Addressing intermittency issues for renewable energy resources in British Columbia from the supply and demand perspectives.

by

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In the
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Abstract

One of the greatest limitations of renewable sources of electricity is the intermittent nature of their supply. Addressing intermittency is fundamental in encouraging adoption of renewable sources of electricity, such as wind power and run-of-river hydropower and maximizing potential greenhouse gas emission (GHG) reductions. This thesis addresses intermittency from the supply side of renewable electricity - by identifying sites where wind power and hydropower resources are complementary - and from the demand side of renewable electricity - with case studies from British Columbia’s (BC) transportation sector and plug-in electric vehicle adoption. The supply and demand approaches present opportunities to mitigate intermittency in renewable electricity both separately and synergistically.

From the supply side of complementarity, I demonstrate how complementarity (anti-correlation) between wind power and hydropower availability could provide a less intermittent supply of renewable electricity. I examine relationships between BC’s wind power and hydropower resources on intra-annual (seasonal) and long-term (multi-decadal) timescales. From the demand side of complementarity I investigate uptake and use of plug-in electric vehicle (PEVs) technologies. PEVs may represent a key technology in the successful transition toward reduced GHG emissions and can mitigate intermittency by being charged when excess renewable electricity is available.

In the four papers comprising this thesis, I demonstrate how complementarity between renewable electricity sources and control of renewable electricity demand are two approaches to mitigating intermittency in renewable electricity. Future complementarity of renewable electricity resources in British Columbia has not been examined previously, and thus provides insights into the long-term stability of these relationships. Furthermore, this thesis is the first to address consumer approaches to controlled charging of PEVs as a means to increasing the adoption of renewable electricity. These findings suggest that systematic planning of both the renewable energy and transportation sectors can reduce the need for electricity storage technologies, increase the use of renewable electricity and thereby reduce GHG emissions.
Keywords: Renewable electricity; intermittency; wind power; hydropower; electric vehicles; vehicle to grid; charging
If there’s one thing I’ve learned it’s that research is what I’m doing when I don’t know what I’m doing. Polly I dedicate this research to you. Here’s to making the most of our time on this pale blue dot!
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Chapter 1. Introduction

1.1. Climate change and clean energy technologies

Climate change caused by increasing concentrations of greenhouse gases (GHGs) in our atmosphere is negatively affecting human livelihoods and natural systems (IPCC, 2014). Human activities are the primary cause of modern climate change and are estimated to be responsible for ~80% of the increase in global mean temperature over the last 260 years (IPCC, 2014). Avoiding substantial changes to the earth system and the consequent negative impacts requires mitigative actions that can lead to a rapid reduction of annual GHG emissions (Denton et al., 2014). Current global GHG emissions reduction targets aim to limit global warming to 2°C above pre-industrial levels (United Nations Framework Convention On Climate Change, 2009). Achieving the 2°C target will require at least a 90% reduction in GHG emissions by 2050 (relative to 2006 levels), and likely removal of GHG’s from the atmosphere (Weaver, Zickfeld, Montenegro, & Eby, 2007).

Greenhouse gas mitigation pathways have been proposed in both the electricity generation and transportation sectors (Pacala & Socolow, 2004), with three particular pathways relating to both sectors and this thesis. The first pathway involves increasing energy efficiency to reduce energy waste. Increasing energy efficiency can reduce emissions from electricity generation (Weisser, 2007) and from the operation of personal transportation vehicles (Michalek, Papalambros, & Skerlos, 2004). The second pathway, known as fuel switching (such as from fossil fuels to renewable sources of electricity) can be used to reduce GHG emissions from electricity generation and from vehicle operation by adopting fuel sources that emit fewer GHG’s (Delarue & D'haeseleer, 2008; Hawkins, Gausen, & Strømman, 2012). The third pathway involves changing behaviour to reduce electricity consumption (Lehman & Geller, 2005) and to the use of vehicles for personal transportation (e.g. reducing kilometres traveled).
(Chapman, 2007). This thesis incorporates each of these three pathways but focuses on the role of fuel switching in the electricity generation and personal transportation sectors. In particular, I address how the electricity and transportation sectors can help to mitigate GHG emissions by reducing fossil fuel consumption. Of the GHG mitigation pathways currently available, switching the fuel used in electricity generation has the potential to account for 27% of global GHG emissions reduction required to achieve the 2°C target. Likewise, switching the fuel used in personal transportation could contribute to around 16% of the GHG emissions reduction needed to achieve the 2°C target (Williams et al., 2012).

For the purpose of this research, I will use the term "renewable electricity" to indicate electricity generated from intermittent sources such as wind turbines and small-scale "run-of-river" hydropower projects (where electricity is generated from the real-time flow of water, and little to no water is stored). In Canada, electricity generation accounts for 12% of total annual GHG emissions (Environment Canada, 2015b). However, because 79% of Canada’s electricity is generated from non-GHG-emitting sources, such as storage-based hydropower (commonly associated with dams), nuclear, and intermittent renewable energy sources (e.g. wind power), the 12% contribution represents a relatively low share of emissions compared with other nations (Statistics Canada, 2014). As demand for electricity increases, Canada will need to continue producing electricity from low- and zero-emissions sources to help meet GHG emissions reduction targets established to keep global temperatures below 2°C warming. Renewable electricity and large-scale hydropower, which do not produce nuclear waste or GHG emissions when operated, are preferred sources of electricity for meeting increased demand. Specifically, intermittent renewable electricity may be preferred to large-scale hydropower because renewable electricity may exhibit a reduced long-term impact on the environment (Abbasi & Abbasi, 2000; Evans, Strezov, & Evans, 2009).

Although renewable electricity offers the benefit of lowering GHG emissions, adoption of renewable electricity poses challenges relative to traditional fossil fuel-based electricity generation. For example, renewable electricity may generate a lower return on investment and resource quality varies with global location (Lambert, Balogh, & Gupta, 2012). More importantly for this research, sources such as wind energy and run-of-river
hydropower are often intermittent because the natural resources that control them vary with weather patterns. Electricity sources such as fossil fuels and nuclear, are known as ‘dispatchable’ because they produce or ‘dispatch’ electricity exactly when needed. In contrast, solar, wind, and run-of-river hydropower electricity resources rely on regional climate and associated weather patterns to generate electricity. Because these climate and regional weather patterns vary, so does the supply of renewable electricity. As a result, this intermittent renewable electricity is ‘non-dispatchable’ and may not be available exactly when needed.

