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Electric Vehicle Charging to Support Renewable Energy Integration in a Capacity Constrained Electricity Grid

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Summary

Digby, Nova Scotia, is a rural area serviced by an aging 69 kV transmission line that often operates at the export capacity limit because of a local wind field. This study examines the potential of charging of electric vehicles to achieve two objectives: 1) add load to relieve export capacity; 2) charge EVs using renewable energy. With a 10% adoption rate of EVs, time-of-day charging increased local renewable energy use by 20%. More significantly, ideal smart charging adds 3 MW of load when power exports face constraints, allowing more than enough additional renewable generation capacity to fully power those vehicles.

Keywords: Smart Grid; Renewable; Transmission; Load management; Dynamic charging

1 Introduction

The Municipality of Digby (Figure 1, left) is embarking on an ambitious strategy to alter its energy consumption and production, for greater utilization of locally produced renewable energy. Transportation represents a major energy end-user, totalling 38% of all energy used in Nova Scotia [1]. While Canada has significant fossil fuel resources, there is no petroleum production in Nova Scotia, so transportation fuels represent a significant economic trade deficit for the region. In contrast, Nova Scotia in general, and the Digby area in particular, have superb renewable energy resources [2, 3]. Electric vehicles (EVs) thus represent an opportunity to not only vastly reduce energy consumption for transportation, but also to transition from imported fossil fuels to locally produced renewable energy.

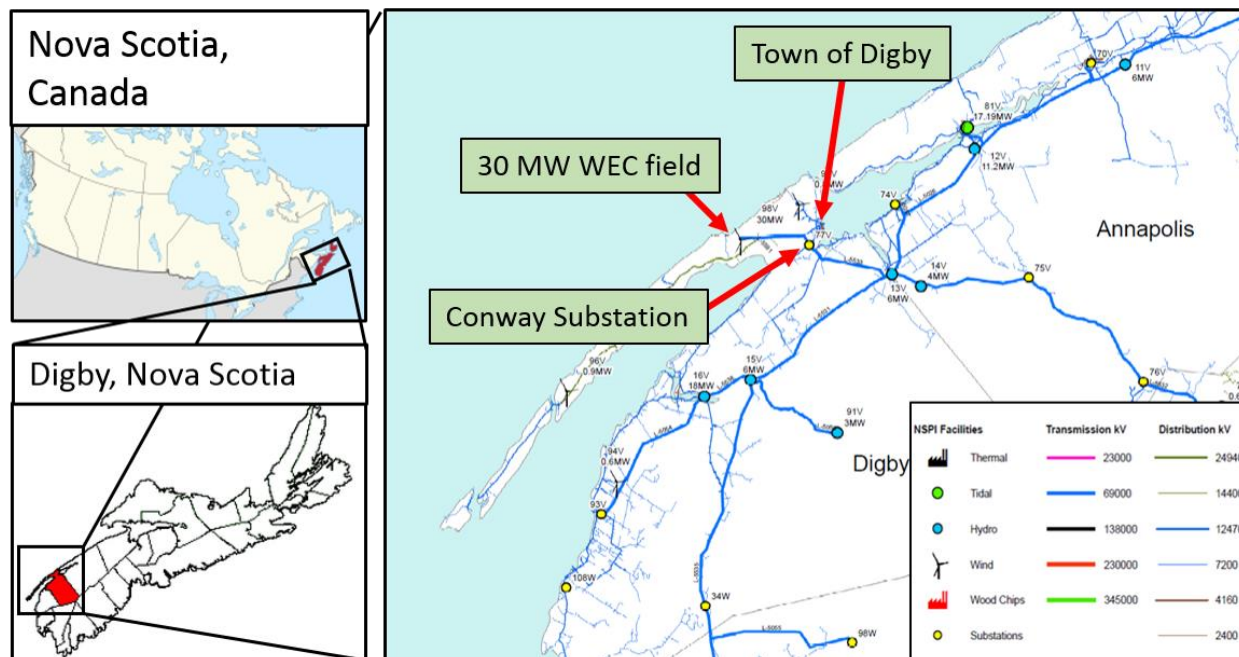


Figure 1 Location of Digby (left) and transmission and distribution maps (right)

The electrical transmission system of the area is shown in Figure 1 (right). It consists of 69 kV lines servicing the Town of Digby via Conway Substation. Other 69 kV lines connect nearby communities and collect from small hydroelectric facilities inland. In 2010 a 30 MW wind energy converter (WEC) field was commissioned on the Digby Neck, causing Digby to become a net exporter of electricity. This 30 MW wind field was sized to meet summertime transmission export limits when local loads are at their minimum and the risk of overloading lines is at its greatest. As a consequence, further development of renewable electricity generation is not possible, absent one of three conditions: Either 1) the transmission system is upgraded to increase the export capacity, 2) renewable generation must be curtailed when transmission limits are reached, or 3) electrical load must be added locally, so that the additional power produced can be used locally and not contribute to overloading of the transmission system.

