significantly reduced or eliminated.

Historical data is available for the contributions of various generation sources to the 'public grid' (see Box 1) upon which electric vehicles are likely to be dependent. Figure 6A provides information on the GHG intensity of the Alberta public grid, measured as both the direct combustion emissions and the life cycle emissions. Future projections are based on the Alberta government's 50-year off-coal policy in mid 2015, not the more rapid coal retirement policies that were proposed in late 2015. In the earlier, off-coal policy, new generation must be replaced by generation sources equivalent to, or better than, natural gas combined cycle plants emitting approximately 418 kg CO_2/MWh.

When the scenario data depicted in Figure 5 where combined with emissions intensity data from Figure 6A, it was possible to calculate the impact of the four scenarios on the CO_2 footprint of the public grid (Figure 6B). Note that

Box 1: The Public Grid vs. Behind the Fence Generation in Alberta

In Alberta, about 30% of the electricity used in the province is generated by industries and institutions 'behind the fence' (BTF) in order to meet their own needs. Natural gas is their preferred fuel and cogeneration is often used to provide both heat and power.

Power generation in excess of the needs of BTF generators is often used to supplement the 'public grid', which currently gets the majority of its electricity from dedicated coal-fired power plants. The public grid is most likely to provide the power for electric vehicles.

22 (S&T)2 Consultants Inc 2011. Shale Gas Update for GHGenius. Link

23 Miller et al. 2013 Anthropogenic emissions of methane in the United States. PNAS 110: 20018-20022 (www.pnas.org/cgi/doi/10.1073/pnas.1314392110); Howarth 2015. Methane emissions and climatic warming risk from hydraulic fracturing and shale gas development: implications for policy. Energy and Emissions Control Technologies. 3: 45–54; Howarth, R et al., 2014. A bridge to nowhere: methane emission and the greenhouse gas footprint of natural gas. Energy Science & Engineering, doi: 10.1002/ese3.35.

24 Heath et al. 2014. Harmonization of initial estimates of shale gas life cycle greenhouse gas emissions for electric power generation. PNAS 111: E3167–E3176 (http://www.pnas.org/cgi/doi/10.1073/pnas.1309334111)

the proportional projected impact of EV deployment was relatively small: the fast EV scenario, for example, required about a 9% increase in grid generation by 2040. Nevertheless, that amount still represents about 3.5 Mt CO_2e/yr of additional emissions associated with power generation.

In the current study, the emissions associated with vehicle manufacturing were not included, for a number of reasons:

- It seems unlikely that the vehicles would be manufactured within Alberta and the current study was focused on Alberta's emissions;
- If the vehicles were manufactured in Ontario, the low carbon footprint of that province's grid would lower the overall carbon footprint of vehicle manufacturing (EV or ICE) compared to a vehicle produced in a U.S. state that has a more carbon-intense grid. To our knowledge, such an analysis has yet to be published.
- If the next decade brings a significant increase in car sharing (especially self-driving, car-shared vehicles), the number of vehicles on the road could be dramatically reduced. While the kilometres travelled per vehicle would increase, the contribution of vehicle manufacturing to the overall environmental footprint of personal transport would be proportionately reduced.

Certainly, the GHG footprint associated with vehicle manufacturing is an issue that needs to be considered in a full systems level analysis of options for LDV deployment. It will be considered further in the following section.

4.4. Carbon footprint for new personal vehicles traveling 15,000 km/yr

Using the 'well to wheels' data described in the previous section, and assuming 15,000 km/yr travel made up of city (60%) and highway (40%) driving, it is possible to project the annual emissions of new gasoline-powered or EV cars (Figure 7A) and trucks (Figure 7B) into the future.