Although the electricity storage industry is constantly developing, technologies such as batteries, compressed air energy storage and flywheel energy storage are not easily implemented (Denholm, Ela, Kirby, & Milligan, 2010). Large-scale storage has been difficult to sell into electricity markets as a result of high costs, the array of grid balancing services storage provides, and the challenges the electricity markets have in quantifying the value of these services (Denholm et al., 2010; Ibrahim, Ilinca, & Perron, 2008). Nevertheless, alternative methods are able to buffer the intermittent supply of electricity from renewable sources. One approach to alleviating intermittency in renewable electricity involves incorporating different types of renewable energy available at complementary (anti-correlated) time periods into the electricity grid system, providing a more consistent supply of electricity (Cross, Kohfeld, Bailey, & Cooper, 2015). Another approach to alleviating intermittency in renewable electricity is to shift electricity demand to reflect supply; for example, by using emerging transportation technologies such as vehicles powered by electricity and charging such vehicles when intermittent renewable electricity is available (J. Bailey & Axsen, 2015). Like the electricity sector, the Canadian transportation sector and its associated vehicle technologies represent another area where deep GHG emission reductions may be possible.

Canada’s transportation sector (including passenger, freight and off-road emissions) accounted for 24% of GHG emissions in 2014 (Environment Canada, 2015b). Half (12%) of transportation sector emissions are generated by passenger transportation (Environment Canada, 2015b). To reduce emissions from the transportation sector, Canada’s provincial governments (e.g. British Columbia) are promoting vehicle fuel-switching and the adoption of vehicles that can be powered by
electricity, known as plug-in electric vehicles (PEVs) (J. Bailey, Miele, & Axsen, 2015). PEVs can be divided into two broad categories: plug-in hybrid electric vehicles (PHEVs) powered by either grid electricity or gasoline (such as the Chevrolet Volt), and pure electric vehicles (EVs) powered solely by electricity (such as the Nissan Leaf or Tesla Model S). Because of a reduced or zero dependence on liquid fossil fuels for operation, PEVs may represent a key technology in the successful transition toward GHG emissions reduction, especially if the electricity used by PEVs is generated by renewable electricity (Williams et al., 2012).

In addition to reducing GHG emissions from vehicle operation, PEV charging presents opportunities for mitigating intermittency in renewable electricity supply through utility controlled charging (UCC). UCC broadly refers to the ability of an electric utility to control the charging of PEVs by managing when charging occurs, the rate at which charging occurs (e.g. kW), and perhaps managing if and when some electricity is discharged from the PEV battery back into the electricity grid. As a result, UCC could influence the timing and rate of PEV charging and therefore better align electricity demand with the availability of renewable electricity. Alignment of demand and supply could reduce the need for complicated energy storage or additional backup that goes with renewable electricity thus reducing the costs of using renewable electricity, increasing renewable electricity uptake, and potentially lowering the cost of abating GHGs in a given region.

This thesis approaches the issue of intermittency in renewable electricity from both the supply and demand perspectives using different case studies based more broadly in Canada and specifically in BC. BC provides a unique case study from several perspectives. The province has a relatively high capacity for renewable electricity generation primarily because of its strong hydrological and wind-based resources. BC has implemented a series of climate policies as part of its 2007 Climate Action Plan (LiveSmart, 2008), including: the Clean Energy Act, ensuring that 93% of electricity generation comes from clean or renewable sources (when excluding large hydropower, five percent of electricity generation in BC is from ‘renewable electricity’ as defined earlier) (Government of British Columbia, 2010a); a carbon neutral public sector policy (Government of British Columbia, 2008a); and North America’s first ever revenue neutral
carbon tax (Government of British Columbia, 2008b). In the last decade, BC has also provided some support for PEVs and other alternative-fuel vehicles through its Clean Energy Vehicle Program, which provides $7.5 million for point-of-sale incentives for electric vehicles, $1.59 million for investments in charging infrastructure, and $500,000 for research, training, and public outreach on clean energy transportation technology (CEV for BC, 2015). However, even with pro-PEV policies, as of 2015 PEVs make up less than 1% of new vehicles sales in Canada (Axsen et al., 2015).

Systematic planning in both the electricity and transportation sectors can reduce the need for storage technologies, facilitate low-cost deployment of renewable electricity, and reduce GHG emissions. Optimising connections between the energy and transportation sectors relies on an understanding of both supply and demand sides of the intermittency problem in renewable electricity generation. This thesis focuses on supply and demand aspects of the problem by addressing the following research goals:

1) Demonstrate how the multi-decadal and seasonal behavior of BC’s wind speed and runoff (a proxy for hydropower) resources has changed in the past 30 years, and how they are projected to change between 1979 and 2099.

2) Examine the complementarity between BC’s wind and runoff resources on seasonal and multi-decadal scales, over the periods 1979 to 2099.

3) Identify regions of BC where wind energy development is likely to be optimal given projected relationships between BC’s wind and runoff resources.

4) Investigate the scope for utility controlled charging of PEVs, which may match electricity demand with the supply of intermittent renewable electricity in BC.

5) Establish if increased public charging infrastructure may lead to increased uptake of PEVs, which would in-turn increase the potential of UCC in the future.

1.2. Chapter scope

This thesis is divided into six Chapters, with Chapters One and Six as the introduction and conclusion respectively. The remaining Chapters represent four research papers, presented here as Chapters Two through Five. Chapters Two and
Three address the supply side of the intermittency issue in BC by identifying where wind and hydropower resources exhibit complementary (anti-correlated) temporal behaviour. Chapters Four and Five address the demand side of the intermittency issue in BC and more broadly in Canada. Specifically, Chapters Four and Five focus on potential for PEVs to complement the supply of intermittent renewable electricity by providing demand for renewable electricity when it is available.

1.2.1. Chapter 2: Wind-hydro complementarity on decadal timescales

Chapter Two explores relationships between wind energy density and hydroelectricity generation potential in BC, specifically from large-scale storage hydropower. One of the challenges with wind power is that it is not always available when needed, e.g. when electricity demand is high and when supply of other forms of electricity is low. This is also true (though to a lesser extent) for large-scale storage-based hydropower, which although often considered dispatchable is influenced by annual and seasonal hydrometeorological fluctuations.

Wetter periods provide excess streamflow and thus hydroelectricity, which makes wind energy less valuable. However, during drier periods, wind energy becomes more valuable because it can offset low water levels by generating electricity and allowing hydroelectric dams to conserve water. Identifying regions where wind energy is anomalously high during periods of low streamflow (i.e. anti-correlation) could moderate climate related variability in provincial electricity supply. Previous investigations into complementarity have demonstrated that historically, onshore wind farm development on BC’s north coast could moderate climate variability in provincial electricity supply (Cross et al., 2015). To further previous research, I seek to identify regions where wind energy might be more available during drier periods by understanding the long-term relationships between hydrometeorological and wind speed behaviour in BC. As such, this research informs the long-term development of electricity infrastructure and identifies where wind power may best offset low-water levels over the next 85 years.

Identifying regions of the province where wind power is anti-correlated with BC’s main hydropower resources (represented by runoff) facilitates the co-management of
hydropower and wind resources so that they provide a more balanced supply of electricity. In other words, if one resource is available when the other is not, then the supply of electricity is less variable (Figure 0.1).