Option 1 is not being considered by the provincial electricity system manager in short or long term planning due to prohibitive cost. Option 2, while occasionally implemented by the grid manager when conditions require, is a reactive approach that is undesirable due to the loss in renewable energy, and compromising the economic viability of renewable energy projects. It is under the premise of Option 3 that this study is conducted.

By evaluating the time-dependent load of charging EVs and their interaction with existing loads and generation, this study will quantify the influence of EVs on the electricity grid, and the use of renewable

electricity generation for powering those EVs. In addition, charging strategies that are successful in reducing or controlling the export transmission loads could simultaneously permit increased local generation. As an objective, this study investigates the potential of adding controlled EV charging, thus allowing more renewable capacity. Could the added energy production be sufficient to provide the necessary energy to charge the EVs, making them a net benefit to Nova Scotia's grid?

2 Data Sources / Research Methods

An investigation of an EV fleet's impacts on the electrical grid requires an understanding of the vehicle fleet. Specifically, to understand the energy requirements of vehicles, it is necessary to know 1) how many vehicles of various types are in use in the area, 2) how much energy these vehicles use each day (how far they drive and how much fuel is consumed to do so), and 3) during what period of the day they are parked, indicating when vehicles would plug in to the electricity grid. With those data and an assumed adoption rate of EVs, aggregate charging loads impacts can be estimated.

The following subsections describe the regions of analysis, the data sources related to vehicle populations in the area, the survey tools used to gather vehicle use information, and the data available on grid loading and renewable electricity generation.

2.1 Vehicle Populations

The total vehicle population in Digby comes from Provincial vehicle registration data [4], however, the population served by the Conway electrical substation (Figure 1) does not correspond to a specific Provincial jurisdiction. The inferred population of vehicles has therefore been computed by scaling data from:

- The Town of Digby with an area of approximately 3 km² and a population of 2152.
- Digby County, consisting of the Town (above) and two Municipal Districts which combined have an area of approximately 2,515 km² and a population of 18,036.

To establish the population served by Conway, estimates of Town and Municipal population were combined with a building count using satellite imagery. The resulting population estimate for the Conway service area is 9000 people. Table 1 groups the transportation fleet of Digby by vehicle type, lists how many of each type are registered in the Town and in the County, and gives the proportional vehicle population serviced by Conway Substation (Figure 1, right), corresponding to this population estimate.

Table 1 Classes of vehicles, estimated numbers that operate in the regions of analysis in Digby

Vehicle type	Digby Town (count)	Conway Area (estimate)	Digby County (count)
Population	2152	9000	18,036
Motorcycle	74	316	646
Small Car	353	1275	2151
Medium Car	347	1238	2053
Large Car	247	884	1472
Van / SUV	131	504	921
Pickup	370	1577	3218
ATV	76	401	971
Bus (diesel)	0	9	38
School Bus (diesel)	0	3	13
Freight Van (diesel)	105	356	546

2.2 Vehicle Use

To gather information on vehicle use, energy consumption, and the timing when EVs would be plugged-in, a variety of survey techniques were used.

For business vehicles, a selection of businesses in Digby County were interviewed by telephone. The selection of business types called for this study was made based on the perceived likelihood that they would have commercial vehicles (i.e. registered vehicles used exclusively or primarily by the business). Forty-seven business were interviewed by phone. Respondents were asked what business vehicles they used, how much they were used, and when during the day such use took place. Where specific information was not provided, average values for the vehicle type were used.

To gather the corresponding information about Digby area household vehicle use, both telephone and online survey methods were used. A total of 22 households were interviewed in depth in telephone surveys. In addition, there were 79 unique responses to an online survey that was promoted on the Municipality's website, and a newspaper advertisement.