Despite the high carbon intensity of the Alberta grid, over the period 2016 to 2040 EVs emitted from 921 to 1,736 kg CO_2e per vehicle per year lower GHG emissions than similar sized gasoline-powered vehicles. The declining carbon intensity of ICE vehicles up to 2025 was due to the projected implementation of the CAFE standards, as discussed previously (Figure 4). After 2025, the more rapid improvements in GHG emissions from EVs (Figure 7A&B) were attributed to the continued improvement in the carbon intensity of the Alberta grid (Figure 6A).

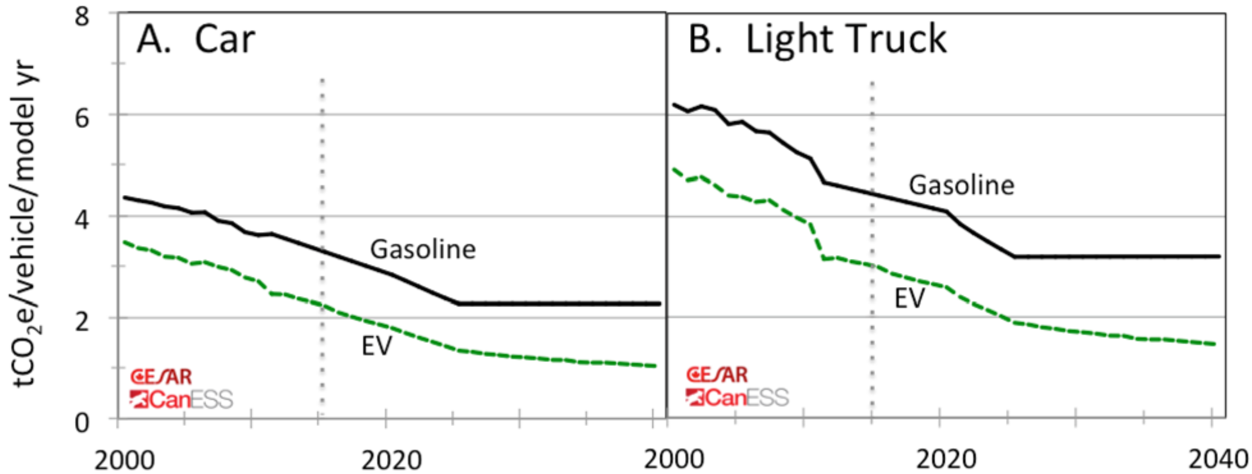

Figure 7. Projected annual emissions of new gasoline-powered or EV cars (A) or light trucks (B) in Alberta traveling 15,000 km/yr assuming 60% city and 40% highway. The calculations took into account the CAFE standard for fuel efficiency, gasoline from the Alberta oil sands and EVs using power from the Alberta public grid, including upstream emissions for coal and natural gas recovery and processing.

While these numbers should reflect the within-Alberta emissions associated with the LDV choices, as noted previously, the calculations of carbon footprint do not consider the energy or GHG emissions associated with vehicle manufacturing.

As summarized in Box 2, the emissions associated with manufacturing can be substantial, estimated as almost twice that of an equivalent ICE-powered vehicle. When the manufacturing and use phases are both taken into account, it has been estimated that a grid intensity of less than 600-700 kg CO_2e/MWh is needed before an EV will have a life cycle GHG benefit that will make it better than an ICE vehicle. The precise threshold depends on a wide range of factors including the grid intensity where the vehicle components and vehicles are manufactured and charged, the number and kinds of batteries used within the vehicles and the number of km driven in the lifetime of the vehicle.

In Alberta, the grid intensity is expected to drop below 700 kg CO_2e/MWh sometime over the next 10 years, and with the government's new off-coal policies, this may be a decline that is sooner and more precipitous than what is shown in Figure 6A.