Figure 0.1 A schematic to explain the benefits of complementary supply of and demand for renewable electricity. In a) wind and hydro resources have not been planned to account for anti-correlation in supply. In b) wind and hydro resources have been developed in regions with better temporal complementarity to reduce intermittency. In c) the inclusion of PEV demand disrupts the balanced supply and in d) PEV technologies are being controlled by utilities and charged when renewable electricity is available, which leads to a less variable supply of renewable electricity or a supply that better matches demand.
Previous research suggests that long-term relationships between wind speed and reservoir inflow behaviour can be examined together to improve wind farm site selection (Cross, Kohfeld et al., 2015). However, this research has been constrained by limited data availability (both temporally and spatially) and also demonstrated that different sources of data (such as measured, re-analysis and modeled) can result in different conclusions (Pryor, Barthelmie, & Schoof, 2012). Furthermore, previous research has not addressed the question of how relationships between hydropower and wind resources might change as climate changes in the future. Chapter Two develops previous research by addressing three objectives. First, we compare the influence of data selection by examining different sources of wind speed data available for BC, which includes measured wind speed data from meteorological stations, model output from a Canadian regional climate model, and re-analysis data, which combines both measured data and model output. Second, Chapter Two examines how the behaviour and trends in wind data align with model-simulated runoff, used to represent BC’s hydroelectric resource. Finally, Chapter Two investigates how the relationships between wind energy density and runoff might change in the coming century using regional climate model simulations. The goal of Chapter Two is to infer where wind energy development and hydrological resource development is likely to be optimal in the coming century, given projected changes in the relationships between BC’s wind energy density and hydrometeorological resources.

1.2.2. Chapter 3: Seasonal and regional wind-hydro complementarity

While Chapter Two focuses on interannual to decadal relationships, Chapter Three investigates seasonal behavior in BC’s wind energy density and runoff resources in regions identified as key for future wind farm development. Since a consistent source of electricity is beneficial on both long (decadal) and short (seasonal) time periods, understanding complementary, anti-correlated behavior between wind energy density and hydroelectric resources over both timescales is important. Chapter Three looks at six regions in BC where wind energy infrastructure is proposed or under development and examines projected changes in the wind energy density and runoff resources in these areas for the periods 1980-2009 and 1970-2099 respectively. Examining long-term
seasonal differences is important because the average lifespan of a wind farm is ~20 years and understanding how current wind farms may perform in future is key for resource planning (Martinez, Sanz, Pellegrini, Jiménez, & Blanco, 2009).

Chapter Three also addresses the relationships between wind energy density and "run-of river" hydropower resources, where electricity is generated from the real-time flow of water and developments tend to be smaller than those of large-scale hydropower. I include this analysis because as BC’s population grows and electricity demand increases, run-of river hydropower is likely to contribute to a larger fraction of BC's total electricity production. As a result, understanding the relationships between wind speed and local scale run-off behaviour (important to run-of-river hydropower) is likely to become as important as understanding the relationships between wind energy density and large-scale centralised hydropower. In both cases, our approach of understanding complementarity between wind energy density and run-of river hydropower is beneficial to providing a consistent supply of electricity.

1.2.3. Chapter 4: Anticipating acceptance of utility controlled charging

Chapter Four approaches intermittency in renewable electricity from the demand perspective and from a finer (hourly) timescale by investigating consumer acceptance of utility controlled-charging (UCC) of plug-in electric vehicles (PEVs). As explained in Section 1.1 UCC broadly refers to the ability of an electric utility to manage charge times, charging rates and even perhaps discharge of electricity back to the grid. As a result, UCC could be used to better align electricity demand with the intermittent availability of renewable electricity. For example, the electricity available from wind power can be intermittent over the course of a day (Figure 0.2) and so UCC could be used to align vehicle charging demand with times when intermittent renewable electricity is most available, and therefore could help better manage BC's future electricity supply and demand (Figure 0.1).
Figure 0.2  A 3-day wind energy generation profile, aggregated from California’s wind turbines. Ideal PEV charging demand may occur around Jan 08 at 2pm or Jan 09 at 12pm, when wind energy generation is high. Equally, low wind energy generation around Jan 09 at 2am implies that no PEV demand would be useful, if wind power were the only source of electricity (California ISO, February 24, 2010).

However, UCC requires consumer uptake of PEV technology (purchase of the vehicles) and consumer acceptance of UCC (enrolment in a charging program), and many potential barriers could limit adoption of UCC. Potential concerns among consumers could include personal privacy, a feeling of loss of control, and the potential inconvenience of not having a fully charged PEV (Parsons, Hidrue, Kempton, & Gardner, 2014; Salmela & Varho, 2006). Chapter Four explores consumer acceptance of UCC by implementing a web-based survey of new vehicle buyers in Canada (n = 1470) and using statistical analysis to investigate consumer acceptance of UCC. Specifically in Chapter Four, I use discrete choice methods, which quantify consumer tradeoffs and in this case, establish what aspects of UCC are most important to consumers. Finally, I simulate the adoption rates of UCC among different types of potential PEV consumers. This study builds on previous research into pairing renewable energy technology with PEVs (Axsen & Kurani, 2013) and research into controlled charging of PEVs (Parsons et al., 2014) and is the first of its kind to address this type of UCC where intermittent renewable electricity is the focus.
1.2.4. Chapter 5: Awareness of infrastructure and interest in Plug-in electric vehicles

While UCC could be important for energy management and in particular for the uptake of renewable electricity, the potential for UCC is limited without adequate adoption of PEV technology. PEV adoption may be hindered by barriers such as vehicle cost, technology unfamiliarity and refuelling capabilities in public locations and at home where around 80% of current PEV charging events occur (Egbue & Long, 2012; Lane & Potter, 2007; Sierzchula, Bakker, Maat, & van Wee, 2014; Smart & Schey, 2012). Each barrier can be reduced by policy support, and global regions vary in their adoption of PEV-oriented policies. Some regions such as California adopt supply-focused policies, which may mandate that a certain portion of vehicles sold to consumers emit no emissions (a zero-emissions vehicle mandate) (Collantes & Sperling, 2008). Likewise, PEV oriented policies may require that fuels used in a given region generate low-carbon emissions when burned (a low-carbon fuel standard). Alternately, other regions such as Norway adopt strong demand-focused policies, which include financial (e.g. vehicle rebates) and non-financial incentives (e.g. reserved parking for PEVs) and the development of both public and home charging infrastructure (Sierzchula et al., 2014).

Chapter Five focuses on demand-focused policies, specifically the development of charging infrastructure. Policymakers often seek to increase the visibility of PEV chargers in public locations to foster familiarity and interest in PEVs. However, the actual effect of prevalent and visible public charging stations on PEV demand remains unclear. Chapter Five assesses the current levels of visibility for public PEV charging infrastructure within Canada and identifies whether or not a statistically significant relationship exists between consumer awareness of public charging infrastructure and interest in purchasing a PEV.

