Advanced Automotive Systems, Electrification, and an Overview of Relevant Policy Concerns

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Introduction*

The word "sustainable" refers to any system that can maintain itself by relying on resources available for continual reuse. By this definition, transportation systems based on non-renewable fossil fuels are unsustainable over the long-term. The twentieth century witnessed the rise of petroleum-based transportation systems, driven primarily by the internal combustion engine (ICE) fueled by gasoline or diesel. As a result, the twenty-first century is now witnessing catastrophically rising emissions and smog levels, pernicious greenhouse gases (GHGs), and climate change phenomena. These environmental events have added to economic insecurity concerns caused by highly variable fuel prices and uncertain petroleum supplies, insofar as those supplies emanate from outside the North American marketplace. Weakened global demand for oil due to continuing recessionary and slow growth in many developed and emerging economies has driven down the average price of a barrel of Brent Crude to $83 per barrel (in November 2014). [1, 2] The resulting drop in fuel costs (both gasoline and diesel) has supported the use of petroleum fuels by vehicle owners who are less concerned about the costs of fueling up. [3, 4] Perhaps more problematically, the variability and unpredictability of globalized oil pricing mechanisms constitute significant economic barriers for jurisdictions reliant primarily upon stable oil royalties and revenues for social service funding. [5]

In manufacturing jurisdictions, such as Ontario, the variability in the pricing of petroleum-based fuels constitutes a barrier to economic growth. As the Government of Ontario has noted in its *Long Term Energy Plan*, "Oil and natural gas, as well as the pipelines that deliver these products are essential to the quality of life and economic prosperity that Ontarians enjoy." [6] Perhaps not surprisingly, the *Long Term Energy Plan* has focused its rhetoric on encouraging domestic supplies of oil and natural gas via major pipeline installations and infrastructure expansions, which are presumably expected to enable more predictable and stable fuel sources for the province's manufacturing and transportation-based economy.

In sum, the pursuit of sustainable, low-emissions transportation systems in any jurisdiction will involve overlapping interests, some of which run counter to provincial policy efforts in Canada to ensure low-cost, stable supplies of petroleum fuels. Achieving energy and transportation sustainability will require, therefore, a multi-faceted industrial and public policy approach that unites technological innovation, economic productivity, and infrastructure design with explicit public leadership.

On the technological front, a world of sustainable transportation will require a series of new enabling technologies. This paper is dedicated to a survey of some of those technologies in so far as they support low-emissions, electrified transportation as a replacement solution for carbon-intensive mobility over the long-term. Specifically, these enabling technologies include new generations of advanced automotive systems that will supplement and replace internal combustion engines (ICEs) powered by petroleum-based fuels.

Gasoline and diesel are currently the world's most prominent forms of propulsion energy. Judged using social, political, economic, and environmental metrics, those

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sources of fuel fail to address the long-term sustainable growth needs of the world's population. By contrast, electrified propulsion systems that rely on electricity as a transportation fuel can provide sustainable solutions for the transportation needs of a growing global population, particularly if the sources of electricity are renewable in nature, including hydro, solar, wind, and tidal power. If renewably-generated electricity is developed as a primary, reliable, and ubiquitous source of transportation fuel, then it is possible to imagine a world in which ICE technology is incrementally replaced over the next century with hybridized and fully electrified propulsion systems. To achieve those goals on the vehicle side of the sustainable transportation continuum would mean designing, prototyping, mass manufacturing, and ultimately selling new electrified transportation technologies that are as reliable, as scalable, as safe, and as culturally conventional as ICE technologies are today.

Social and cultural transitions in transportation thinking and practices could be motivated by targeted policies that complement the evolving technological landscape in electrified transportation

The pursuit of what can only be deemed to be a profound and socially transformative shift in power-generation and propulsion technologies over the next century requires one to underscore the relevance and (possibly) causally antecedent nature of changed behavioral patterns and expectations with regards to transportation overall. Private and public investments in research and development are unlikely to be sufficient if the socio-cultural contexts within which they occur are ones hostile to the acceptance, integration, and viable commercialization of such technologies. Social and cultural transitions in transportation thinking and practices could be motivated by targeted policies that complement the evolving technological landscape in electrified transportation, helping thus to overcome the profound and ingrained individual, fleet, and industrial dependence upon petroleum-based transportation systems. For example, newly electrified systems will need to demonstrate undeniable fuel economy and cost savings for the electric vehicle (EV) buyer, along with unparalleled efficiency (i.e. low- or zero-emissions) for the environmental consumer and for public agencies interested in reducing the negative effects of smog and pollution in general. Electrified technologies will also have to demonstrate ease of use (i.e. complementary infrastructure) for superior convenience and exceptional affordability for both individual buyers and fleet owners.

Through a mélange of demand-side incentives, such as consumer/dealership rebates, high-occupancy lane approvals, free charging stations, easy parking access, and preferred insurance rates, along with targeted supply-side investments, such as R&D support for high-risk innovations within university and college engineering departments as well as small-to-midsized enterprises within the automotive supply chain, the vision for a low-emissions, sustainable transportation society could be operationalized incrementally in decades to come.

This paper explores the profound improvements to drivetrain technologies required to support this incremental transition. The improvements summarized here include ameliorations to motors, batteries and energy storage devices, and power electronics as well as smart- and micro-grid systems required to power new propulsion technologies. Combined, these technologies pose the possibility of overtaking current drivetrain technologies composed of inefficient, energy-intensive heat engines. The guiding principle shaping the current discussion is one in which hybridized and fully electric vehicles are assumed to constitute a majority of passenger vehicles sold worldwide by 2050.

Published with the support of Natural Resources Canada, Electric Mobility Canada's *Electric Vehicle Technology Roadmap* (evTRM) states an expectation that public and private investments combined ought to produce a shift in consumer adoption profound enough to result in at least 500 000 highway-capable plug-in electric-drive vehicles on Canadian roads by 2018. Electric Mobility Canada (EMC) is a not-for-profit industry organization composed of more than 140 OEMs, suppliers, utilities, government agencies, and non-government organizations involved in electric mobility across North America. Its 2010 *Roadmap* states a belief among its member organizations that these vehicles will have more Canadian parts content than vehicles on Canadian roads in 2008. [9] As of November 2014, just under 10,000 plug-in hybrid and all-electric vehicles have been sold across Canada. Thus, the expectation that 500,000 plug-in electric cars would roam Canadian roads by 2018 no longer holds sway; however, there is a continued and reasonable belief in steady worldwide growth for electrified and electric-drive vehicles, which include hybrid, plug-in hybrid, and battery-electric vehicles. [10] Among some observers, exponential growth of these vehicles is on the horizon, despite small sales quantities to date. As *The Economist* recently reported, although only a "modest" 250,000 plug-in cars drive silently along American roads (and currently account for under one per cent of all vehicles sold so far in the USA), those sales have been doubling annually since the 2000s as more models of plug-ins and all-electric vehicles hit dealership showrooms year by year. Notably, this doubling in annual sales among plug-in and battery-electric vehicles overshadows the seemingly paltry five per cent annual growth for the entire car industry across the USA over the same time period. [11]

In this paper, expectations for continued exponential growth for plug-in hybrids and battery electric hybrids will be situated within a landscape demonstrating ongoing and significant barriers still facing advanced automotive systems. A number of important innovations to overcome these barriers are already under-way, motivated largely by stringent emissions regulations in the United States, the European Union, and now China. The furtherance of these technologies through sustained private and public investment in research, development, and commercialization is, however, key to shaping a globally sustainable automotive industry over the next half-century. Thus, insofar as the industrial implementation of cutting edge technologies plays a role in achieving that goal – a goal articulated by the International Energy Agency in 2011 as enabling a reduction in global emissions to 50 per cent of current CO2 level through the electrification of a predominant portion of world's automotive and transportation systems [12] – the following discussion presents a review of technological pathways to focus on going forward.

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Alternative fossil fuel options

While the following discussion is focused on enabling technologies related to electrified transportation, other enabling technologies for low-emissions or at least lower-emissions transportation should be noted. A full discussion of fuel technologies based on "clean" diesel, compressed natural gas (CNG), liquefied natural gas (LNG), and hydrogen fuel cells is beyond the remit of this paper. However, the rising prominence of unconventional sources of natural gas in North America is a relevant factor to highlight here.