Box 2: Vehicle Manufacturing and the Greenhouse Gas (GHG) Costs associated with Plug in Electric (EVs) compared with Internal Combustion Engine (ICE) Vehicles

A study by Hawkins et al. (2013)[1] is among the most cited assessment of the carbon cost of manufacturing electric vehicles. Focused on the situation in Europe, their report estimates that the greenhouse gas (GHG) cost for manufacturing EVs (87 to 95 g CO_2e/km) is about twice that associated with production of a similar vehicle relying on ICE propulsion (43 g CO_2e/km). Given the carbon intensity of the typical European natural gas grid (643 g CO_2e/kWh), the carbon footprint for manufacturing accounted for almost half the entire life cycle cost that also included the generation of the electricity needed to fuel the vehicle.

At this grid carbon intensity, Hawkins and coworkers concluded that EVs had a similar life cycle footprint to a conventional diesel-fueled vehicle, so a grid intensity of less than 643 g CO_2e/kWh would be needed to ensure that EVs were better for climate change mitigation than conventional ICEs in Europe.

While the carbon intensity of Alberta's public grid is declining, it is currently over 700 g CO_2e/kWh, suggesting that EVs in Alberta would not be better than conventional ICEs in carbon footprint. However, there are a number of reasons why the threshold grid intensity in Alberta is likely to be higher than the 643 gCO_2e/kWh reported in the European study. These include:

- **Gasoline fueled LDV have lower efficiency than diesel.** In Canada, most personal LDVs are gasoline fueled and gasoline ICEs have about 15% more life cycle GHG emissions than similar diesel vehicles (Hawkins et al. 2013) that are more prevalent in Europe. Also, if one assumes that the refined petroleum products come from Canada's oil sands, the life cycle emissions associated with gasoline production and use are likely to be higher than that in Europe.
- **LDVs are driven further in Alberta than in Europe.** In the Hawkins et al (2013) study, the expected driving lifetime was assumed to be 150,000 km, a value that may be reasonable for Europe, but not for Alberta or Canada. Adjusting that lifetime to a more typical 250,000 km would reduce the life cycle GHG emissions by 37 g CO_2e/km, equivalent to a 20% reduction in per km emissions.

In addition, there are other recent trends that point to EV's having a more positive effect on the climate change footprint relative to ICE vehicles in Alberta:

- **New Policies for Alberta's Public Grid.** In fall 2015, the Alberta government announced a new climate change plan that included an accelerated coal plant retirement and 30% renewables on the Alberta grid by 2030. If deployed, this would result in a more precipitous decline in the C intensity of the Alberta grid.
- **Movement towards EV, Self-driving and Car-Sharing vehicles.** The current movement to EV, self-driving and car-sharing vehicles would result in fewer vehicles serving more people and having a higher driving lifetime. That would reduce the per km contribution of EV manufacturing to the life cycle GHG footprint of such vehicles.

While it is not possible to accurately predict the future, it seems likely that the life cycle GHG cost for EVs will soon be lower than similar ICE vehicles, if they are not already, even in Alberta.

1 Hawkins et al. 2013. Comparative Environmental life cycle assessment of conventional and electrical vehicle. J. Industrial Ecology 17: 53-64.

4.5. Province wide projections of GHG emissions from personal light duty vehicles

When the well-to-wheel GHG emission factors were applied to the scenario projections in Figure 5, it was possible to calculate the province-wide GHG emissions associated with light duty vehicles used for personal transport (Figure 8). Note that the current emissions were estimated to be about 13 Mt CO_2e/yr and with implementation of the CAFE standard, these are projected to decrease to about 10 Mt CO_2e/yr by 2040 (Figure 8A). However, with the slow, medium and fast EV scenarios, reductions to 9.3, 7.4 and 5.9 Mt CO_2e/yr by 2040, respectively, were projected. Therefore, by 2040, the fast EV scenario was projected to result in a 43% reduction in the total province-wide GHG emissions associated with the personal use of light duty vehicles.