1.2.5. Overall scope of the thesis

The findings presented in the following Chapters demonstrate potential for GHG emission reductions from both the supply and demand aspects of intermittent renewable electricity. From the supply side, this thesis identifies regions of anti-correlation between wind and hydropower resources (e.g. south western BC) and where BC’s intermittent
renewable resources might be best developed to maximise the use of renewable electricity in the long-term. From the demand side, this thesis identifies potential for adopting utility controlled charging among car-buyers in Canada and that some consumers are motivated by the GHG emission reduction potential of UCC. This thesis also demonstrates that to maximise PEV adoption, and thus UCC, regions should focus on supply side policies, and perhaps develop household charging infrastructure before focusing on public charging infrastructure. I recommend that long-term strategic planning of electricity grid infrastructure along with integration of the electricity generation and personal transportation systems can play a key role in minimising long-term GHG emissions.

1.3. References


UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE, 2009. *Copenhagen Accord*.


Chapter 2. Past and future inter-annual relationships between wind speed and runoff behaviour. Implications for renewable planning development in British Columbia.

2.1. Abstract

In hydroelectric dominated systems, the value and benefits of electricity are higher during extended dry periods and lower during extended or extreme wet periods. By accounting for regional and temporal differences in the relationship between wind speed and reservoir inflow (streamflow) behaviour during wind farm site selection, the benefits of electricity diversification can be maximized. We use British Columbia (BC) as a case study because clean energy and self-sufficiency policies in BC make benefits of increased wind power generation during periods of low reservoir inflow particularly large. The goal of this work is to help maximize the value of wind power by characterising the projected relationships between wind speed and streamflow behaviour between 1979 and 2099. We identify historical trends and correlations between wind energy density (WED) at 80m elevation and surface runoff, which we use to represent hydroelectricity generation potential in BC. Trends and correlations vary depending on the source of data used for WED, and we compare results from the Integrated Surface Database, the North American Regional Reanalysis Dataset and two different versions of the Canadian Regional Climate Model. We then demonstrate how the WED and runoff resources are projected to change between 1979 and 2099, using Canadian Regional Climate Model (CRCM) simulations forced with a greenhouse gas (GHG) emission scenario equating to twice the global emissions of 2000 by 2055. These simulations project trends of increasing WED (~2%/decade) throughout BC’s northern and coastal regions, but decreasing WED (~2%/decade) in the southern and interior portions of BC. Although these trends are geographically distinct when we consider the entire time period from 1979 to 2099, the CRCM simulations also show high, inter-period variability when we
estimate trends over shorter (30-year) time periods (which are more representative of the lifespan of wind turbines). Spatial patterns of trends in WED change depending on the 30-year time period considered, but the Spearman ρ, correlations between WED and our proxy for hydroelectricity (runoff) are projected to be spatially consistent over the period 1979-2099. Negative correlations (ρ = -0.2) between WED and runoff are projected in southern BC and the US Pacific Northwest, with persistent correlations in southern BC in both the long-term (1979-2099) as well as all of the 30-year time windows between 1979 and 2099. These negative correlations are prevalent in three out of the four datasets we compared for the time periods of 1979 and 2004. The persistence of the negative correlations points to BC’s southwest region as a potentially valuable location for future energy planning efforts.

Although persistent negative correlations are more frequently due to low WED and high runoff conditions, which may be less desirable in hydroelectricity dominated systems, there are some regions where WED is indeed higher in some regions during years of anomalously low runoff. Regions of the Alaskan coast and the eastern coast of Vancouver Island exhibit positive WED anomalies (+15%) during periods of low flow, which could have a moderating effect on climate related variability in provincial electricity supply.

2.2. Introduction

Global electricity demand is expected to increase by approximately 80% between 2012 and 2040 (International Energy Agency, 2014). As demand increases, so does the need to supply electricity derived from low-carbon, renewable sources, which may help to reduce global greenhouse gas (GHG) emissions. Wind power has been a prime candidate for meeting demand and, consequently, the global capacity for wind power generation has increased by approximately 650% over the past 10 years (Global Wind Energy Council, 2013).

Although wind power offers GHG emission benefits relative to fossil fuels, the intermittent availability of wind power can make grid integration difficult (Lund, 2005). One solution is to pair wind power with large-scale hydroelectricity reservoirs that offer a
large storage capacity because conversion of wind-sourced energy into potential hydroelectricity makes it easier to regulate (Woo et al., 2013). However, a large body of water at high elevation is required to make a substantial contribution to a regional electricity grid (Denholm et al., 2010). Further, the flooding of land for the development of large hydroelectricity facilities can generate negative environmental impacts, and infrastructure development often entails significant upfront capital investment (Evans et al., 2009). Understanding how the behaviours of wind and hydrological resources are linked could help to overcome these disadvantages by exploiting the most beneficial timing between wind speed and hydrological variability. Specifically, planning based on understanding the climatic behaviour of wind speeds and runoff, can facilitate wind power development in areas with higher wind speed when hydroelectricity generation is low (and vice versa) such that the resources are complementary (anti-correlated).

We investigate the complementarity of wind speeds and runoff in British Columbia (BC) and the broader Pacific Northwest (PNW) region of Washington, Oregon and Idaho where complementary wind and hydrological resources could be particularly valuable. BC’s Clean Energy Act (Government of British Columbia, 2010a) mandates that at least 93% of BC’s electricity generation must come from clean or renewable sources such as wind or hydropower. BC’s Clean Energy Act also includes a self-sufficiency requirement, stating that electricity generation within BC must be able to meet all domestic demand by 2016. Therefore, in years of low reservoir inflow (streamflow), BC must meet its electricity demand using means other than hydropower. At present, BC’s hydrological resource meets ~85% of provincial electricity demand and represents the foundation of provincial electricity production. However, electricity demand in BC is projected to increase 40% by 2030 (BC Hydro, 2013). Because of the Clean Energy Act, BC will need to generate electricity from predominantly renewable sources to meet demand while balancing potential environmental and social costs associated with energy development.

A large portion of British Columbia’s current large hydropower resource exists in the Peace region (Figure 2.1), which represents approximately 40% of total annual hydroelectricity generation (BC Hydro, 2014a). Because of the lifetime of infrastructure associated with large-scale hydropower, the Peace region of BC will likely continue
providing a large portion of BC’s electricity in future. As a result, we focus this study on the long-term (decadal) complementarity between runoff in the Peace region and wind speeds throughout BC and PNW.

Figure 2.1  Our study domain extends from 45° to 65°N and 110° to ~150°W. The fine dash box surrounds the region of focus. In this research we use output from a regional climate model whose extent is outlined with the large dash lines and a regional reanalysis product whose extent covers the entire study region.