Those sources of natural gas existing in "unconventional" forms, such as coal bed methane, gas hydrates, and shale gas, have been made accessible in recent years by new extraction technologies, including intensive hydraulic fracturing. These technological innovations have helped to make Canada the world's third top natural gas producer, and they have played a significant role in driving down the price of natural gas products overall. For these reasons, natural gas is oft-cited as an abundant energy resource that is affordable, safe, locally produced, and reliable as a non-imported product across North America. [13, 14]

Natural gas now serves as an enabling technology for low-cost, lower-emissions transportation based on a domestically available fuel source.

The degree to which unconventional natural gas-powered transportation might offer viable low-emissions alternatives to gasoline and diesel-based transportation systems remains to be determined. For example, cars and trucks equipped with compressed natural gas (CNG) powertrains use the combustion of methane stored at high pressures to convert stored energy in the CNG into kinetic energy, i.e. propulsion. In doing so, they enable reduced emissions when compared to traditional ICE systems, since CNG combustion produces fewer GHGs and noxious gases compared to gasoline or diesel combustion. [15] However, there are technological limitations to CNG powertrains, including the volume of space required for CNG storage on board and the resulting difficulties in designing small-sized, long range, CNG powered vehicles. [16] Thus, CNG-powered vehicles typically require additional gasoline or diesel systems for range-extension (i.e. dual fuel systems). Despite the requirement for range-extending petroleum-based ICEs onboard, CNG dual-fuelled systems nonetheless demonstrate significant reductions in greenhouse gases (GHGs), including carbon dioxide, carbon monoxide, and nitrogen oxides, when put into operation. In addition, due to the relative cheapness of CNG compared to gasoline or diesel, these vehicles enable overall cost reductions for owners. [17]

Both CNG and LNG-powered vehicles already exist in the United States and worldwide. According to the U.S. Department of Energy, natural gas serves as a primary fuel for approximately 112,000 vehicles in the USA and 14.8 million vehicles worldwide. The DOE reports that natural gas vehicles (NGVs) that run on compressed natural gas (CNG) typically achieve high-mileage, which is ideal for "centrally-fueled fleets that operate within a limited area", while liquefied natural gas (LNG) serves as an ideal choice for long-distance driving requirements. Aftermarket conversions to LNG powertrains have become popular among some truck fleets, while CNG manufactured cars, such as the Honda Civic Natural Gas (CNG) model, have been sold to both individual and fleet consumers in the US for more than four years now. Although CNG and LNG technologies require further analysis in terms of their ubiquity and access for individual consumers, and although they face a series of technological barriers in terms of their integration into powertrains for small vehicles, it is fair to say natural gas now serves as an enabling technology for low-cost, lower-emissions transportation based on a domestically available fuel source, which already benefits from existing and widespread distribution and fuelling infrastructure. [18]

Electrified automotive transportation for the twenty-first century

The following discussion on electrified transportation technologies is divided into five sections. The first section reviews industrial and public policy initiatives that are already shaping technological innovations in advanced automotive systems and electrification. The second section describes efficiency improvements in ICEs. The third section explores cutting-edge technologies related to advanced automotive systems for hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs). The fourth section describes the relevant role of smart grid systems and charging infrastructure. The fifth section reviews demand-side and supply-side policy innovations developed by provincial and federal governments in Canada in recent years to encourage EV adoption and advanced EV manufacturing.

As we will see, to achieve the IEA's stated objective that 100 million hybrid or fully electric vehicles need to be on roads worldwide by 2050 to enable transportation sustainability in the long-term, a series of technological and policy innovations will need to be pursued over the next five year period.

Industrial and policy background

The global financial crisis (or the "Great Recession") sparked by the U.S. subprime mortgage crisis from 2008 onwards resulted in some of the worst years in automotive sales in America since the early 1980s, with U.S. car and truck sales totalling a mere 10.6 million units in 2009 (down from 13.5 million in 2008). [19] The spread of the global financial crisis in 2009 led to a worldwide decline in automotive sales with new-car sales collapsing from more than 70 million to fewer than 50 million in the same year. By 2013, the European Union was still experiencing constricted growth in the automotive sector, despite multiple government bailouts of ailing banks, protective measures to ensure the viability of the Euro, and injections of cash to offset drooping domestic consumption. Though the European Union posted a 0.3 per cent quarterly growth rate in the second quarter of 2013 (marking the end of a long recession in the region), national austerity measures taken to reign in public finances across member states, including France, Italy and Spain, continued to restrict the capacity of consumers to buy new vehicles well into 2014. [20] The fact the region slipped back into recessionary conditions by the third quarter of 2014 has led to varied expectations related to vehicle sales over the next year.

But despite Europe's problematic economic conditions, the rapidly growing economies of Asia and especially China, which overtook the United States as the world's single largest automotive market in 2009, have bolstered global automotive sales in recent years. Though China reports highly variable monthly automotive sales, it has continued to demonstrate strong growth over the past half-decade. In 2012, it reported 15.5 million passenger vehicles sold, and according to the China Association of Automobile Manufacturers (CAAM), vehicle sales in China rose 20.3 percent in October 2013 from 2012 levels. [21, 22]

On the other hand, by the end of 2013, North America's automotive industry had also recovered to pre-recessionary levels, both in terms of manufacturing and sales numbers. By the fall of 2014, vehicle sales had increased across the United States, Canada, and Mexico, reaching more than 19 million units (with an estimated 1.79 million units sold in Canada by the end of the year). [23, 24] Six years after the Great Recession unfolded, the global automotive industry has regained much of its pre-crisis momentum. Vehicle production around the world grew from nearly 78 million in 2010 to over 81 million in 2012, with that number projected to rise beyond 100 million worldwide by 2015 as emerging markets in China and Central South America drive a worldwide growth in sales.

In contrast to its US and German counterparts, the Spanish government advanced an explicit industrial policy strategy characterized by a combination of horizontal and sectoral policy measures in late 2010.

In sum, the automotive industry is growing, but it is also changing.

Governments across North America, Europe, and now Asia are seeking to limit emissions and smog by attempting to shift not only the source of electrical power, but also the source of transportation fuel. Environmentally minded policy pressures have shaped advanced automotive innovations since the turn of the present century, and they have been especially effective in shaping new product lines since 2009. These pressures have encouraged and – in the case of California, at least – enforced injections of research funding and industrial investment in the development of electrified and low-emissions powertrains. A notable public policy tool in this respect is the Corporate Average Fuel Economy (CAFE) standards overseen by the U.S. National Highway Traffic Safety Administration (NHTSA). The 2012 iteration of those standards mandates North American cars must double their fuel efficiency to 54.5 mpg by 2025; Canada has adopted the same standard, requiring significantly cleaner cars on Canadian roads in just over a decades' time.

In California specifically, the Zero Emissions Vehicle (ZEV) regulations have mandated additionally requirements for zero emissions automotive technologies, requiring automotive manufacturers to sell a certain percentage of ZEVs – including hybrids, plug in hybrids, battery electric vehicles, fuel cell vehicles and some "clean" gasoline vehicles – as part of their overall fleet of sales. A vehicle manufacturer's ZEV requirement is calculated as a percentage of all passenger cars and light-duty trucks ranging between 0 to 8,500 pounds brought into the state for sale. As of 2012, "large volume" manufacturers including Chrysler, Ford, GM, Honda, Nissan and Toyota were required to offer varying numbers of ZEVs based on the overall number of units brought into the state for sale. For example, Chrysler is required to bring into the state for sale more than 118,000 such units, Ford is required to bring in more than 143,000, General Motors nearly 160,000, Honda nearly 230,000, Nissan more than 135,000 and Toyota at nearly 297,000. Manufacturers who comply with these mandated targets earn ZEV credits. Those manufactures that fail to comply with the ZEV regulations are fined penalties of $5,000 per ZEV credit not realized. The overarching objective of the current ZEV program is to achieve 1.5 million ZEV vehicles in California by 2025, supporting thereby the state's 2050 target an overall reduction of GHGs from the transportation sector to 80 percent less than 1990 levels.

The European Union has also adopted a series of robust policies aimed at generating sustainable modes of transportation reliant upon domestic "clean" electricity supplies. The objective outlined in these policies is to simultaneously lower emissions from power generation and transportation, while also promoting energy independence of the (now) 28-member union vis-à-vis other major energy markets, including Russia, the United States, and China. The EU's *Renewable Energy Directive* (RED) mandates that levels of renewable energy across the region must reach 20 percent of total energy consumption by 2020 with a 10 per cent share of that transition emanating from the transportation sector. The EU has also approved an amendment to its *Fuel Quality Directive* (FQD), which mandates a six per cent reduction in GHG intensity of fuels used in road transportation by 2020. [25]

These combined North American and European policy tools have chipped away at traditional ICE technologies for over a decade now. The design constraints imposed by public policy requirements for extremely efficient combustion engines (note, the ZEV mandate was first put into action in 1990), resulted in varied responses in the late-1990s by global auto companies. Toyota offered its first Prius product in 1997 with mass manufacturing starting in 2000; Honda offered its all-electric Honda Insight as early as 1999; Ford entered the market offering the Ford Ranger EV in 1997, and the Ford Th!nk in 1999. Those first-generation offerings, however, failed to sell significant numbers of units in any jurisdiction worldwide.