This change can more easily be seen in Figure 9A. The cumulative GHG benefits of each scenario relative to the reference scenario is shown in Figure 9B. Compared to the reference scenario, in the

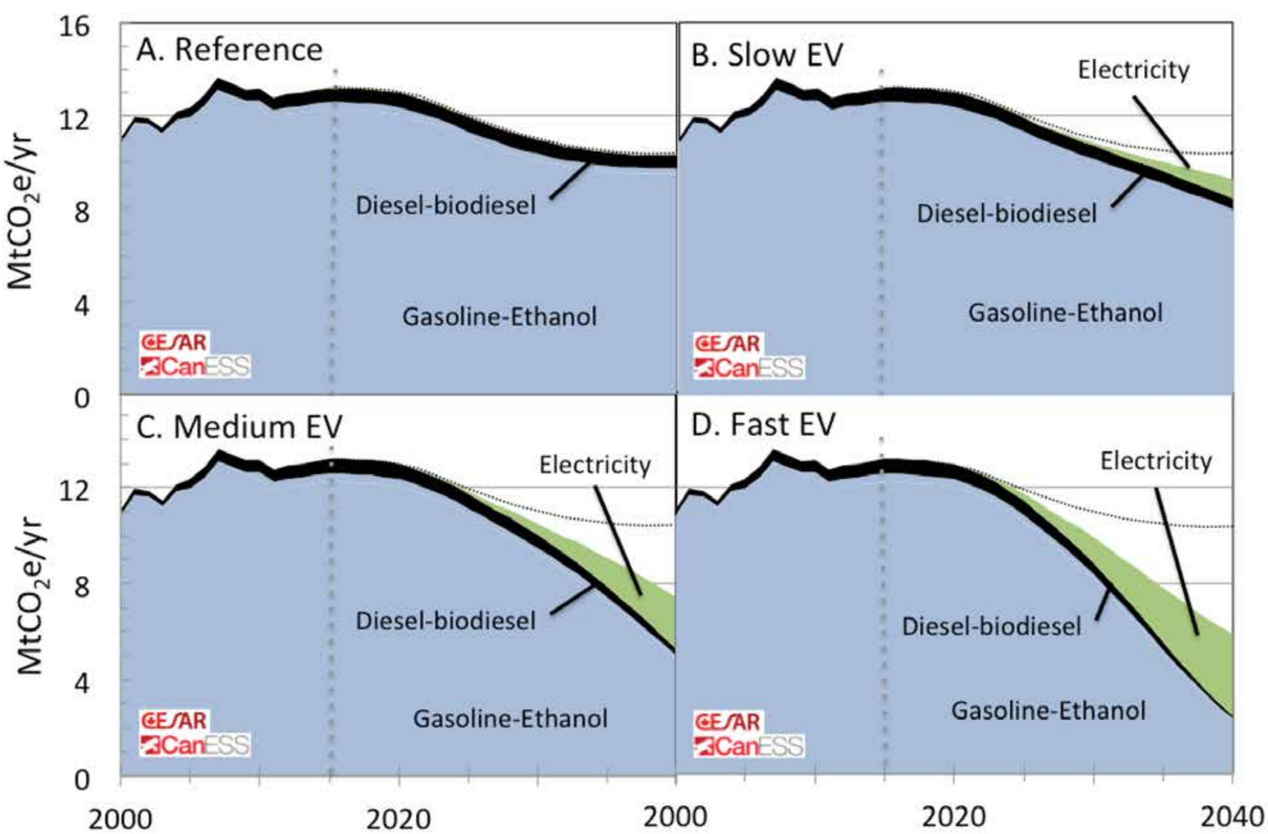

Figure 8. Well-to-wheels greenhouse gas (GHG) emissions associated with the projected energy use of personal vehicles (Figure 4) for the reference scenario and three different scenarios for EV deployment (Panels A to D). See Figure 2 for scenario assumptions. The dashed lines in panels B to D show the total GHG emissions in the reference scenario (Panel A) to illustrate the magnitude of the reduction for each scenario.

fast EV scenario, the light duty vehicles for personal transport were calculated to result in 31 Mt CO_2e lower GHG emissions by 2040. Cumulative savings to 2040 for the medium and slow EV scenarios were 17 and 6 Mt CO_2e, respectively.