2.3 Renewable Generation and Load

A variety of data concerning local, regional, and provincial electrical system conditions, including WEC field production, were available for this research, supplied by the provincial utility, Nova Scotia Power Inc. or its affiliates. The variables available to this research are shown in Table 2 (refer also to Figure 1, right, for a map of electrical grid infrastructure). Note that for most of the system loading analysis, power transmitted on L5581 is used for the WEC field output, rather than the turbine data referred to in the first line of Table 2.

Table 2 Digby electricity infrastructure measured data points and sampling rates

Category	Name	Detail	Variables	Sampling rate	Data collection period
Generation	WEC field	30 MW capacity	Wind speed, Wind direction, Ambient temperature, Real power, etc.	10 minute	Jan 2011 – Dec 2013
Transmission	Line L-5581	Connects WEC field to Conway	Real power, Reactive power	20 second	Jan 2014 – Jun 2014
	Line L-5533	Connects Conway to Provincial Grid			
Distribution	Distribution Lines 301 302, 303	Connects Conway to Digby Loads	3-phase currents		
Substation	Conway (77V)	Transformer	Primary voltage	1 minute	

3 Analytical Methods

In this section, the steps taken to transform the survey and energy system data into an impact analysis are described.

3.1 Annual electricity consumption of a Digby electric vehicle population

In order to determine the cumulative impacts of EVs in Digby, we assume an adoption rate corresponding uniformly to all vehicle classes of 10% (approximately 600 count). Although aggressive, it is attainable over the medium term given both local and provincial transportation electrification policies [5]. Regardless of technological advances and economies of scale of EVs to support consumer purchase, an adoption rate of 10% takes significant time because of the role-over time of the existing fleet.

These adoption rates do not take into account the differences in behaviors of commercial and private vehicle owners. Commercial vehicle owners may have the financial tools to amortize a high upfront cost and recoup it through operational savings, where private vehicle owners may not; however, private vehicle owners presently have a more comprehensive market and more local dealer engagement. Estimating how these aspects will play off against each other in the coming years is a challenge, so we have defaulted to the equal adoption assumption.

3.2 Electric vehicle charging scenarios

There are three scenarios of EV charging control that represent a range of technology and vehicle – grid interactivity. In this section they are described in the context of how they might operate in the Digby area.

Scenario: Convenience charging

The “convenience charging” case is conceptually similar to mobile phones, in that the vehicle is plugged in and charged right away upon reaching a charge station, without regard to the time of day or the effect on the grid. In this scenario, EVs are likely plugged in immediately upon arriving home, and are charged until they are full. The effect of this charging behavior would not be very different in Digby than in other regions where this scenario results in a charging load peak between 17h and 19h [6, 7], unless there are systematic differences in the driving patterns of vehicles.

Scenario: Time of day charging

Nova Scotia has in place an aggressive “time of day” (TOD) residential electricity tariff. Three different rates (off-peak, 7.3¢/kWh; nominal, 14.25¢/kWh; peak, 18.6¢/kWh) are applied to electrical energy consumed at different times of the day, week, and year. While the rate structure is somewhat complex, for the purposes of this analysis the assumed response by EV drivers to this TOD charging scenario will be to delay charging through the use of a charge timer until after 23h if possible, regardless of the day of the week, or the season of the year. While a more complex response is possible, there would likely be little benefit in a charge timer differentiating between workdays and weekends, and so is uniformly applied for this study.

Scenario: Smart charging

In a “smart charging” scenario, the EV is responsive to conditions and constraints which exist on the electricity grid or in electricity markets. In Digby, the constraint of interest is power export on transmission line L-5533 (see Figure 1). When the WEC field is at maximum generating capacity (30 MW), and the Digby load is low, the transmission line reaches its export limitation. With real-time monitoring, coupled with signaling, the net export on this transmission line could be used to signal EVs the preferred time to charge, and how fast to charge. When signalled, all the EVs with any discretionary charging capacity (i.e., those vehicles that are plugged in but neither charging nor already full) could begin charging, thereby increasing the Digby load and decreasing the net electricity export.

To model the effects of such a strategy, each 24 hour period (noon to noon) was examined in isolation, and charging loads were added to periods when export power was at its highest for that period. It should be noted that in the model, a perfect response to this signal was used. In reality, any charging signal based on either a fixed schedule, or based on some real-time external signal, would only be a suggestion or a price difference, not a strict command. By default, when the vehicle requires charging for an imminent trip, charging will take place regardless of the grid impacts.