Previous research has focused on understanding short-term (seconds-to-days) complementarity between wind power and hydroelectricity (Belanger & Gagnon, 2002; Joskow, 2011; Kiviluoma, Holttinen, & Finland, 2006) but in contrast to the short-term, few have studied complementarity between wind speeds and streamflow on longer, decadal timescales (Cross et al., 2015). The changeable nature of wind speeds and streamflow, which are influenced by climate, induces variability not just on daily timescales but also on annual and decadal timescales, which is why we focus on longer decadal timescales.
Recent work in BC and the US PNW has demonstrated how understanding seasonal-to-interannual complementarity between wind and hydroelectricity resources can have implications for system level, wind-related resource development (Cross et al., 2015). Cross et al., (2015) demonstrated how wind farms in regions with above-average wind speeds during periods of low hydroelectricity availability may have greater value than similar sites where most electricity generation occurs during periods of high inflows and electricity prices are typically lower. To represent the potential long-term complementarity between wind power and hydroelectricity, Cross et al. (2015) investigated relationships between wind energy density (WED) and cumulative useable inflow (CUI) (a metric for hydroelectric availability used by the regional electricity supplier, BC Hydro) over the past 30 years using wind information derived from the North American Regional Reanalysis (NARR) product. The study identified BC’s North coast as a place where anti-correlation (i.e. good complementarity) between wind speeds and hydroelectricity (streamflow) could provide a moderating influence on climate-related variability in provincial electricity supply.

While the work of Cross et al. (2015) represents a first step in using complementarity in wind speeds and streamflow as a means of balancing electricity supply, the results rely on one data source for information on wind speed behaviour, which could present some limitations. First, trends in wind speeds can exhibit large differences in magnitude and even direction, depending on the type of climate analysis used (e.g., observations, re-analysis data, or model simulation) (Pryor et al., 2009). Second, the temporal limitations (1979-2010 only) of the NARR reanalysis product constrain our ability to determine if the 30-yr time period examined by Cross et al. (2015) is representative of longer-term trends in the relationships between wind speeds and streamflow. That is, we do not know if the relationships may have been different in the past, or if they will hold into the future.

A detailed understanding of the relationships between wind speeds and streamflow behaviours over multiple decades is important because these relationships are complicated by large-scale climate oscillations and climate change. For example, the El-Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillations (PDO) have been shown to modify wind speed (Abeysirigunawardena, Gilleland, Bronaugh, &
Wong, 2009; Enloe, O'Brien, & Smith, 2004; Hamlington, Hamlington, Collins, Alexander, & Kim, 2015) and streamflow (Cayan, Redmond, & Riddle, 1999; Hurrell & Van Loon, 1997; Redmond & Koch, 1991; Stahl, Moore, & Mckendry, 2006; Trenberth & Hurrell, 1994) behaviours throughout BC. Warm phases of ENSO and the PDO both result in a high-pressure system over western North America reducing regional air pressure gradients and producing drier, stiller winters in southern parts of BC which are likely to modify BC’s wind speed and streamflow relationship (Fleming & Quilty, 2006; Fleming, Whitfield, Moore, & Quilty, 2007; Kiffney, Bull, & Feller, 2002; Ropelewski & Halpert, 1986; Shabbar, Bonsal, & Khandekar, 1997; Stahl et al., 2006; Tuller, 2004; Whitfield, Moore, Fleming, & Zawadzki, 2010).

Further, the impacts of large-scale climate oscillations on wind speed and hydroclimatic behaviour vary spatially across the province and affect the spatio-temporal behaviour of wind speed and streamflow resources differently by region. When considering streamflow, warm phases of ENSO are positively correlated with increased streamflow in the interior regions and negatively correlated on the coast (Mantua, Hare, Zhang, Wallace, & Francis, 1997). The influence of warm phases of the PDO on low streamflow events is stronger on the coast than inland, and the effect decreases from south to north (Mantua et al., 1997). Location also plays a role in determining average and extreme wind speeds. Peak wind speeds may be higher during cold ENSO phases, with small decreases during warm phases (Gower, 2002; Klink, 2002). Equally, warm PDO phases are associated with a high-pressure system over western North America, lower air pressure gradients, and therefore less storm activity and lower mean wind speeds in the PNW. Accordingly, negative (cold) PDO phases are associated with stronger pressure gradients and higher mean wind speeds (Holt & Wang, 2012).

In conjunction with climate oscillations, climate change (and associated changes in the processes controlling wind speed and hydroclimate) is likely to affect the correlations between wind speeds and streamflow behaviour. Wind speeds are projected to decrease over the next 100 years in the PNW and southern BC (Breslow & Sailor, 2002; Pryor et al., 2012; Sailor, Smith, & Hart, 2008) while changes in streamflow behaviour will depend on how watersheds shift from glacier- and snow- to more rain-dominated regimes (Hamlet & Lettenmaier, 1999; Merritt et al., 2006; Rodenhuis,
Bennett, Werner, Murdock, & Bronaugh, 2007; Whitfield, Cannon, & Reynolds, 2002). Understanding how the wind and hydrological behaviours may change will be essential to examining the future, long-term complementarity in planning wind power and hydroelectricity resources.

To better understand the future, long-term complementary behaviour of wind speeds and streamflow resources in BC and the PNW, we address the following three objectives: first, identify trends in WED in the PNW for the period of 1979-2004 using four different types of historical climate analyses, including meteorological station data, the NARR data product, output from a regional climate model forced with regional re-analysis, and a regional climate model forced with a global climate model simulation. Understanding trends in the WED resource serves as a good precursor to correlation analysis because areas with increasing wind speeds are likely to be preferred for wind energy development. We demonstrate where the four data sets are coherent and where divergences in results occur. We do not seek to validate the model simulations using the NARR and meteorological station data because they are not expected to generate consistent results due to differences in methodology, quality control and spatiotemporal density (Caya & Laprise, 1999; Mesinger et al., 2006; Smith, Lott, & Vose, 2011). Second, using the same climate analyses, we identify regions with persistent inverse correlations between WED and runoff (a proxy measure we establish as representative of the water resources that are most important for current hydroelectric production in BC). Finally, we use regional climate model simulations to examine both historical and future variability in the trends and correlations between WED and runoff. Our overarching goal is to assess if regional changes in climate are likely to impact the WED and runoff relationships that are observed today.

2.2.1. Historical resource characteristics

Throughout BC, mean annual wind speeds and the value of the wind power resource depends on location (Figure 2.2). When examining the North American Regional Re-analysis (NARR) dataset, which is created using a combination of wind speed measurements and modeling techniques, the highest 10m wind speeds over land exist in the northerly, coastal and mountainous regions (annual average ~7m/s) and
lowest wind speeds exist in the flatter, interior regions (annual average ~4m/s). Typically, regions suitable for utility-scale (as opposed to rural-scale) wind electricity generation require annual average wind speeds above ~6m/s at 10m height and are generally represented by the regions of white and orange in Figure 2.2 (National Renewable Energy Laboratory, 2014). Although BC’s southern and central interior regions are unlikely to provide utility-scale resources (aside from high elevation localised topography not captured in Figure 2.2) the coastal, northern and mountainous regions of BC represent a more energy dense wind resource suitable for electricity generation (BC Hydro, 2011).
Figure 2.2  Ten-metre mean wind speeds over the period 1979-2004 as generated by the NARR product (Mesinger et al., 2006). The black dot signifies the location 57.43, -125.83 in the Peace region of BC, where runoff information is extracted for use as a hydroelectricity proxy. Regions in orange are likely sufficient for utility-scale energy generation, white regions are marginal, and blue regions are unlikely to be used in utility-scale electricity generation (aside from localised topography not captured in Figure 2.2).