The continued pressure imposed by the CAFE standards, the ZEV emissions standards, and the EU transportation fuel regulations throughout the first decade of the 2000s encouraged the ongoing production of newly electrified concept cars, as well as expansions of existing electrified product lines, by major auto manufacturers despite weak sales figures worldwide for hybrid, plug in hybrid, and battery electric technologies. An identifiable second round of expanded product offerings starting in 2009 occurred against a backdrop in which Toyota had begun offering its "third generation" Prius technology, while Ford – after signing a patent sharing deal with Toyota to use its Hybrid Synergy Drive (HSD) – had begun offering the world's first hybrid SUV, the Ford Escape Hybrid, in 2004. Pre-recession, Honda had also begun offering its "second generation" battery-electric Insight model. Starting in 2009, Ford, Nissan, Hyundai (including Kia), and GM appeared keen to buttress the now emerging North American and European marketplaces for hybrid, plug-in hybrid, and all-electric powertrains

Because electricity is unparalleled in its efficiency as a source of energy, vehicles become more and more efficient as their electrification level increases.

by offering new models under various brand names. Ford offered consumers a series of electrified products, including the Mercury Milan Hybrid and the Ford Fusion Hybrid, following soon after with the Lincoln MKZ Hybrid (2010), the Ford Focus Electric (2011), the Ford C-Max Hybrid (2012), and the plug-in hybrid the Ford C-Max Energi (2012). Hyundai began offering a variety of Hyundai and Kai hybrid models both in South Korea and worldwide. By 2010, Nissan was offering consumers worldwide its all-electric Nissan LEAF model. By 2011, General Motors began offering consumers the Chevy Volt (also known as the Holden Volt, Vauxhall Ampera, and Opel Ampera in Australia, the UK, and the rest of Europe, respectively). In the meantime, Toyota had already integrated its patented hybrid technology into Highlander, Lexus, and Camry models.

A "third" round of electrified offerings began in 2014, with a slate of new automotive companies entering the mix, suggesting the ongoing push towards lower-emission powertrains is not being stalled entirely by continued low sales figures for hybrids, plug-in hybrids, and battery electric vehicles in general. Buttressed in part by Toyota's announcement of more than 4 million Priuses sold worldwide by September 2014, the third round of electrified offerings includes BMW and Fiat Chrysler. In 2014, BMW began offering its first battery electric model, the BMW i3, in Europe and North America, while Fiat Chrysler began offering its Fiat 500e battery electric model in California.

Categorizing electrified vehicles by "electrification level"

To put these "rounds" of electrified product offerings into context, it helps to categorize the electrified vehicles according to their electrification level.

The "electrification level" of a vehicle is defined as the percentage of the vehicle's electric power to its total power. The electrification of transportation refers both to propulsion and non-propulsion loads in a given vehicle. Therefore, electrification can be understood as a continuum, one that starts with zero per cent electrification (i.e. a car powered solely by a combustion engine) to 100 per cent (i.e. a car powered entirely by a battery pack). The continued push towards ever-increasing levels of electrification in drivetrains will serve as a crucial mechanism enabling the achievement of drastically reduced transportation emissions in the future. [26,27]

Because electricity is unparalleled in its efficiency as a source of energy, vehicles become more and more efficient as their electrification level increases. The greatest increases in the electrification levels of current vehicles come in the form of drivetrain hybridization (i.e. combining a heat engine with an electric motor for propulsion) and complete electrification through the replacement of a heat engine with an electric motor system. Most vehicles on roads today are electrified in some way. Onboard batteries already power radios, interior lighting, and steering. One estimate holds the average passenger vehicle ranges between 10 to 15 per cent electrification. Moving this percentage towards the 100 per cent mark would improve the efficiency of vehicles, reduce emissions, decrease reliance on insecure supplies of gasoline (petrol) and diesel. [26,27

Efficiency improvements in ICEs

The internal combustion engine (ICE) is a technology of the nineteenth century. Indeed, its fundamental principles have not changed in more than 100 years. Therefore, ICEs are not typically considered “advanced automotive systems”. However, improvements to heat engine designs and engine architecture have achieved important reductions in emissions and significant improvements in efficiency over the past three decades. Some of those innovative advancements are reviewed here, as they constitute a complementary path for innovation relevant to the hybridized and fully electric drivetrains.

Engines in light passenger vehicles are getting smaller. There will be an estimated five million engines ranging from 0.8 litres to 1.2 litres on roads by 2020 (primarily in Europe); millions of such small engine cars are already available in Asian and Europe, already. In North America, sub-compact cars such as the 1.2 L engine Chevy Spark and the 1.4L Fiat 500 offer a new combination of multi-speed transmission systems along with advanced combustion systems incorporating direct injection and turbo-charging, which have enabled small engines to achieve better performance standards, while also reducing emissions.

The improved performance of these small engines is also fundamentally dependent upon the light weighting of the vehicles they power. In the 1970s, racecar drivers learned power and weight were inversely related in some manner, leading them to strip their vehicles of anything (radio, carpets, spare tires, etc.) that did not directly add to the vehicle’s overall power. Today, the power to weight ratio has become a core concern among ICE manufacturers. Traditional steel vehicles are struggling to meet, let alone exceed, current emissions standards. The push initiated by environmental standards has set off a new material competition in the industry more broadly. Carmakers have been turning to lightweight metals, such as aluminum, for component parts such as carburetors and intake manifolds. Today, aluminum is a rising metal for more widespread light-weighting efforts throughout vehicle designs, since it has the benefit of dissipating heat better than iron. Contemporary efforts to lightweight vehicles have also incorporated fiberglass, polymers, and carbon fibre. Challenges remain in the area of polymers, since many polymers are unable to rigorously withstand the high temperatures associated with heat engines. Carbon fibre, meanwhile, benefits from being very light and very strong, though these benefits are frequently offset by the fact carbon fibre remains expensive to manufacture and is not recyclable (a fact that runs counter current to the “sustainability” ethos informing light-weighting efforts overall).

In addition to light weighting the vehicle exterior and drivetrain parts, including the engine itself, improvements to ICEs have also focused on increasing the efficiency of the thermodynamic process that fuels cars. The combustion process – i.e. the mixing of oxygen with a carbon-based molecule to produce a powerful exothermic reaction from which energy is harvested for propulsion – is profoundly wasteful when it occurs in the real-world environment of a vehicle drivetrain. Dissipation and heat loss eat up more than 65 per cent of energy in any given vehicle, leaving little more than a third for propulsion or movement. Efforts to refine this process and harness greater amounts of energy from the combustion of petroleum fuels have focused on reducing friction within the engine and drivetrain, i.e. through the use of new coatings and piston squirters in power packs. New tire and body designs have also decreased tire- and aero-resistance that consume energy wastefully, while exhaust energy recovery systems have been innovated to recover combustion heat loss and convert it back into mechanical power.

The most profound area of ICE innovation, however, relates directly to electrification of ICE drivetrains and auxiliary systems. While the electrification of auxiliary systems (such as power steering, air conditioning, heating, pumps, and fans) has achieved marginal efficiency improvements, the incorporation of hybridized electric drivetrains has radically altered the ICE landscape and taken automotive efficiency to an entirely new level. Hybrid drivetrains that combine highly efficient electric motors with gasoline, diesel, or biofuel-powered engines have significantly improved the overall efficiency of ICEs. Further development and commercialization of advanced technologies related to electrified powertrains and electrified mobility more generally will serve as the single most crucial advancement in automotive systems over the course of the twenty-first century.

Advanced automotive systems: hybridization and electrification

The phrase “advanced automotive system” refers primarily to electrified automotive systems. Hybrid, plug-in hybrid and fully electric vehicles offer the possibility of achieving cleaner, greener, cheaper and more secure transportation options as compared to petroleum-powered vehicles. Despite a notable lack of widespread consumer, dealer, and (in some cases) government knowledge and understanding regarding advanced automotive systems, a core group of consumers in North America (primarily California) and Europe (primarily Norway) are realizing the long-term benefits associated with hybridized and fully electric vehicles. In 2013, the combined sales of hybrid, plug-in hybrid and battery electric vehicles worldwide had surpassed two million units sold, with a projected 6.6 million units being sold by 2020. These projections are based on current growth trends, increasing vehicle availability, government supports through incentives, and decreasing HEV/PHEV prices. [28].