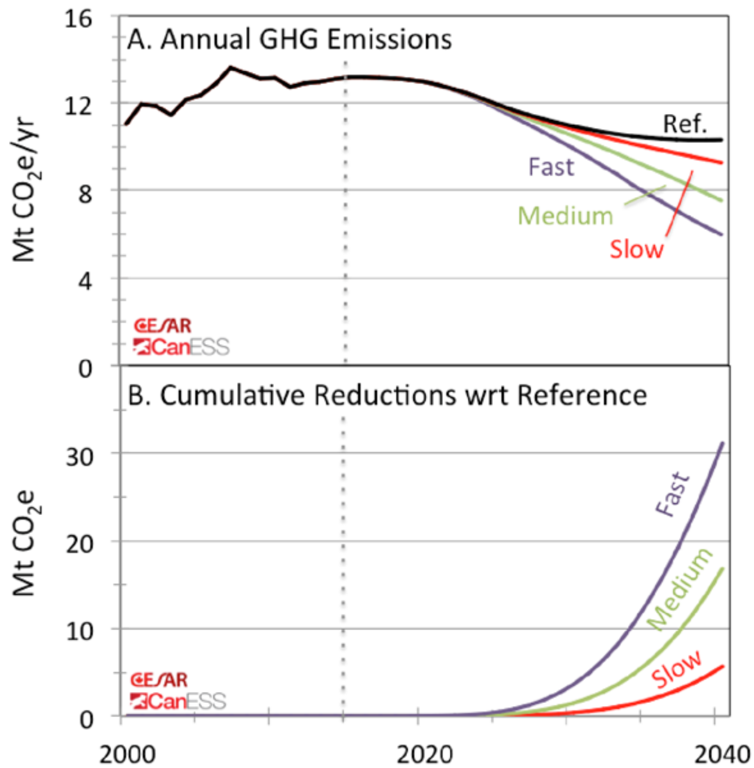

Figure 9. A comparison of well-to-wheels greenhouse gas emissions from scenarios for EV deployment of light-duty vehicles for personal use in Alberta. A. Total annual emissions from each of the four scenarios, including the reference scenario. B. Cumulative emissions reductions for the slow, medium and fast EV scenarios relative to the reference scenario.

4.6. EV Scenario impacts on Oil Demand

From an Alberta perspective, it is also of interest to explore the implications of a move to EVs on the demand for oil in the province, across North America and globally. To carry out this calculation, the gigajoules (GJ) of energy in gasoline or diesel not used were converted into barrel of oil equivalents with a conversion rate of 5. 4 GJ/barrel for gasoline and 5.9 GJ/barrel for diesel.

By 2040, the slow, medium and fast EV scenarios projected reduced oil demand in Alberta (relative to the reference scenario) of 9,000, 23,000 and 36,000 barrels/day, respectively (Figure 10). Assuming that such a shift to EVs would be a North American or global phenomena, not limited to Alberta, the Alberta results were scaled to North American or global levels.

This was done by multiplying the results for Alberta (Figure 10) by the ratio of oil use in North America or globally[25] to oil demand in Alberta for the 2000 to 2013 period or projected to 2040. The Alberta to North American multiplier was 70 times in 2000 (as Alberta consumed 70 times less crude oil than all of North America in 2000)