3.3 Creating Load Profiles

Based on the methods described in section 2.1, a 10% adoption rate gives 600 EVs served by Conway substation. From the survey of driving patterns, and vehicle class specific energy needs, each of these EVs would consume an average of 15 kWh per day. While this value is 2 – 3 times the daily energy needs assumed by some previous studies [8, 9], this difference can be largely attributed to the assumption made here of proportional EV adoption across all vehicle classes, while those studies focused on small and mid-sized passenger cars.

The outputs of the vehicle use surveys were a set of individual vehicle use patterns and average daily energy needs on generic weekdays and generic weekend days. For each vehicle, these data were used to construct individual charging load profiles for convenience charging by drawing electrical load right away when returned to a home parking location, or for TOD charging by drawing load at 23h if parked at home. Charging load for each vehicle were then scaled to the presumed adoption fraction for each class (10% for both), and summed together to produce a regional vehicle fleet charging load.

To produce a smart charging load profile, the sum of vehicle energy was used to ‘fill’ the points of greatest export power in each noon to noon ‘day’. For example, at a historical export power peak of -25 MW, a modified peak export power of -24.95 MW was specified, and the difference in energy between an export power timeseries bottoming out on the modified peak and one following the historical data was computed. If that summed energy was less than the necessary energy for the fleet, then the modified peak export power was increased again to -24.90 MW. This process was iterated until the difference between the original and ‘capped’ export energy curves was equal to the energy needs of the EV fleet. While this methodology could require charging at any time, this does not adversely affect the analytical results because problematic peaks in power export can only occur when both i) wind production is high and ii) local loads are low, which occur only at night.

4 Results

In this section, the interactions and influence of EVs on the electric grid are discussed, with a focus on how they would relate to renewable electricity generation in Digby.

4.1 Description of Existing Conditions

In general, Digby’s electrical load in winter is higher than the load in summer, due to increased need for space- and water- heating, and increased need for artificial light as daylight hours recede. Similarly, winds are stronger in winter, and thus WEC field generated electricity follows a similar seasonal pattern. The WEC field generation averages about 13 MW, while Digby averages roughly 8.8 MW of load, meaning the Digby region is an annual net exporter of electricity. However, Digby’s load can reach well above 18 MW, though only briefly, and can also drop to zero (during a power outage). Meanwhile the WEC field’s output is continuously variable, regularly achieving slightly more than its rated capacity of 30 MW and also regularly becoming a small net load (< 0 MW).

Of greater interest for EVs charging and grid management, daily variations in load and average WEC generation also exist. Figure 2 shows the hourly average load for each of six pairs of months, and shows

how load and wind generation vary throughout the day. The different colored lines show different daily profiles characteristic of different seasons. From Figure 2, the load in Digby (top), in both cold and warm months can be seen to drop by 2 – 3 MW overnight, with a minimum occurring between 2h and 4h. During the winter months, loads peaks twice daily, in the late morning and again in evening. This is characteristic of areas with electric heat that is often turned down at night when businesses are empty and people are asleep, and in homes during the day when people are at work. (A comparison to Provincial load data suggest that Jul-Aug and Sep-Oct load curves would likely be similar to those of May-Jun, while the load curve for Nov-Dec would lie between those of Jan-Feb and Mar-Apr.)