Categories of hybridization

Hybrid electric vehicles (HEVs) rely on the combination of an electric motor with an internal combustion engine for propulsion. In hybrid vehicles, the electric motor is typically powered by a nickel-metal hydride battery or a lithium-ion battery that stores between 16 kWh of energy (e.g. as in the Mitsubishi i-MiEV) to 24 kWh of energy (e.g. as in the Nissan Leaf). [29] The battery can be charged by a gasoline or other fuel-driven generator or through regenerative braking. Hybrid vehicles can travel part-time on electric power with the heat engine shutdown until battery depletion reaches a critical level, or they can operate such that the motor and engine complement one another and propel the vehicle jointly. There are multiple effective and competing powertrain topologies in existence today that vary in terms of how much power is produced by either of the two sources – i.e. stored electricity, petroleum fuel, or a combination thereof – at any given point during the propulsion of the vehicle.

Because of the small size of the energy storage devices used in hybrid vehicles that do not plug in, most HEVs do not travel far on electric power alone. For example, Toyota's new Prius C model travels only about 1 km to 1.5 km in all-electric mode. By contrast, plug-in hybrid vehicles (PHEVs) can travel further in all-electric mode. A typical Chevrolet Volt, for example, can travel between 50 km and 60 km on average using electricity alone. Because HEVs and PHEVs have gasoline-powered engines to support their propulsion, these cars do boast extended ranges comparable to regular ICEs.

Hybrid vehicles can come in three architectural forms: parallel, series, and series-parallel.

Hybrid vehicles can come in three architectural forms: parallel, series, and series-parallel. Parallel systems use electric motors to supplement an ICE engine. A motor and a heat engine power the vehicle in combination (i.e. there are parallel propulsion systems at play). Most parallel hybrid powertrain configurations are not designed to operate in all-electric mode beyond very low speeds. By contrast, a series hybrid uses an electric motor to propel the entire vehicle. In a series hybrid, the electric motor is powered by a generator, which is itself fueled by an internal combustion engine. In series designs, non-renewable fuels are used to generate electricity and the electricity is used to power the car. The efficiency of series hybrid cars clearly demonstrates the extreme efficiencies to be gained from electric propulsion, since series hybrid cars are more efficient than traditional ICEs, despite the fact a fossil fuel is used to power the generator. In a series-parallel hybrid power train, two (or more) electric motors are used to provide both a parallel and a series pathway for propulsion power. Series powertrains tend to be more expensive to manufacture, although the simplicity of their design makes them suitable for large trucks and buses. Plug-in hybrid cars can also be designed using parallel, series, or series-parallel configurations. For example, for daily commuting purposes (i.e. short distances and low speeds), the Chevrolet Volt operates as a series hybrid, where the gasoline pumped into the car powers a generator, which subsequently powers a motor, and thus propulsion.

Beyond their powertrain designs, hybrid vehicles are typically divided into four categories according to the size and function of the battery pack and electric motor: micro-hybrid, mild hybrid, full hybrid, and energy hybrid. The "hybridization factor" of a given vehicle is characterized as the ratio between the car's peak electrical power and its peak total electrical and mechanical power combined. "Micro" hybrids are not usually considered "true" hybrids, because they are not propelled by electric power. Rather, these cars employ a "stop-start" system, which enables a small reduction in CO2 emissions by virtue of the fact the vehicle engine shuts down when it comes to a stop (say, at a stop light), rather than idling. When the driver of a micro-hybrid accelerates, the battery-powered alternator restarts the engine, reducing the CO2 that usually result from combustion-powered acceleration. Micro-hybrids range between five and 10 per cent electrification of all systems (i.e. auxiliary systems) in the car. [26]

Mild hybrids range between 10 to 25 per cent hybridization. The batteries in these cars are usually too small to power the entire vehicle alone, but the addition of an electric motor system significantly improves fuel efficiency overall. Full hybrids involve an electrification level beyond 25 per cent, as they are significantly dependent upon electric power for propulsion purposes. Toyota's luxury Lexus offers an example of a "full" HEV, because it draws on electrical power more significantly for propulsion purposes. Energy hybrids involve the highest level of electrification, as they incorporate the largest onboard energy storage devices among all hybrid vehicles. Plug in hybrid cars operating in "charge sustaining" (CS) mode – meaning the onboard battery pack never fall below a pre-set level of charge, such that the combustion engine kicks in to power the vehicle after a certain level of battery depletion – are considered energy hybrids, because they utilize large energy storage devices in their propulsion operations and during regenerative braking. Note that regenerative braking occurs across all hybrids, plug in hybrids, and electric vehicles. Regenerative braking is a process by which the vehicle's electric motor switches into operating as an electricity generator when the vehicle's brakes are applied. Regenerative braking systems collect energy from the vehicle whenever a driver applies the brakes, by converting the forward momentum and inertia of the vehicle back into stored electrical energy by virtue of the motor-turned-generator onboard. (As an added side benefit, this process helps to slow down the car and thus spares wear and tear on brake pads overall.)

When a plug in hybrid vehicle operates in "charge depletion" (CD) mode – such that the onboard battery pack depletes to nearly zero before the engine powers on for propulsion purposes – it is considered to be a battery-electric or "all" electric vehicle for the period of time during which it operates in CD mode; after that point, the vehicle typically enters CS mode and operates as an energy hybrid (described above). GM's Chevy Volt and Toyota's Prius Plug in hybrid model fall into these dual categories.

Clean petroleum enhancements

Hybrid and plug in hybrid technologies can be made to operate in conjunction with gasoline or diesel powered heat engines. The efficiency of these various hybridized drivetrain designs has been enhanced, thus, by the recent incorporation of cleaner petroleum fuels, such as "clean" diesel and biofuels. In particular, advanced combustion systems for diesel have rendered diesel powered ICEs up to 35 per cent cleaner than typical gasoline engines, while biofuels (including biodiesel, which can burn up to 15 per cent more efficiently than diesel) have enabled complementary reductions in exhaust pipe emissions when used alongside electric motor systems. [30,31] Greater efficiency gains are likely to be achieved by incorporating clean diesel, biofuel, and possibly CNG engines into hybridized drivetrains relying partially or predominantly on electricity for propulsion purposes

Plug-in Hybrid Electric Vehicles (PHEVs)s

Because they serve as bridging technology between hybrids electric vehicles (HEVs) and battery electric vehicles (BEVs), plug in hybrid electric vehicle (PHEV) technologies deserve additional attention here.

The batteries used in most HEVs designed over the past decade have been limited in terms of both power and energy density properties; this is largely because those batteries have been designed to serve a complementary propulsion system onboard, rather than a vehicle's primary propulsion system. To enable significant propulsion, batteries used in automotive applications will be more powerful with greater power and energy density overall. This means they must be designed to connect to the centralized electricity grid system for the purposes of drawing power onboard greater than that which can be generated by regenerative braking alone. The commercial introduction of more heavily electrified vehicles in the form of plug-in hybrid electric vehicles (PHEVs) has influenced the design and manufacture of batteries for vehicle applications in profound ways.

Plug-in hybrids constitute a crucial bridging technology in the socio-economic shift among consumers towards sustainable and zero-emissions transportation options.

Cutting-edge PHEVs combine the efficiency of electricity with extended range systems powered by gasoline tanks and engines. The key innovation associated with PHEVs over and above HEVs is the size and capacity of the onboard energy storage devices, which store large sources of electricity drawn from a central power grid. Plug-in hybrids are more socially and environmentally beneficial over the long-term because their primary source of electricity is supplied by efficiently produced and distributed central electricity supplies, using grid-infrastructure systems rather than internal (i.e. on board) generators or regenerative braking systems. In addition, the electricity they draw can be entirely renewable in nature – i.e. produced from hydro, solar, wind or tidal power (rather than gasoline or diesel, as with standard HEVs).

Like HEVs, PHEVs combine the efficiency of electric motors with the security of small gasoline (or diesel) engines; this combination provides consumers with the freedom to drive long-distance highway routes without concern since PHEVs can operate like HEVs – i.e. on gasoline-powered electricity or gasoline-powered engine systems alone. But PHEVs benefit from being able to go further and longer than HEVs on *only* electric power; thus, they enable further radical reductions in emissions form transportation fuels over the long-term. Examples of PHEVs include the Chevy Volt, the Toyota Prius Plug-in Hybrid, and the Ford C-MAX Energi Plug-In Hybrid.