25 From http://www.indexmundi.com/energy.aspx?country=ca&product=oil&graph=consumption

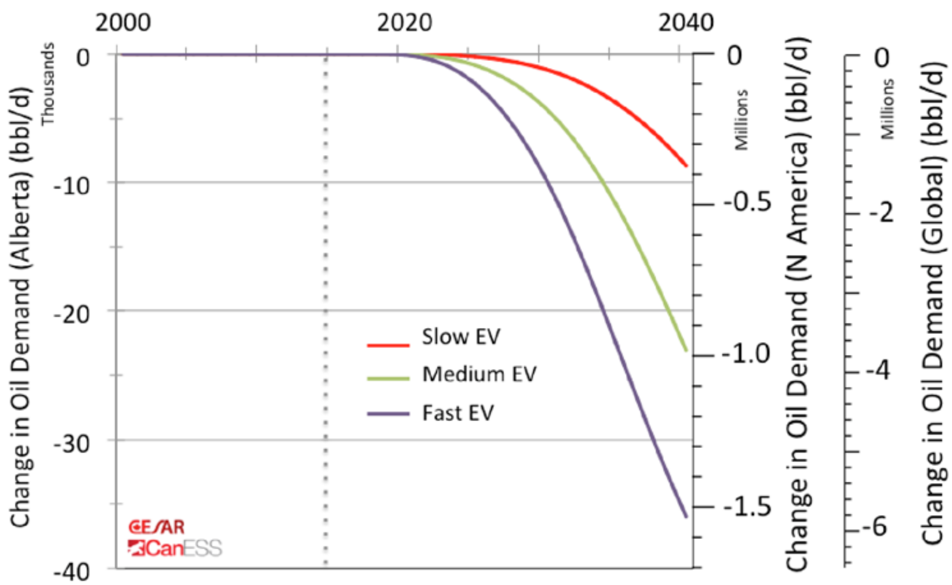

Figure 10. A comparison of the projected reduction in demand for oil, relative the reference scenario for the slow, medium or fast EV deployment scenarios in Alberta. See Figure 2 for details on the scenarios.

but declined to 43 times in 2040. The Alberta to global multiplier ranged from 225 in 2000 to 165 in 2040.

For the fast EV scenario, North American demand for oil was projected to decline, relative to the reference scenario, by 1.5 million bbl/day, while global demand was projected to decline by about 6 million bbl/day (Figure 10).

To put these numbers in perspective, global oil demand is currently about 90 million bbl/d, so the decline represents approximately a 7% reduction. This may not sound like a lot, but a small change in the supply- demand balance for oil has been shown to have a large impact on price. This is because oil tends to be 'priced at the margin' so when supply exceed demand, even if only by

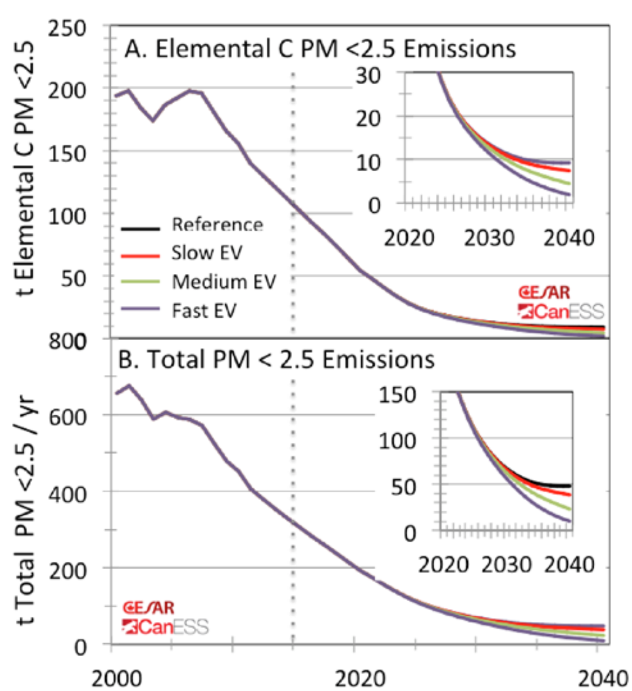

Figure 11. The effects of EV deployment on particulate matter emissions from personal uselight duty vehicles in Alberta.