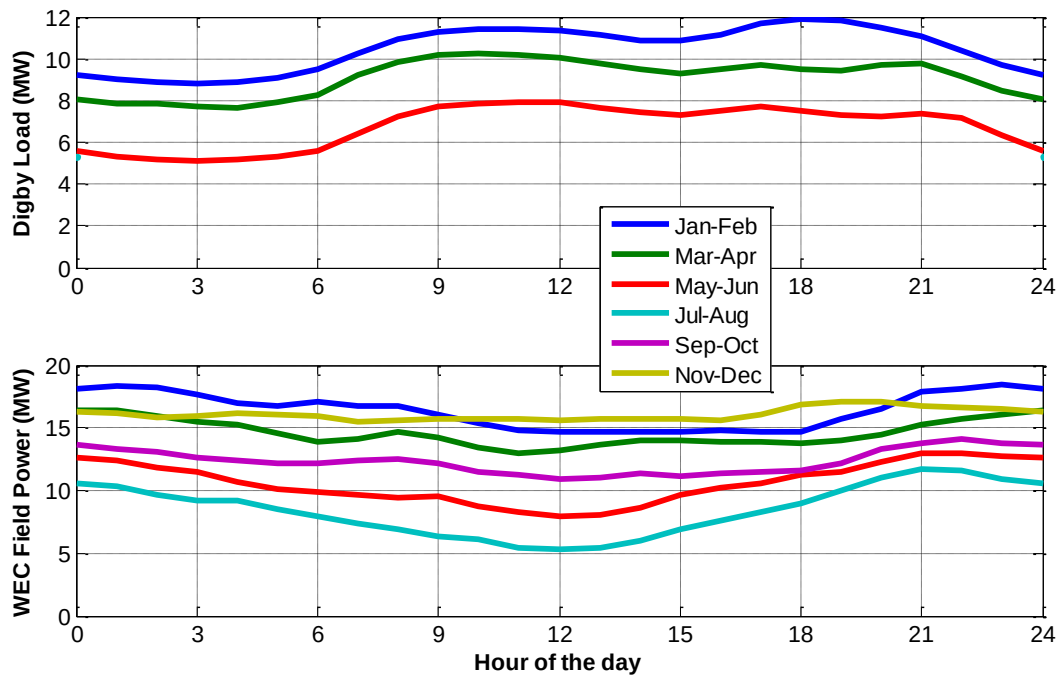


Figure 2: Average electricity power as a function of month pairs (colored) for Digby load (top), and 30 MW WEC field generation (bottom)

The hourly average electricity generation of 30 MW WEC field (Figure 2, bottom) exhibits a different pattern. Wind turbine generation is typically higher during the night and lower during the day. This is especially apparent in Jul-Aug, when average wind output averages just over 5 MW (17% of nameplate capacity) at 12h, and a peaks at 12 MW at 21h - 22h. This is substantial variation considering it is an average over 120 days (two months for two years). Of course Figure 2 represents general trends only, and at any given time of the year, the WEC field might be producing nothing, or might be at its maximum output of 30+ MW.

4.2 Impact of EV charging on the electricity grid

To illustrate the impacts of the three charging scenarios on the electricity grid, in Figure 3 we examine the first week of June, 2014. During this period, Digby Load (red, right axis) was quite low at 4 – 8 MW. The WEC field's generation (green, left axis) experienced both periods of low generation (such as June 3) and high generation (June 6). Consequently, Transmission Line L-5533 (blue, left axis) experiences periods of net import (positive values, e.g. June 3), and net export (negative values, e.g. June 6). Note that export values approaching -26 MW are of concern because of transmission constraints.

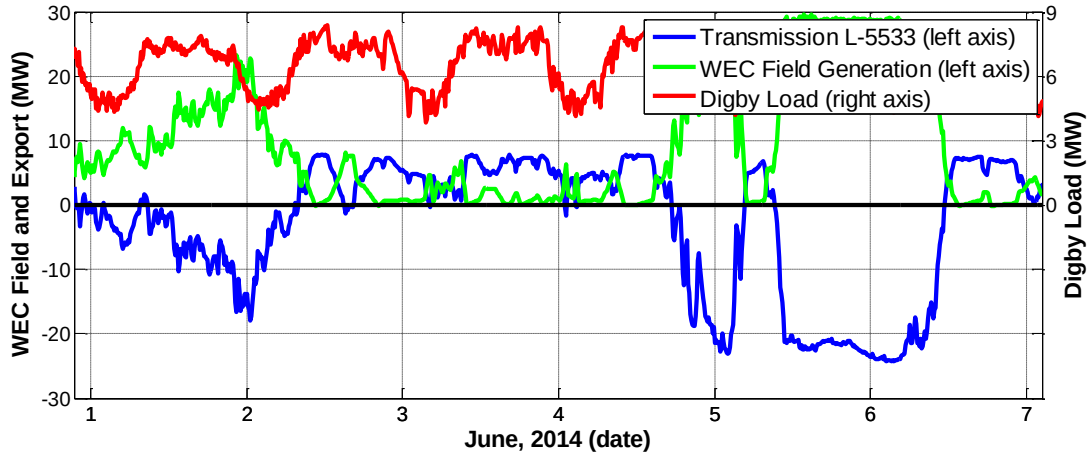


Figure 3 Electricity flows of transmission, generation, and load in Digby in June

In Figure 4, the fleet charging load profiles described in section 3.2 are plotted as a timeseries for the same week in June, 2014, along with the unmodified export power timeseries from Figure 3. Charging loads for convenience charging (yellow), TOD charging (cyan) and ideal smart charging (magenta) are read on the right axis, while unmodified export power on L-5533 (blue) is read on the left axis to clearly illustrate times of concern for export.