Plug-in hybrids constitute a crucial bridging technology in the socio-economic shift among consumers towards sustainable and zero-emissions transportation options. Since most commercially available PHEVs today can run on fully electric power for distances ranging between 20 and 80 kilometers between charges, these vehicles can easily address the daily travel needs of the vast majority of daily commuters in fully electric mode, where the electricity used is drawn from efficient centralized grid systems. Indeed, recent studies of commuting behavior have demonstrated 97 per cent of car trips in the United

Kingdom are less than 80 km long, while 50 per cent of trips across Europe are less than 10 km. In the United States, approximately 60 per cent of vehicles travel less than 50 km per day. These ranges are fully within the pure electric ranges of many PHEVs currently on the market.

Battery Electric Vehicles (BEVs)

Battery electric vehicles (BEVs) are powered entirely by their electric battery packs, which draw power from central grid systems as well as regenerative braking mechanisms onboard while the car is in motion. The batteries used in BEVs are charged primarily from the grid system at home during the evening or nighttime, at work places during the daytime, or at drive-in charging stations at malls, cinemas, or hotels that use grid-connected chargers or independent photovoltaic panel systems and large energy storage devices to enable charging stations that are "off grid".

Critically, BEVs remain cost prohibitive for first-car buyers and non-luxury car buyers due to the expensive nature of the battery packs.

The key benefits of BEVs stem from their extreme efficiency as compared to ICEs and even HEVs or PHEVs. Electric motors can be made to operate with efficiency levels above 98 per cent compared to less than 30 per cent for ICEs. BEVs also boast low costs for operation due mostly to the low price of electricity, combined with low maintenance costs annually; since there is no heat engine, there are fewer parts that require servicing on a bi-annual or annual basis. The low cost of electric *motors* and the very low level of noise associated with electric drivetrains has buttressed consumer adoption and commercialization of EVs over the past half-decade within those jurisdictions – such as California – where zero emission vehicles are publicly supported through consumer incentives or manufacturer penalty programs by local governments.

Importantly, BEVs produce zero emissions when renewable resources supply the electrical grid system from which these cars draw their electric powers. In such cases, BEVs are zero emissions when judged from Source to Wheel (STW) – i.e. the only sources of greenhouse gas emissions produced over the entire lifetime of the vehicle are those associated with the manufacture, assembly, and transportation of the vehicle parts to the manufacturer and dealer.

Critically, BEVs remain cost prohibitive for first-car buyers and non-luxury car buyers due to the expensive nature of the battery packs. The energy and power densities of batteries currently available serve as the primary limiting factors facing BEVs, both in terms of range and cost. The lack of worldwide mass manufacturing of batteries has kept the price for these energy storage devices relatively high. The announcement of a "gigafactory" supported by the founder of Tesla Motors, Elon Musk, has altered recent dialogues in the debate over the cost-effectiveness of BEVs for individual consumers.

To put the situation in context, in 2009, lithium-ion batteries were priced at about $1,000 a kilowatt-hour (kWh). Estimates today hold that prices have slipped to approximately $400 to $750 a kWh. A key milestone would be to achieve pricing around $200 or less per kWh to drop the price of an average electric vehicle overall, rendering it a low cost vehicle option for most middleclass consumers. Musk's attempt to build a battery gigafactory in Nevada (which is slated to begin mass production of batteries for propulsion purposes by 2017) might result in a worldwide drop in battery prices for EVs, PHEVs and HEVs. [32]

In addition to Muck's gigafactory goals, the fact BEVs, PHEVs and HEVs are continuing to experience something akin to exponential worldwide as of 2014, the price point for batteries is expected to drop significantly over the next five years due to sheer demand. Across the United States, a total of 31,000 battery electric (BEV) and 36,000 plug-in hybrid electric (PHEV) vehicles have been sold since January 2014 for a total combined sales figure of more than 67,000 units sold to date in 2014, as compared to 50,000 for the entirety of 2013. Meanwhile, across Europe, electric car sales increased more than 77 per cent in the first half of 2014, growing from 15,500 BEVs sold in 2013 to more than 27,000 BEV units sold to date in 2014. More broadly, over the past five years, more than five million hybrid vehicles (HEVs) have been sold with an additional 500,000 plug-in hybrid and battery electric sales worldwide. [33, 34]

In addition to the culturally popular Tesla Model S and Nissan Leaf (the world's most popular highway capable all-electric vehicles), the BEV market now includes the Ford Focus Electric, the Mitsubishi i-MiEV, the Smart ED, the Chevy Spark EV, the Toyota RAV 4 all-electric, and the BMW i3, along with a series of all-electric Chinese-made vehicles only available in China, such as the Chery QQ3 EV.

Drivetrain innovations enabling advanced automotive systems

Whether located within the powertrains of HEVs, PHEVs or BEVs, electric drivetrains include three basic elements: (1) electric propulsion motors, (2) batteries and energy storage devices, and (3) power electronics and controls (including converters and inverters). These combined devices have enabled the development of HEVs, PHEVs, REVs (Range Extended EVs), and BEVs vehicles that are reliable, rugged, and scalable. Further innovations are required, however, to render hybridized and all-electric drivetrains even more efficient, more cost effective, and more culturally conventional than they are today. Such innovations will need to enhance the power and energy densities of these devices, while maintaining light weight characteristics and low costs.

Electric Motors for Vehicle Applications

An electric motor is a machine that converts electrical energy into mechanical energy by virtue of magnetic fields. All electric motors consists of two core features: a stator, which does not move, and which possesses current-carrying windings or permanent magnets; a rotor, which rotates, and which provides a magnetic field produced by other electrical current-carrying windings or attached magnets located between the rotor and stator's magnetic fields. Over the past century, scientific developments have refined motors by improving the magnetic materials they rely upon and by improving the switching devices they use by shifting from mechanical switches to electronic ones. In addition, advancements in computer modeling software, simulation tools, and manufacturing capabilities have also buttressed incremental motor advancements.

There are three types of motors frequently used in automotive applications: permanent magnet (PM) motors, induction motors, and (more recently) switched reluctance motors (SRMs).

Permanent magnet motors have long been a staple of the electrical application industries. These motors rely on the direct excitation of electrons, whereby the electric current in the rotor is obtained by electromagnetic excitation using permanent magnets strategically placed within the motor itself. The high power densities and high efficiencies associated with these motors are due primarily to the energy density found in the rare-earth metal magnets used in these motors – i.e. neodymium (NdFeB) and samarium–cobalt (SmCo). The high power density and efficiencies associated with these magnets have been combined with powerful semiconductor devices that enable efficient switching mechanisms. There are two types of permanent magnet motors: brush motors and brushless motors. Historically, most electric applications have used brush permanent magnet motors. Indeed, these motors have been around since the first invention of direct current (DC) electric motors in the early nineteenth century. There are, however, significant constraints on these motors within the automotive industry, including problematic friction and heat losses between brushes and other motor components, the unsafe sparking that occurs between brushes and motor components when the motor is in operation, and the difficulties posed in cooling DC motors in general.

As a result, industrial applications have motivated innovations in brushless permanent magnet motor technology, which has become popular among automotive manufacturers over the past two decades due to their higher efficiencies. Brushless PM motors experience less friction and less heat loss due to the lack of brushes, and they also demonstrate safer heat dissipation properties due to a lack of sparking between brushes and other motor components. These motors tend to last longer due to lessened wear-and-tear overall, as compared to their brush counterparts, and with the recent development of electronic switching, which has further improved efficiency levels among these machines, brushless PM motors have become “prime movers in vehicle propulsion”. [35]

In comparison to permanent magnet motors, automotive manufacturers have also begun integrating alternating current (AC) induction motors in electric propulsion applications. These motors are relatively inexpensive to manufacture, in part because of a lack of rare-earth metal magnets. Induction machines require less maintenance in general, as compared to permanent magnet motors, because they contain no brushes and thus experience less friction degradation. Induction motors do face some obstacles, however. Primarily, induction motors are difficult to control from a speed perspective, which requires advanced motor control innovations to address. Induction motors have become popular for a series of automotive applications beyond propulsion, however, including engine starting and braking, speed reversals, and acceleration.

Despite their varied technological limitations, permanent magnet motors and induction motors are the most popular types of motors used in HEV, PHEV, and BEV manufacturing.