1% to 3%, there can be up to a 300% change in price. This happened in 2008 and again in 2014-15.

For a province like Alberta that is so dependent upon oil production and its export to markets, it is important to understand and be prepared for the potential impacts of EVs on the local economy.

4.7. EV Scenario impacts on Criteria Air Contaminant (CAC) Emissions from Light Duty Personal Vehicles in Alberta

The shift to electric vehicles also promises to result in reduced Criteria Air Contaminants (CACs), including particulate matter (Figure 11), hydrocarbon and methane emissions (Figure 12), and oxides of nitrogen and sulfur (Figure 13). These plots show only the reduction in tailpipe emissions from the vehicles. Of course many of these gases will be generated by thermal power generation, especially if electricity is generated from coal power.

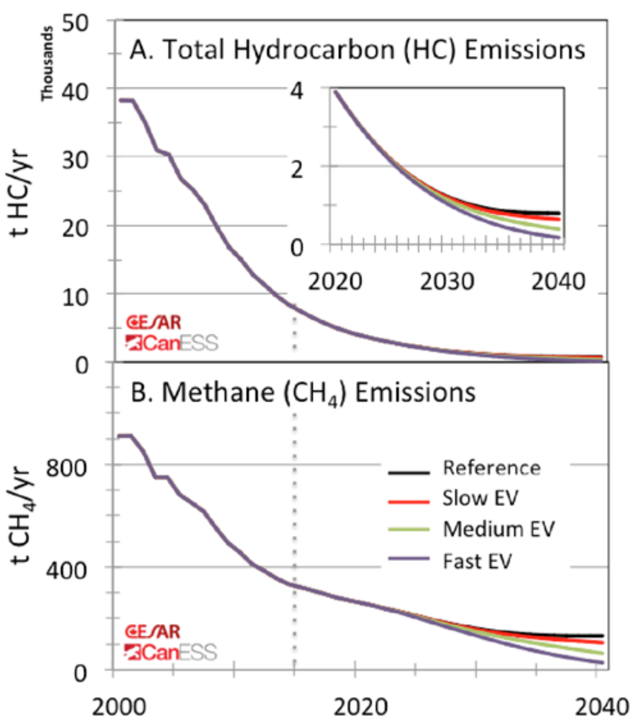

Figure 12. The effects of EV deployment on total hydrocarbon (A) and methane (B) emissions from personal use light duty vehicles in Alberta.

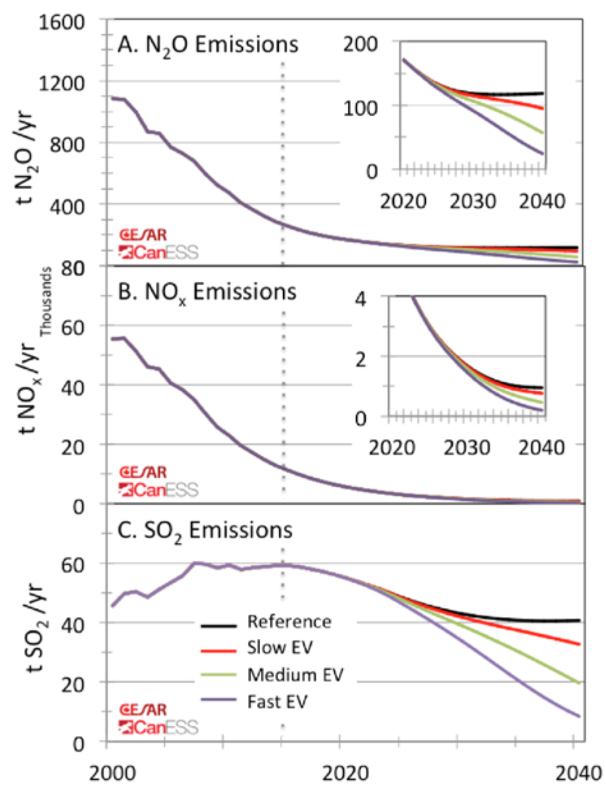

Figure 13. The effects of EV deployment on N_2O (A), NO_x (B) and SO_2 (C) emissions from personal use light duty vehicles in Alberta.