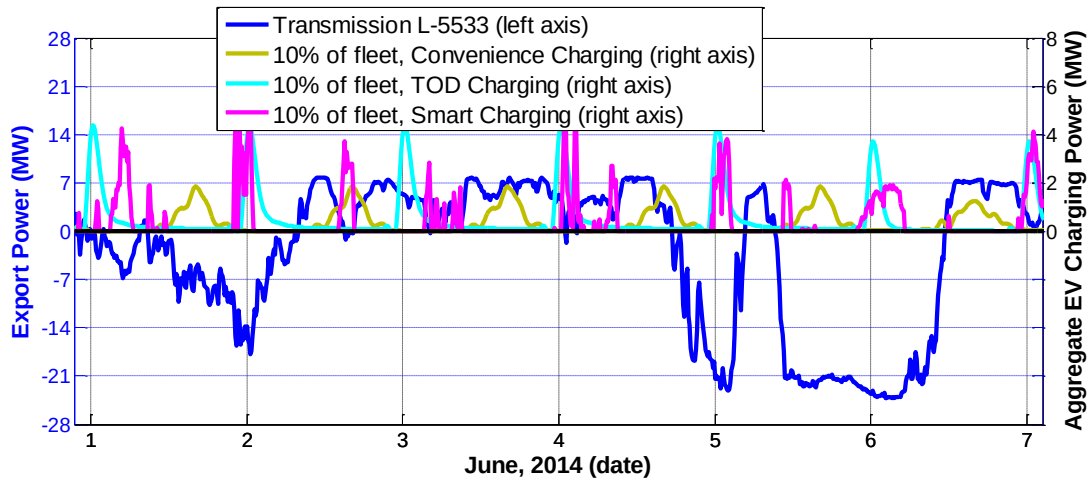


Figure 4 Electricity profiles of Convenience, TOD, and Smart charging compared with unmodified Transmission L-5533 in June

Figure 4 shows that convenience charging (yellow) adds about 2 MW of load quite consistently, with the load somewhat normally distributed around 17h. This is the likely EV load scenario if no policy and/or tariff is put in place to encourage EVs to charge at specific times. The TOD charging scenario (cyan) will add over 4 MW of load (slightly less on weekends), which ramps up quickly every night beginning at 23h. The smart charging scenario (magenta) can add as much as 6 MW of load (10 kW per vehicle), coordinated precisely with each day's peak exports on L-5533. It is evident that smart charging is highly variable in power, which will cause EVs to charge at various rates when signalled. It is likely that EV owners would be willing to accept such signals given an appropriate tariff or incentive, so long as they occurred overnight, thus having minimal impact on vehicle readiness for travel.

Note that, when the assumed smart charging logic is applied to June 3 (a low wind day) it causes the majority of the charging to occur in the morning when vehicles are likely in use. As previously stated, this scenario is not problematic for the overall results, because such conditions, when Digby's loads are not at their minimum, do not negatively impact the export transmission infrastructure.

To determine the extent to which EVs might actually help address the grid constraint on Transmission L-5533, their influence is directly applied to L-5533 power to create a modified load time-series in Figure 5.