However, increasing consumer demands for differing performance characteristics in HEVs, PHEVs, and EVs, along with growing mass manufacturing requirements among original equipment manufacturers, has impelled suppliers to innovate motor technologies that are ever more efficient, ever more powerful, and ever more simplistic to manufacture and assemble. Thus, over the past decade, increased attention has been focused on cutting-edge switched reluctance motor (SRM) technologies. These motors demonstrate wider ranging of torque and speed, as well as higher efficiencies overall, as compared to permanent magnet and induction motors. SRMs boast simplicity in design and construction, cost-competitiveness in manufacturing (in part, due to a lack of rare earth metals), and high tolerance features for powerful performance in propulsion applications.

The future viability of electric powered vehicles integrating permanent magnet motors, induction motors, or switched reluctance motors for propulsion applications will require continued investment and innovation to achieve improved manufacturability and cost effectiveness for manufacturers.

Advanced designs that integrate motors with electronic switching devices have further propelled the development of SRM technologies among HEV, PHEV and EV manufacturers. Indeed, the rise of powerful power electronics for controllers and switches has served as an oxygen line breathing life into a budding SRM industry. In SRMs, power is delivered to windings in the stator (i.e. the stationary portion of an electric motor) rather than the rotor (i.e. the rotating part of the motor), which enables a simplified mechanical design. Historically, however, SRMs have required complicated electrical designs because switching systems are required to ensure power is delivered to the different windings of the motor. In recent years, advanced power electronics have addressed this complication by enabling electronic switching, thereby simplifying electrical designs for SRMs and opening up the possibility of competitive SRM manufacturing in the future. Beneficially for those consumers in extremely cold or hot climates, SRMs have demonstrated the ability to operate in extreme environmental conditions. Because they are simpler to manufacture, they may be preferable from the perspective of mass manufacturing and worldwide supply chain development. SRMs continue to suffer from a series of drawbacks. They experience serious torque ripple, which involves periodic and unwanted increases and decreases in torque, and they produce unwanted noise when the machine is in operation.

In sum, the future viability of electric powered vehicles integrating permanent magnet motors, induction motors, or switched reluctance motors for propulsion applications will require continued investment and innovation to achieve improved manufacturability and cost effectiveness for manufacturers.

Power electronics

As noted above, power electronics have enabled a transition away from less efficient mechanical switches to more efficient electronic switches in motors.

In addition, power electronics are used to control and convert electric power in dynamic systems elsewhere in vehicle powertrains. Power electronics include inverters (switches), inductors (amplifiers), and converters, which produce desired effects (such as energy conversion or mechanical motion) by controlling system variables, such as voltage and current. Controllers manage the application of power in an electric vehicle to ensure electrical energy has been converted into mechanical energy as efficiently as possible, and applied for the purposes of traction or any other specified use in the vehicle.

The biggest challenge facing the development of power electronics resides in determining a fine balance between the efficiency of these devices and their power densities, while maintaining low cost. Because switches are sensitive to temperature, they can burn out at high temperatures, improving the performance of power electronics will require the design of better switches and better cooling systems, as well as more efficient topological designs for inverters that simultaneously demonstrate higher power density properties.

The development of more powerful and cost-effective power electronics has constituted an important factor over the past decade of HEV, PHEV and BEV innovation. The ongoing enhancement of these devices will, no doubt, constitute one of the twenty-first century's most important scientific and technological "revolutions" in transportation.

Research focused on reducing recharge times for all types of batteries in HEVs, PHEVs and BEVs will help to overcome the battery-related limitations and consumer anxieties currently associated with hybrid and electric vehicles.

Batteries and energy storage

Batteries intended for electric vehicles are judged by the metrics of power density, energy density, weight, volume, life cycle, temperature range, and cost. Battery technology constitutes a core area requiring further innovation and development. Today, nickel-metal hydride (NiMH) batteries remain popular among some manufacturers, including Toyota, whose line-up of Priuses relies on (NiMH). By contrast, battery electric vehicles, such as the Nissan Leaf and Tesla Model S, which have greater electric energy requirements, rely on lithium-ion (Li-ion) batteries, because of the high energy and power densities associated with Li-ion batteries, as well as their longer life cycles.

Problematically, Li-ion batteries still face numerous hurdles, including especially their expense. Li-ion batteries are more expensive and not as widely manufactured as (NiMH) batteries, leading the U.S. Department of Energy's Advanced Research Projects Agency for Energy (ARPAe) to declare Li-ion batteries typically account for up to 65 per cent of the cost of a BEV today. In addition to cost, Li-ion batteries need further innovation include improving and optimising their energy storage capacity to increase their power densities. Scaling the production of batteries (i.e. their mass manufacturing) will help to reduce the total cost of HEVs, PHEVs and BEVs, although mass manufacturing of Li-ions for vehicle applications has yet to occur on a global scale.

From a technical perspective, Li-ion batteries also face serious challenges when applied to propulsion systems. In PHEVs and BEVs, for example, they experience frequent deep discharge cycles, whereas batteries in conventional

ICEs and HEVs do not. “Deep discharge” refers to the fact energy stored in batteries is used up almost entirely, driving the battery to near empty or empty before being recharged. Research to improve the durability of batteries given deep discharge cycles is an area requiring increased investment over the next decade.

Relatedly, research focused on reducing recharge times for all types of batteries in HEVs, PHEVs and BEVs will help to overcome the battery-related limitations and consumer anxieties currently associated with hybrid and electric vehicles.

Grid infrastructure

As previously noted, the socio- cultural integration of electric and hybrid-electric vehicles will rely upon robust public policy leadership and infrastructure investments that enable ubiquitous electric mobility. Consider the comparative case with ICEs. In the case of gasoline or diesel powered vehicles, the infrastructure required to enable these vehicles to operate on a daily basis in a seemingly unproblematic manner includes fueling stations located at reasonable and frequent intervals along city streets and highways, as well as pipeline, shipping, rail, and trucking infrastructure that moves unrefined petroleum products located in oil deposits across Canada, the USA, and globally to refineries and upgraders and then onwards to fueling stations for use by consumers as vehicle drivers. Because gasoline and diesel are not free in most jurisdictions around the world, this infrastructure also includes pricing meters that allow fuel stations to know how much fuel is being pumped into any given car, thereby generating a specific price point for consumers.

By comparison, electrified transportation will require a different set of infrastructure capacities and provisions. In the case of electric or hybrid-electric powered vehicles, this infrastructure includes charging stations (at private homes and public or semi-public sites, such as workplaces and malls). These stations will vary in electrical capacity, ranging from 120 Volt simple wall outlets to 240 Volt AC Level II charging systems to high voltage DC Fast-chargers. These charging stations will need to be connected to secure and powerful electricity distribution systems, which might also include local energy storage devices connected to local energy generation devices, such as local solar panels and wind turbines, or distant generating plants where large quantities of electricity are produced en mass by virtue of hydro power, gas burning, coal burning, nuclear fission, or large-scale wind farms. Since electricity is “shipped” via above- or below-ground transmission lines, electric vehicles do not require pipeline, rail, shipping, or trucking networks to “ship” fuel supplies from distant regions to local charging stations. They do, however, require redundant, secure, and reliable generation and transmission systems. And because electricity is not free in most jurisdictions around the world, the infrastructure required also involves metering capabilities so that electricity generators and suppliers know exactly how much electricity is being “pumped” into a car, thereby generating a price point for consumers. In brief, the development of advanced drivetrain technologies must go hand-in-hand with the development of robust electricity generation, distribution, and pricing infrastructure to enable electric vehicles as

The development of advanced drivetrain technologies must go hand-in-hand with the development of robust electricity generation, distribution, and pricing infrastructure.

a viable and sustainable transportation solution that can replace petroleum as a primary propulsion fuel.

In addition, to argue in favour of the cleanliness, greenness, and "sustainability" of electrified transportation, alternatively powered vehicles will be required to prove the source of electricity they rely upon comes from low-emissions supplies. That might mean establishing and integrating policy innovations at various jurisdictional levels to encourage private and public investment in renewable electricity generation – i.e. hydro, solar, wind, tidal, and even nuclear (as a zero-emissions option). Policy innovation with regards to electricity generation and transmission is typically complex and heavily dependent upon local, regional, or national jurisdictional controls over energy supplies and pricing. These matters necessarily form part of the overall sustainable transportation dialogue, since "low"- or "zero"-emissions vehicles will be judged from "Source to Wheel" (STW) rather than from the perspective of tailpipe emissions alone. [7, 8]

Smart grids

While a full discussion of energy and electricity policy in Ontario, Canada, or worldwide is beyond the remit of the present paper, a short review of enabling technologies within the "smart grid" landscape will demonstrate some of the grid-side technological solutions required to enable an incremental transition to low-emission transportation systems over the next century. "Smart grids" refer to modern electrical grid systems that use digitized information and communications technology to collect massive amounts of data related to the behavioural patterns of suppliers and consumers. Those data are converted into action mechanisms that allow utilities (such as Hydro Quebec, B.C. Hydro or Ontario's Hydro One) to maximize renewable energy supplies, manage peak loads, avoid blackouts due to crisis loads, and improve the efficiency, reliability, profitability, and long-term sustainability of the production and distribution of electricity overall.