Consequently, the benefits shown in Figures 9-11 would only be realized by communities that are exposed only to tailpipe emissions, but not to emissions from large thermal power plants.

The CACs reductions associated with EV deployment over the next 25 years are projected to be in addition to the reduction in emissions achieved by automobile manufacturers should they adhere to the regulations defined by the CAFE standards.

5. Conclusions

The transformation to plug-in electric vehicles (EVs), if it occurs over the next decade or two, is unlikely to be a decision that will be made in Alberta. The same can be said about car sharing and self-driving vehicles.

Rather, these transformative technologies will be a result of innovation, public perceptions and marketing strategies that will be developed elsewhere, but result in a plethora of new choices that will be made available to consumers in Alberta. Municipal, provincial and federal governments may be able to speed or slow this transformation, but they will not be able to control whether it occurs or not if it is moving forward in other parts of North America and the world.

Whether these transformations are good or bad for the province – whether the province 'rides the wave' or is 'swamped by it' – is largely a choice that the province and its communities need to make. Clearly, it would be sensible to prepare for and make the most of the transformation if it is coming.

For example, perhaps Alberta, like Ontario[26], should permit the testing of automated vehicles and related technology on-road. With such regulation, Alberta companies could conduct research and development to support opportunities to bring automated vehicles to market.

The scenario models developed and reported here are focused only on EVs. The models show potential environmental benefits, including lower emissions of GHGs and criteria air contaminants, associated with the transformation from internal combustion vehicles to EVs.

The most significant projected environmental benefit was associated with the reduction in GHG emissions. In the fast EV scenario, cumulative emission reductions for the province were projected to reach 31 Mt CO_2e/yr by 2040 relative to a 'business-as-usual' reference scenario in which EV deployment in 2040 was little higher than it is today (see Figure 9)

However, the projected EV benefits assume that the electrical grid in Alberta becomes significantly cleaner, in terms of GHG emissions, than it is at the present time. Shifting from coal-fired power generation to lower emitting sources (like renewables and natural gas)

26 https://news.ontario.ca/mto/en/2015/10/ontario-first-to-test-automated-vehicles-on-roads-in-canada.html

must be a priority, but it is also important that the upstream emissions from the lower emitting sources (especially natural gas) are minimized and tightly regulated. The province must ensure that if natural gas is to replace coal in the generation of electricity in the province, it is not as bad or worse than coal in the well/mine-to-grid emissions.

Increasing the GHG benefits of a shift to EVs would benefit from the more rapid coal retirement, and the increased role for renewable that has recently been proposed by the province of Alberta.

In a provincial economy dependent upon oil recovery and export, a North American or global transformation to EVs would likely have a negative impact on the price received for each barrel of oil and therefore on the strength of the provincial economy (see Figure 10). This reality emphasizes the importance of diversifying the economy of the province while focusing on improving the efficiency and reducing the environmental footprint associated with recovering, processing and moving the oil to market.

Over the last 30 years, technological innovations (especially digital technologies) have transformed the music, movie, book, media, photographic and telecommunications sectors. Companies that dominated these sectors 25 years ago either no longer exist, or are a shadow of their former selves.

There are many who predict that personal, light-duty vehicle transportation is the next major sector that is on the cusp of technology disruption and transformation. EVs are part of this transformation, but when combined with car sharing and self-driving vehicles, the implications of this convergence for the design of our cities, the future role for public transport, and the jobs available for citizens, are at least as important as the future of the province's fossil energy industry.

Policy makers and the public need to be plugged into these potential changes that both threaten and provide opportunity for the province and the communities it supports.