The annual streamflow resource in the Peace region of BC demonstrates a distinct increase around April (the Peace river curve in Figure 2.3), increasing to maximum flows around May / June and a smaller rainfall-dominated increase in discharge around October. Although the overall magnitude of potential reservoir inflow rates depends on data source used, all data sources show general agreement with regard to the seasonal pattern of potential inflow rates. In particular, the temporal
variability of the Canadian Regional Climate Model driven by the NCEP-DOE Reanalysis 2 (CRCM-NRA) and an ensemble mean of the regional climate model driven by a global climate model (CRCM-ENSM) mirror the peak flows of the Cumulative Usable Inflow (CUI), our proxy of available hydroelectric generation obtained from BC Hydro.

Figure 2.3 Annual mean runoff estimates by data source. The CUI has been standardised and is the only metric using the right-hand y-axis. The discharge (mm/month) represents total monthly discharge over a 45km² area.
2.3. Data and methods

2.3.1. Observations and model simulations

To generate relevant results for the renewable energy planning community, we converted 10m wind speed time series into 80m WED time series. We used Hueging et al., (2013) and Manwell et al., (2010) to extrapolate 10m wind speeds $U(z_r)$ up to wind speeds at typical hub heights of 80m $U(z)$ where $r$ is the original reference height of 10m (equation 1). In equation (2), we estimate monthly mean WED from the time series of wind velocities falling in a given month, where $U$ is wind speed at a height of 80m, $i$ represents the beginning of the summation index and $N$ is the time period (1 month). We assume a constant air density ($\rho$) of 1.225g/m$^3$ and a power law exponent ($\alpha$) of 0.2 as suggested by the International Electrotechnical Commission (IEC) for areas over land (IEC, 2005).

$$\frac{U(z)}{U(z_r)} = \left(\frac{z}{z_r}\right)\alpha$$

(1)

$$WED = \left(\frac{1}{2}\right) \rho \frac{1}{N} \sum_{i=1}^{N} U_i^3$$

(2)

We analyse four different sources of 10m wind speed data:

1) The Integrated Surface Database (ISD) (Smith et al., 2011) contains hourly observations of wind speed compiled from over 100 original data sources. Before release, the ISD data underwent an automatic quality control including checks for distribution values/limits, and consistency between parameters (Lott, 2004). For the purpose of this research, we only included a location if it met the following completeness criteria:

- Hour – at least 7 measurements per day
- Day – at least 90% of days in month
- Month – at least 11 months in a year.
- Year – at least 3 years with valid months and days, by the above criteria.
After compilation, visual inspection and the application of completeness criteria, we were left with 60 stations in our study domain each with complete monthly time series (Appendix Table A.1).

2) The North American Regional Reanalysis (NARR) (Mesinger et al., 2006) is produced by the National Center for Atmospheric Research (NCAR) and the National Centers for Environmental Prediction (NCEP). We extracted reanalysis output for the two 10m wind components at a resolution of $\sim 32 \times 32$ km for 1979–2004 from the NARR to provide 3-hourly 10m wind speeds. The NARR project is an extension of the NCEP-DOE Global Reanalysis that uses the high resolution NCEP Eta Model and its data assimilation system, the Noah Land surface model, and several additional datasets to increase the resolution and generate a more highly resolved reanalysis product for North America (Kanamitsu, Ebisuzaki, Woolen, Potter, & Fiorino, 2000).

3) We obtained model-simulated wind speeds from the CRCM version 4.2 (Mladjic et al., 2011), developed by the Ouranos Consortium originally described by Caya and Laprise (1999). The CRCM is a state-of-the-art model of regional climate based on gridded finite-difference techniques (Caya & Laprise, 1999; Cayan et al., 1999). The CRCM horizontal grid is uniform in a polar stereographic projection, and is used operationally at a 45km grid mesh, which allows a good description of the processes important for the regulation of hydrological regimes at a regional scale (Music et al., 2012). We used results from four simulations of the CRCM driven by two different types of boundary forcing:

a) The first simulation used boundary forcing conditions provided by the NCEP-DOE Reanalysis 2 (Kanamitsu et al., 2000). This simulation (hereafter CRCM-NRA) spans the period from 1979-2004 and incorporates pseudo-observations (as periodic forcing) into the model simulation (Figure 2.2).

b) The remaining simulations were ensemble members, generated from slightly different initial climate states of the German Coupled Global Climate Model (ECHAM5) which has a horizontal resolution of approximately 1.87° latitude-longitude (Jungclaus et al., 2006). Both global and regional simulations were performed using the IPCC SRES A2 GHG and aerosol projected evolution after the year 2000 (Nakicenovic et al., 2000).
The A2 scenario equates to global GHG emissions of approximately 17 gigatons of carbon dioxide per year (Nakicenovic et al., 2000) and evolves similarly to the IPCC's more recently adopted relative concentration pathway 8.5 (Rogelj, Meinshausen, & Knutti, 2012).

We refer to these simulations as CRCM-EM1 through CRCM-EM3. When presenting an average of these three simulations we use CRCM-ENSM (ensemble mean).

4) We used the simulated, monthly mean runoff (mm/month) from each of our CRCM simulations as our representation of available streamflow and by extension, potential hydroelectric generation. As with wind speeds we use an ensemble mean (CRCM-ENSM) where appropriate.

2.3.2. Analysis methods

As mentioned in Section 2.3.1, we use time series of the monthly mean WED to represent wind power potential at each grid cell. To create a proxy for hydroelectric potential for the entire province of BC we generated a monthly time series by calculating the average of monthly mean runoff at the location (57.43, -125.83) and the surrounding 8 grid points. This location (57.43, -125.83) is in the Peace River region where streamflows are responsible for ~40% of BC’s large-scale hydropower generation today (BC Hydro, 2014a). To demonstrate how our monthly mean runoff proxy is representative of hydroelectric generation potential, we used a mean annual cumulative usable inflow (CUI) metric provided by BC Hydro and correlated it with our monthly mean runoff proxy (Figure 2.4). Since CUI is only available for the period 1979-2004, this could not be used for the full time period of our analysis (1979-2099). This is why we generated a new proxy for CUI using runoff.
Correlations between BC Hydro’s CUI, a proxy for hydroelectric generation potential, and our monthly mean runoff proxy calculated around the location 57.43, -125.83. Panel a displays output from the CRCM-NRA and panels b, c, and d present each of the three CRCM ensemble members discussed in Section 2.3.1.