In June 2013, the European Union and the United States jointly announced a partnership to support a series of EV-Smart Grid Interoperability Centres to promote e-mobility grid-integration, consumer adoption, and technological innovation and development. The program aims to support job creation over the next decade by buttressing the development of an EV industrial eco-system that commercializes innovations in both grid-side technologies and vehicular technologies by fast-forwarding and spearheading harmonized technology standards and interoperability across the regions in terms of vehicle-to-grid and grid-to-vehicle communications infrastructure, regulations, and safety standards. Supported by the US Department of Energy, through Argonne National Laboratory, and the European Commission, through the Joint Research Centre (JRC), the mandate of the program includes providing "a predictable framework that gives innovators confidence to bring their e-mobility products to market" in a globalized automotive industry. [36] The program expects to achieve its policy goals by constructing new EV and PHEV testing laboratories, exchanging European and American technical staff, pursuing joint publications on interoperability of e-mobility technologies and systems, and engaging with and guiding automotive industry groups and utilities across the two jurisdictions.

Since 2009, the European Commission launched the Smart Grids Task Force (SGTF) to reach consensus over the regulatory direction for the deployment of Smart Grids across Europe. In 2011, the EC issued a Mandate for Smart Grid standards to the European Standardisation Organisation, creating an inventory of smart grid projects based on best (and worst) practices across member states. The upshot was the adoption of a *Recommendation for the Roll-out of Smart Metering Systems* and in 2012 issued *Guidelines for Conducting Cost Benefit Analysis of Smart Grids*. In 2013, these recommendations and guidelines resulted in a "Directive on the Deployment of Alternative Fuels Infrastructure" (AFID), which recommended the EC adopt a standard approach across member nations to facilitate a single market for alternative fuels (including electricity as a transportation fuel) and associated infrastructure, focus on redressing "missing links" in public and private infrastructure deployment, and remove technical and regulatory barriers to the integration of alternative fuel vehicles across the EU. The proposal adopted by the European Parliament in June 2014 includes setting a minimum number of public and private charging stations across member states by 2020, which incorporate intelligent (i.e. "smart") metering systems that help to ensure grid reliability and redundancy. The proposal also includes a recommendation for standardized AC and DC plug specifications for PHEVs and EVs. Currently there are multiple options available on the marketplace, frequently determined by automotive OEMs on a proprietary basis. [37]

In Canada, smart grid technologies have been supported most explicitly in British Columbia, Quebec, and Ontario.

In Canada, smart grid technologies have been supported most explicitly in British Columbia, Quebec, and Ontario. Ontario's *Green Energy Act* (2009) institutionalized the drive towards smart grid developments, primarily at the time to reduce consumption and ensure reliability of the overall grid system for Ontario consumers. Since its inception in 2011, the province's Smart Grid Fund has also served as an innovation vehicle for research and development that will directly affect EV-readiness across the province. The fund's stated objectives include more efficient grid operation, increasing electricity generation diversity and focusing attention on renewable sources of electricity, enabling an EV-ready grid system and encouraging reduced electricity consumption for consumers where appropriate (i.e. by reducing loads caused by inefficient practices and technologies). The province claims the fund has supported 600 new jobs and invested in 11 projects in total since its launch in 2011. [38] Most of those projects focus on hardware and software solutions aimed at managing peak loads and intelligently shutting down appliances or powering them up when electricity is in high or low demand, respectively.

From an EV-charging perspective, especially where time-of-use rates apply, these smart grid enabling technologies will allow for the most efficient use of abundant electricity supplies during low-peak hours and the avoidance of heavy loads in the form of EV charging during peak periods of consumption across the province. They will also ensure EVs are charged at times (i.e. over night) when electricity rates are at their cheapest or, alternatively (which may be of more importance in provinces still reliant on coal production), they will allow EVs to charge when coal generation is low and natural gas or hydro, solar, or other renewable sources of electricity are online.

Grid systems in the developed world, including North America, Europe and much of South America, are fully capable of handling increased loads due to PHEVs and BEVs. But the ability of utilities to draw on renewable energy during recharging is crucial to the argument that PHEVs and BEVs are more sustainable forms of transportation from Source to Wheel (STW). [40] "Smart" grid systems that ensure vehicles charge themselves during peak renewable periods, which – in the case of wind- and solar-intensive grids such as Germany's – often occurs during mid-day, will help to advance the integration of PHEVs and BEVs in variant grid systems. Thus, ongoing policy focus on smart grid technology includes preparing the system for additional EV and PHEV loads to ensure reliability and security of electricity transmission.

One final area for grid-side technological and policy innovation relates to EVs and PHEVs as mobile energy storage devices that could serve as back-up emergency sources of power to buttress electricity systems under severe pressure. When considered as mobile sources of energy storage, PHEVs and EVs could benefit grid systems by providing energy capacity to operators when needed. Such feed-in mechanisms would help to smooth peak load curves, thereby increasing the efficiency of existing generation systems. If electric vehicle owners are enabled (through regulatory advancements, for example) to participate competitively in the electricity market, they may be able to generate long-term value by using their cars to provide electricity back into the grid system. Grid system operators could view this as a possible means of creating a new group of grid resources that can help to render their systems more sustainable over the course of the twenty-first century. [41]

A DC fast charger can add anywhere between 60 to 100 kilometers of range to a light-duty PHEV or BEV in about 20 minutes.

Charging stations

Charging stations for plug-in hybrid electric vehicles (PHEVs) and all-electric vehicles (BEVs) are classified according to the rate at which the batteries are charged. Charging times can vary between 15 minutes and 24 hours depending upon the type of charger used (AC Level I, AC Level II or DC Level II fast-charging) as well as the level of battery depletion at the time of recharging. Most homeowners will find AC Level I or AC Level II the most convenient options. Level I charging provides charge using a standard 120V AC plug (common in homes already). All PHEVs and BEVs sold to consumers come with a Level I charging cord set, which allows car owners to plug their vehicles into common electrical outlets in garages.

By comparison, AC Level II charging is a convenient option for homes, workplaces, and other locations (such as corporate parking lots) where users wish to charge quickly during the daytime. However, Level II charging does require 240V or 208V electrical service, and it requires installation of specialized equipment. Many homes across Canada have 240V service available already, but the charging equipment itself can add to the overall price of a PHEV or BEV purchase. The price for a Level II charging station in Canada can vary between $600 CAD and $1,000 CAD; in Toronto, for example, a Nissan AC Level II charger currently sells for $899.00 CAD as of October 2014. Home installation

costs range from $400 to $1,100 (before taxes). Therefore, it costs a consumer about $2000 CAD to buy and install one AC Level II charging station. If the home also requires upgrades to electrical panels or underground cables, those installation costs can increase further. The benefits of AC Level II charging are evident, however; rather than the 24 hours it takes to charge, say, a Nissan Leaf 2015 model using AC Level I 120-volt plug in outlet, an AC Level II 240 Volt charger could power up the car and fully charger the battery within 3.5 hours.
DC Fast-charging allows for the most rapid form of recharging. A DC fast charger can add anywhere between 60 to 100 kilometers of range to a light-duty PHEV or BEV in about 20 minutes. However, these chargers cost thousands of dollars per unit with additional installation and infrastructure costs.

If political pressure to reduce emissions continues to grow within the American context, and if electric cars continue to benefit from rebate support and grow among new consumer adopters as a mobility option, utilities (both public and private) will need to work with municipalities as well as regional and state governments to encourage the purchase and installation of workplace, corporate, and public charging stations. Such infrastructure investments will provide consumers with convenient and ubiquitous charging options at locations amenable to their daily commutes and travel habits, much as gasoline and diesel fuelling stations are today.

Policy Innovations and Possibilities

Policy investments related to electrified vehicles worldwide fall into two broad categories: demand-side consumer incentives (such as vehicle rebates for EV purchases) and supply-side innovation investments (such as the Smart Grid Fund, which helps offset the cost of high-risk R&D for EV-readiness technologies). In this section, we explore Canada's approach to demand-side and supply-side incentives and policy mechanisms.