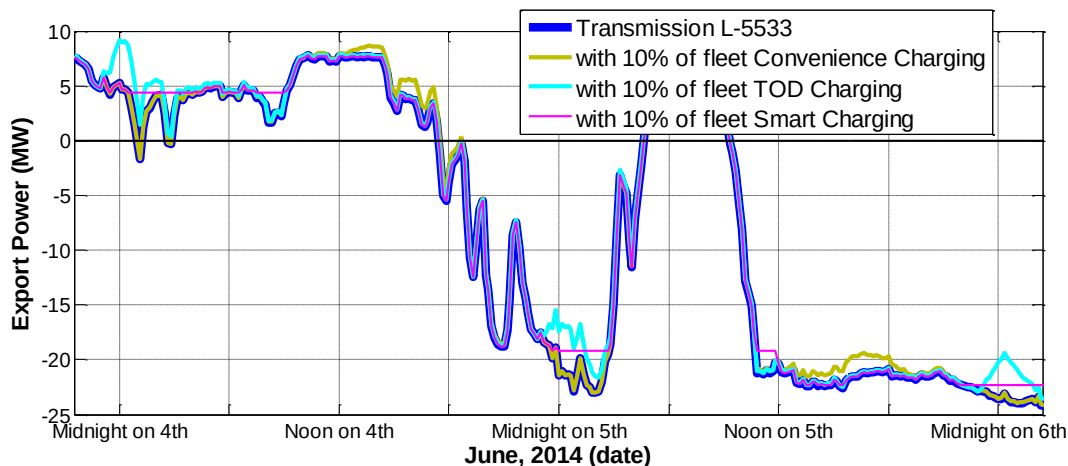


Figure 5 Time-series plot of electricity exports out of the Digby Neck area in the first week of June, 2014. The unmodified line power (black line), and line power resulting from three EV charging algorithms are shown (green, red, and cyan).

In Figure 5, it can be seen that while convenience charging (yellow) does modify the L-5533 export, it is not often helpful. For example on June 4, it adds load when Digby was importing electricity already. On June 5 convenience charging happens to reduce relatively high exports, but not reduce the maximum exports of the day. TOD charging (cyan) also provides helpful load to modify L-5533. It reduced exports from -23 MW to -21 MW on June 5. It is also helpful on June 6. Smart charging (magenta) is seen in Figure 5 to cause highly controlled load modification on L-5533. This can be noted by the horizontal magenta lines that show the modified exports. On June 5 it reduces export from -23 MW to -19 MW. On June 6 it reduces export from -24 MW to -22 MW. These modification occur precisely when required, as this is an idealized implementation.

To more strategically quantify the effects of charging algorithm, each was applied to every day during the first half of 2014, the period for which detailed generation output and transmission system data were available. The original export power curve and the three resulting modified export power curves were then sorted into exceedance probability curves, which are presented in Figure 6 in linear (left) and logarithmic (right) plots.

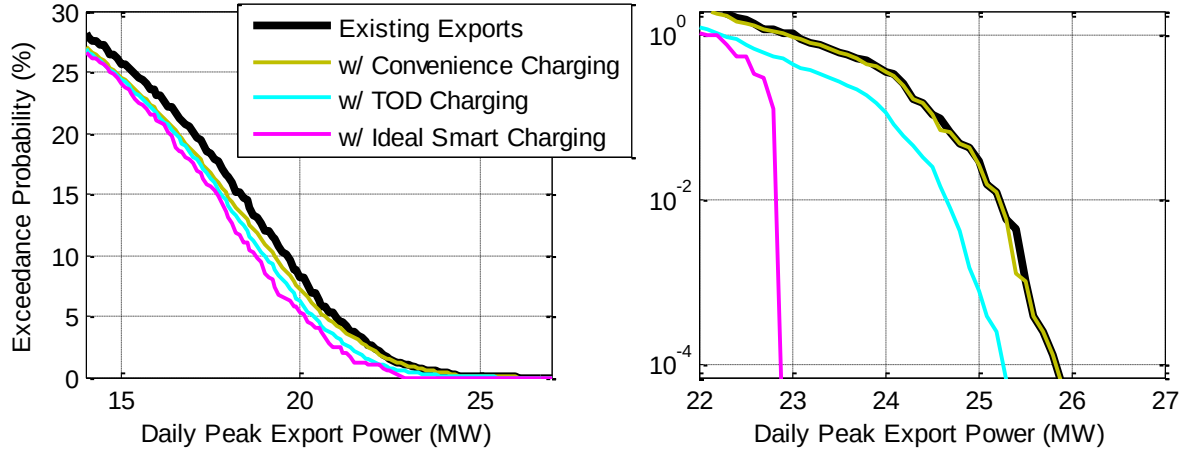


Figure 6 Line 5533 export power, exceedance probability, showing effects of three charging strategies applied to 10% of Digby vehicle fleet

The plot on the left of Figure 6 shows a broad range of export powers, and shows that all charging algorithms reduce the frequency of exports somewhat compared to the existing export exceedance probability (black line). However, export powers below about 23 MW are of no concern since they are well within existing transmission capacity. In the right plot of Figure 6 the same data are shown in greater detail, showing only exports between 22 MW and 27 MW, which correspond to exceedance probabilities of about 2% and less, and using a logarithmical distribution for the y-axis. From the right plot of Figure 6, it is evident that convenience charging (yellow) has very little effect on the most challenging export conditions. In contrast, TOD charging (cyan) reduces the worst exports by about 0.6 MW, while Ideal Smart Charging (magenta) reduces the worst exports by 3 MW.