In all circumstances, the correlations between our runoff proxy and CUI are high and range from 0.83 to 0.9. This suggests that the runoff in this location represents CUI well. To investigate the influence of using different grid cells around the Peace River region on the relationship between runoff and CUI we calculated the sensitivity of the correlation between CUI and runoff for six different grid cell selection scenarios. Since the time series in these areas were similar we did not find large differences in
correlations between the runoff proxy and CUI ($\rho$ range = 0.76-0.90) (Figure 2.5). Herein, our analysis uses scenario 6 in the generation of a runoff proxy, which as discussed is generated by calculating an average of the 9 grid cells at and around the (57.43, -125.83) location.

**Figure 2.5**  Sensitivity of the correlation between CUI and runoff for different grid cell selections and each ensemble member. Runoff scenarios 1-4 represent the monthly average of the grid cell at 57.43, -125.83 and its 3 closest grid points to the southeast, northeast, northwest and southwest respectively. Runoff scenario 5 represents the grid cell at 57.43, -125.83 alone. Runoff scenario 6 (our chosen scenario) represents a mean of the chosen grid cell and its closest 8 neighbours.

For all four sources of WED and runoff from the CRCM, we estimated linear trends in the monthly WED and monthly mean runoff, respectively, and grouped these time series into five periods (Table 2.1). We use the time period of 1979-2004 for period
1 because it represents the full temporal extent of the CRCM-NRA simulation, and because it allows for the optimal combination of temporal extent and data density when comparing datasets and simulations.

Table 2.1 Different time periods used to investigate WED and runoff.

<table>
<thead>
<tr>
<th>Period</th>
<th>Temporal Extent</th>
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<tbody>
<tr>
<td>1</td>
<td>1979-2004</td>
</tr>
<tr>
<td>2</td>
<td>2010-2039</td>
</tr>
<tr>
<td>3</td>
<td>2040-2069</td>
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<tr>
<td>4</td>
<td>2070-2099</td>
</tr>
<tr>
<td>5</td>
<td>1979-2099</td>
</tr>
</tbody>
</table>

We removed the seasonal component from the monthly time series to investigate changes in the interannual variability and trends of WED and runoff. Seasonal data may induce spurious correlations due to regional seasonality rather than climate patterns (Griffin, Kohfeld, Cooper, & Boenisch, 2010). We used the R function stl, Seasonal Decomposition of Time Series by Loess, to deseasonalize our data (R Core Team, 2014). This algorithm iteratively uses loess (locally weighted scatterplot smoothing) to identify the seasonal pattern, long-term trend, and residuals of a time series.

To estimate trends from the deseasonalised monthly time series of WED and runoff we used ordinary least squares regression, which facilitates comparison with previous wind trend studies (McVicar et al., 2012; Pryor et al., 2009). To understand the relationships between WED and runoff, we calculated the Spearman rank correlation coefficient between monthly WED and monthly runoff totals for each data source (outlined in Section 2.3.1). In both the trend and correlation analyses we considered results significant at the \( p \leq 0.1 \) level. In the case of the CRCM-ENSM simulation, we calculated results using an average of the three ensemble members for both the WED and runoff metrics. In prior testing we investigated results from each ensemble member separately. Prior testing also investigated results when calculating the average trend (or correlation) where the trends (or correlations) were significant (\( p \leq 0.1 \)) in two or more of the ensemble members. We only present the CRCM-ENSM because the CRCM-ENSM results were consistently similar to those in prior testing. Since the goal of this analysis is to establish general patterns of trends and correlation, we follow previous studies and
tolerate a 10% chance for a type 1 error (Cross et al., 2015). We summarise the WED and runoff correlation pairings in Table 2.2.

Table 2.2  WED and runoff pairings used in the correlation analysis.

<table>
<thead>
<tr>
<th>WED Data / Simulation</th>
<th>Runoff Simulation</th>
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</thead>
<tbody>
<tr>
<td>ISD</td>
<td>CRCM-NRA</td>
</tr>
<tr>
<td>NARR</td>
<td>CRCM-NRA</td>
</tr>
<tr>
<td>CRCM-NRA</td>
<td>CRCM-NRA</td>
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<tr>
<td>CRCM-ENSM</td>
<td>CRCM-ENSM</td>
</tr>
</tbody>
</table>

In addition to trend and correlation analyses, we used two additional methods to better understand the potential of complementarity between WED and runoff resources in providing a less intermittent supply of renewable electricity. First, where we observed negative correlations, we identified the cause of the anti-correlation, i.e. we identified whether the anti-correlation was due to a higher frequency of high WED-low runoff conditions or due to a higher frequency of high runoff-low WED conditions. We presumed that a utilities planner working with existing infrastructure (dominated by hydroelectricity sources) may be most interested in regions where negative correlations are due to a higher frequency of high WED-low runoff conditions rather than low WED-high runoff. At each grid point, we calculated the 5-year running means for the WED and runoff respectively. We identified at each grid point if the monthly value was above (“high”) or below (“low”) its corresponding 5-year running mean. Finally, for each time period we estimated the ratio between the frequencies of these two occurrences, i.e. how often were anti-correlations due to higher WED and lower runoff. Much like the trends and correlations, we considered results significant at the $p \leq 0.1$ level.

Second, we identified whether wind energy densities during the lowest runoff years were significantly different from those in other years. For each period, we generated two populations; one comprising WED values in lowest runoff years and the other comprising WED in the remaining years. We used a non-parametric Mann-Whitney U (aka Rank Sum) test to determine if the two populations were considered distinct at a significance level of $p \leq 0.1$. This test was performed for the three and five lowest inflow years for each of the periods examined to test if the results were robust across low inflow years in general, or were a product of the particular years in question. The
purpose of this analysis was to identify broad regions of interest in which the patterns of wind speed behaviour were different from runoff during extreme years. Again we chose a significance level of $p \leq 0.1$ to avoid eliminating sites that may still have beneficial wind speed availability. This second method to investigating potential complementarity follows the approach of Cross et al., (2015).

2.4. Results

2.4.1. Trends in wind energy density behaviour between 1979 and 2099

*Period 1, 1979-2004*

In period 1, the four climate analyses demonstrate different trends in WED (Figure 2.6). The ISD data exhibit high spatial variation, suggesting decreasing WED north of 60° latitude and mixed trends in the southwest of BC. In contrast, the NARR data suggest increases of around 5-10%/decade throughout the entire study region (Figure 2.6). The NCEP-driven CRCM simulation (CRCM-NRA) shows increases in WED in the Peace River region (north-central BC and Alberta), the Northwest Territories and off the coast of Haida Gwaii of around 5%/decade, but decreases of more than 10%/decade in the Yukon and Alaska. The ensemble mean of the CRCM matches most closely with the NCEP-driven CRCM and suggests increasing trends of around 6%/decade in the southern portion of the study area and decreasing trends (~3%/decade) along the north coast. Relative to NARR, both CRCM simulations show fewer areas with significant WED trends and more spatial heterogeneity.
Figure 2.6  Significant ($p \leq 0.1$) decadal trends (%) of the NARR, CRCM-NRA, and the CRCM-ENSM monthly mean WED. Overlaid are decadal trends at ISD stations (represented as triangles) between 1979 and 2004. The black dot represents the location of our runoff proxy.