Demand-side incentives

In 2010, Natural Resources Canada commissioned an *Electric Vehicle Technology Roadmap (evTRM)*, researched and published by Electric Mobility Canada -- an industrial association and consortium of fee-paying members whose objective it is to promote electrified transportation adoption, integrating, and public investment. The *evTRM* states as its guiding vision "At least 500 000 highway-capable plug-in electric-drive vehicles on Canadian roads, as well as what may be a larger number of hybrid-electric vehicles. All these vehicles will have more Canadian content in parts and manufacture than vehicles on the road in Canada in 2008." [42] The *evTRM* was intended to serve as a public policy guidebook articulating supply-side and demand-side milestones to be achieved by 2018 by virtue of public and private investments with the ultimate goal of achieving the vision described above, i.e. approximately 15 per cent of Canadian car purchases being BEVs and PHEVs combined. A summary of its core prescriptions for demand-side and supply-side incentives and public investments is found in Table 1.0 below.

The evTRM states as its guiding vision "At least 500 000 highway-capable plug-in electric-drive vehicles on Canadian roads, as well as what may be a larger number of hybrid-electric vehicles.

Table 1.0: Summary Chart: Electric Vehicle Technology Roadmap (2010-2018) Investment and Policy Prescription

Demand-Side Prescriptions	
Vehicle adoption and purchase programs	• instantiation and maintenance of vehicle rebate programs by the federal government starting a $2,500 per vehicle based on a 4 KWh battery pack and ranging up to $7,500 per vehicle for larger battery packs (i.e. BEVs) • provincial tax credits for vehicle purchases, ranging from $2,500 for vehicles with 16 kWh batteries and increasing per kWh of battery capacity • free public charging mechanisms supported by provincial, municipal, and private utilities • transition to full BEV and PHEV fleet adoption by public authorities, including federal, provincial and municipal authorities
Infrastructure development	• ubiquitous charging options/stations on federal, provincial, and municipal highways, roads, and streets, respectively • provincial HOV lanes open to "green" vehicles
Supply-Side Prescriptions	
Batteries and Energy Storage Devices	• increasing energy density • reducing costs • reducing weights and volumes • improving efficiency through improved control systems • improved packaging to optimize thermal, mechanical, and electrical safety • adding manufacturing scale
Codes and Standards	• harmonize North American standards related to the integration of EV components, including charger interfaces • develop harmonized standards for the conversion of used vehicles to electric traction • amend building codes to require outlets for charging EVs is included in all new buildings. • review and reassess regional regulations that create barriers to EV and PHEV manufacturing innovation, including component parts innovation
Research and Development for Real World Conditions	• testing charging infrastructure in major regions of Canada to measure impact on local grid systems • demonstrating vehicle use in real-world conditions to assess reliability and durability of energy storage components

To date, the *evTRM* has achieved mixed success. Demand-side rebates have been introduced in the provinces of British Columbia, Ontario, and Quebec. Starting in 2011, B.C. point of purchase rebates offered rebates on EV purchases of up to $5,000 depending on battery size (the program ended in 2013). In Ontario, an EV rebate program provides incentives ranging up to $8,500 depending upon battery size. In Quebec, an EV rebate program that began in 2012 offers up to $8,000 in incentives. These programs mapped on to rollouts of top EV models in Canada; the Nissan Leaf became available for individual purchase in December 2011, while the Tesla Model S only became available to Canadian consumers in 2012. Problematically, those rebates continue only in Ontario and Quebec with no indication of a federal incentive program in the near future.

The implementation of "green" enabled HOV lanes has also experienced varying degrees of success. In Ontario, where the province adopted a plan in 2007 to add more than 450 km of new HOV lanes on 400-series highways in the Greater Golden Horseshoe over 25 years, the Green Plates program – which fits EVs and PHEVs with special green coloured licence plates – has enabled EV and PHEV drivers to use HOV lanes until July 2015 even when only one occupant is in the vehicle. No other province has adopted the "green" HOV lane policy.

The production of the RAV4 electric vehicle is part of Toyota's "Project Green Light', announced in 2011 to support the development of low-emissions, highway-capable products.

Supply-side innovations

To address supply-side innovation objectives articulated in the *evTRM*, the Government of Canada invested $10 million in federal funding to support a Canada Excellence Research Chair (CERC) in Hybrid Powertrain research, housed at McMaster University in southern Ontario for seven years. The CERC in hybrid powertrain, Dr. Ali Emadi, has the mandate of advancing technological achievements related to electric motors and power electronics systems for hybrid powertrains specifically. There has been no national or provincial investment, however, in an EV technology R&D centre or commercialization centre of the sort articulated and identified in the *evTRM*.

In addition, in April 2011, the Government of Canada funded Toyota Motor Company through its Automotive Innovation Fund to support the development and manufacturing of Toyota's all-electric RAV4 sports utility vehicle with a repayable loan of $70 million over a maximum of five years, with the Province of Ontario supporting with project with an additional non-repayable grant of $70 million, and Toyota declaring its own investment in the project to be $506 million. The production of the RAV4 electric vehicle is part of Toyota's "Project Green Light', announced in 2011 to support the development of low-emissions, highway-capable products. The RAV4 EV is the first Toyota electric car to be produced outside of Japan. [43]

The *evTRM* is now being revised and updated in a policy initiative being led again by Natural Resources Canada and Electric Mobility Canada (EMC). On the demand-side, focal points include continued provincial rebates for EVs and PHEVs, as well as proposed additional federal rebates for EV and PHEV purchases to motivate consumer adoption. The increasing approval and advertisement of "high-occupancy lanes" (HOV lanes) for "green vehicles" will also figure prominently in that document, based on preliminary industry feedback garnered from automotive OEM members at the EV VE 2014 Electric Mobility conference held in Vancouver in October 2014.

On the supply-side, the focal point for the updated *evTRM* will be on grid-side investments in charging infrastructure – including both the quantity of publicly-available charging stations (including AC Level II and DC Fast-charging stations) across the country, and especially in urban communities, as well as "smart" metering systems that enable EV owners to minimize electricity costs and loads to the grid based on smart charging cycles that allow the vehicle to charge during the cheapest time-of-day rates by virtue of mobile owner controls or vehicle and grid intelligence systems. The new *evTRM* is set to be released by 2016 in time for the international Electric Vehicle Symposium (EVS) 2016 in Montreal, Canada.

Meanwhile, large scale investments in research, development, and commercialization of electrified transportation technologies are no doubt required to develop the supply chain and innovative eco-system required by the next generation of automotive and transportation original equipment manufacturers (OEMs). The precise mechanisms by which governments ought to approach this issue to maximize the benefit of taxpayer backed investments in electrified transportation technologies are still unclear due in large part to the novelty of the industry itself. In the United States, a recent development has included public investment in a series of commercialization centres, which bear upon the development of EV components though the centres themselves are not earmarked specifically for EV technologies. In May 2013, the Obama Administration announced the launch of a competition for three innovation institutes funded by a federal commitment of $200 million across five agencies, including the departments of defense, energy, and commerce, NASA, and the National Science Foundation. In January 2014, the Department of Energy announced funding for the first of these three institutes with $75 million in federal dollars constituting seed financing for the Next Generation Power Electronics Manufacturing Innovation Institute in Raleigh, N.C. In February 2014, the Obama Administration announced the second such innovation institute, named the Lightweight and Modern Metals Manufacturing Innovation (LM3I), headquartered in Detroit; the latter institute brings together 60 industry consortium members, including world leading aluminum, titanium, and high strength steel manufacturers, as well as university researchers. [44]

Such centres can support emerging start-ups and help small to mid-sized enterprises (SMEs) operating in automotive and communications supply chain to innovate powerful and inexpensive products and services for future transportation OEMs, including those technological innovations required for cars to meet imminent emissions standards.

Conclusion

The technological advancements required by advanced electrified automotive technologies converge a future combination of industrial and public investments as key drivers behind a low-emissions and sustainable transportation future. High-risk technologies may bring significant reductions in emissions, but continued and sustained investment over the long-term is required to render the cutting-edge concepts outlined here more than just unique toys for the affluent, who can afford pricey Tesla models, or the environmentally conscious consumer, who buys a Nissan Leaf out of sheer principle rather than cost calculation. To mainstream HEVs, PHEVs, and BEVs, the automotive landscape must incorporate advanced automotive system innovation, design, and manufacturing. This will require coordinated industrial and public leadership.

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