5 Discussion

Because Digby is a net exporter of renewable energy, any EV charging in Digby will often be using locally generated renewable electricity. Even using the convenience charging algorithm, about 49% of EVs' energy would be from local WEC output. Using the TOD charging strategy, this fraction is improved to 59%, as charging events are pushed to the overnight hours when exports are more likely. Using real-time control to find each day's period of peak export in the smart charging algorithm means that 85% of the time EVs would charge from local WEC-sourced power.

While these fractions make EVs seem attractive for local consumers, it is worth noting that any renewable electricity subtracted from the greater grid supply will require additional generation elsewhere [10]. Thus the greater question is whether any charging strategies can facilitate adding increased renewables to the grid, and whether such additional capacity can make up for the additional energy demand to power the EV fleet. This question can be answered from the preceding analysis is discussed below.

The TOD charging strategy, implemented for 10% of Digby's vehicle fleet, reduced export peaks by about 0.6 MW. The fleet consumes about 9 MWh of electricity each day. In order for 0.6 MW of additional capacity to provide the annual energy to power such a fleet, it would need to have an annual capacity factor of about 62%. Thus the answer to the question of whether these additional cars can be powered from local renewable electricity is, unfortunately, 'no', unless an exceptionally high capacity factor renewable resource, significantly better than the existing WEC field, can be found.

The smart charging strategy, in contrast, could free up 3 MW of export capacity. An additional 3MW renewable energy resource with an annual average capacity factor of just 12% would therefore fully power the fleet of smart charging vehicles. As has been discussed, the load profile derived from the smart charging

scenario is idealized and could not fully be realized as it requires 100% participation, arbitrarily high charging power per vehicle, and vehicles to be plugged in and ready to accept charge precisely when needed, albeit, they would systematically be needed overnight. Determining exactly how such an idealized algorithm would translate into a real world response is beyond the scope of this study and would require an extremely detailed knowledge about not only drive cycles but about vehicle owners' responses to whatever incentive structure is put in place.

That being said, it seems reasonable to assume that the export attenuation resulting from real world smart charging would be more effective at the stated goal of capping export power than the convenience TOD response. If real world smart charging could attenuate export peaks by one third of ideal smart charging, and thereby free up 1 MW of transmission capacity to new generation, then that renewable resource would have to produce at 37% capacity factor to produce all of the 9 MWh /day needed by the vehicle fleet. Since the existing WEC produces at greater than this capacity factor, this is a very favorable finding.

6 Conclusions

Digby is a region with abundant renewable energy resources, but electricity export constraints. Many such regions presently exist, and many more will develop given the ubiquity of renewable energy generation policy. Electric vehicles can support such policy as they reduce energy consumption for transportation, and can use locally generated electricity from renewable resources, while acting as controllable loads. The objective of this study was to determine the impact that EVs have on the electricity grid for various charging control strategies, and if this is complementary to renewable energy generation.

Three charging strategies were evaluated for their effect on the interaction between renewable electricity generation and export transmission constraints. Convenience charging (not signalled) will occur in absence of any policy or electricity tariff. This will add electricity load to Digby, but will do so at existing peak load periods (~17h) when export capacity is of no concern. The use of either time of day charging (scheduled) or smart charging (signalled) will incent drivers to charge overnight, or when additional load is most needed to alleviate electricity grid constraints.

Scheduled and signaled charging strategies would increase the fraction of transportation energy sourced from local renewable electricity generators from an already high 49% for convenience charging, to 59% for TOD charging, or 85% for smart charging. More importantly, these strategies were shown to be effective at addressing grid considerations: Using a 10% EV adoption rate, such charging algorithms could provide 0.6 and 3 MW of additional transmission capacity respectively. This could enable new renewable energy generation, such as a negligible cost WEC field control strategy upgrade, that on an annualized basis could provide all the energy needed to power the vehicle fleet.

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Dr. Lukas G. Swan is an associate professor of Mechanical Engineering at Dalhousie University where he conducts research, supervises the Renewable Energy Storage Laboratory. Lukas is involved with both R&D and commercial aspects of a broad array of renewable and alternative energy technologies. His passion is sustainable and efficient energy generation, storage, and conversion mechanisms, with the intent of displacing conventional fossil-fuel use. Drawing on his experience consulting for manufacturers of EVs, he has set his research objectives on

developing energy storage technologies and management methods to allow for the increased integration of renewable energy with the electricity grid.