**Periods 2-4, 2010-2099**

During each of periods 2 to 4, the CRCM-ENSM simulation shows spatially and temporally distinct trends (Figure 2.7). Period 2 (2010-2039) exhibits increasing WED trends of around 5%/decade, primarily along BC’s coast and into the US PNW coastal region. During the mid and latter portions of the century (periods 3 and 4), WED
increases by around 6%/decade on BC’s coast and in period 3 WED is projected to decrease by around 5%/decade in the Northwest Territories. Similar magnitudes of decreasing trends also occur in the southern portion of the study area during period 4 (2070-2099). The most prominent feature in period 4 is the clear spatial differences between trends where decreases in WED occur in the southern region of the study area and increases occur in the coastal and northern regions.

Figure 2.7 Significant decadal WED trends estimated from the CRCM-ENSM simulations. Each ensemble member trend is estimated separately, and this figure highlights the mean trend at each location where at least two ensemble members suggest a significant trend.
**Period 5, 1979-2099**

Period 5 (Figure 2.7) represents the entire temporal extent of our study (121 years) and is therefore useful for understanding long-term behaviour. Period 5 appears to represent a composite of the WED trends experienced during periods two, three and four, with a range of around -2%/decade (south eastern portion of the study area) to +2%/decade (north and coastal regions of BC). These trends suggest that, overall, monthly mean WED will increase in the northern and coastal regions and decrease in the southern regions of BC by 2099, compared to 1979.

**2.4.2. Runoff behaviour between 1979 and 2099**

Unlike the CRCM WED trends, the monthly CRCM runoff data show slightly more consistent behaviour within each of the five time periods (Figure 2.8). Most periods are dominated by increasing trends, where increases (~15%/decade) are greatest on the Alaskan coast and the eastern coast of Vancouver Island. During periods 2 and 4 (Figure 2.8, c and e respectively), negative trends of approximately -10%/decade exist in central Alberta and for period 2 around Washington State and Southern BC. Across 121 years of period 5, the study region experiences a consistent increase in runoff (~5%/decade) throughout BC, although regions near the coast and around the Yukon and Alaska exhibit increasing trends closer to 15%/decade.

Panel b in Figure 2.8 displays the trends in monthly runoff from the NCEP-driven CRCM for the period 1979-2004 which generates the CRCM-NRA runoff proxy. This simulation exhibits decreasing trends of more than 15%/decade in southern BC, the northwest US, and parts of the Yukon and Canada’s Northwest Territories. Although some positive trends are seen near the BC coast in the CRCM-NRA, the dominant positive trends in runoff (~15%/decade) are found in northern Alberta.
Figure 2.8  Significant decadal trends (%) in the CRCM-ENSM monthly mean total runoff for each period (a and c-e). Panel b represents the significant decadal trends (%) in the CRCM-NRA monthly mean total runoff for the period 1979-2004. The black dot in each panel of Figure 2.8 is the location where we extract the runoff time series (Section 2.3.2)
2.4.3. Anti-correlation between WED and runoff from 1979 to 2099

*Period 1, 1979-2004*

The most notable correlation pattern is an east-west pattern of negative correlation ($\rho \sim -0.1$) on the coast and positive correlations ($\rho \sim 0.1-0.15$) inland, seen in the NARR and (to a lesser extent) the CRCM-NRA comparison (Figure 2.9). All three gridded products feature anti-correlation between WED and runoff in regions off the coast of BC, but to varied extent and spatial distribution. Significant anti-correlation between the CRCM-ENSM WED and runoff are found mainly in southwestern BC, the northwest United States and the Yukon. In the CRCM-ENSM, almost no positive correlations are observed inland. The small number and heterogeneity of correlations in the ISD stations make it difficult to draw definitive conclusions, in that only 10 of the 60 stations show significant correlations ($\rho \sim 0.1$). Of these, positive correlations at approximately 6 sites around the Rockies and eastern BC agree with the NARR and CRCM-NRA simulation (Figure 2.9).
Figure 2.9  Significant correlations between monthly mean WED and runoff for various sources of wind speeds and runoff. We compare the NARR, CRCM-NRA and CRCM-ENSM monthly mean WED with those from the ISD (represented by triangles) between 1979-2004. The black dot signifies the location used to create the CUI proxy.

Periods 2-4, 2010-2099

While the magnitude and extent of significant correlations between WED and runoff depend on the 30-year time period considered, some consistent spatial patterns emerge (Figure 2.10). The negative correlations observed in southwestern BC during period 1 (1979-2004) remain throughout periods 2 (2010-2039) and 3 (2040-2069).
Positive correlations ($\rho \approx 0.2$) appear later in the century during period 3 in northern BC and the Northwest Territories and shift southward to central BC during period 4. In the last part of the century (2070-99), positive correlations dominate, with negative values found at only three CRCM grid cells.

Figure 2.10  Significant correlations between the CRCM WED and runoff at the point discussed in Figure 2.1 (CUI proxy). The black dot signifies the location used to create the CUI proxy.
Period 5, 1979-2099

Although we identify differences in spatial correlation patterns between the 30-year periods, an overall latitudinal divide in the correlation pattern emerges, with positive correlations ($\rho=\sim 0.2$) in the north and negative correlations ($\rho=\sim -0.2$) in the south. This conclusion is reinforced in period 5, which shows correlations calculated for 1979-2099 (Figure 2.10). Period 5 exhibits a north-south divide between positive and negative correlations, respectively.

2.4.4. Characterizing correlations and identifying wind density anomalies in low-runoff years

What causes the negative correlations?

For the CRCM-ENSM, the negative correlations observed in southern BC in periods 1 and 2 are dominated by a higher frequency of high WED–low runoff sites (orange dots in Figure 2.11). However, few of these locations are significantly different (at 90% confidence) from a standard binomial distribution, i.e. a 1:1 ratio (large orange dots in Figure 2.11). In contrast, the negative correlations observed in southern BC in the longer-term future are dominated by a higher frequency of low WED–high runoff sites (blue dots in Figure 2.11) and particularly in period 3 where the ratios are significant (large blue dots in Figure 2.11). Over the longer time period of 1979 to 2099, period 5 suggests a tendency for increased occurrence of low WED-high runoff conditions in southern BC and the PNW. Apart from the historical period 1, there is no suggestion of regions where negative correlations are due to a significantly higher proportion of high WED–low runoff sites.
Figure 2.11 Relative frequencies of high WED-low runoff and high runoff-low WED instances. Orange points demonstrate more frequent high WED-low runoff conditions. Blue points demonstrate more frequent low WED-high runoff conditions. Larger points are significantly different from a binomial distribution at a confidence level of 90%.
**WED anomalies in low-runoff years**

WED anomalies in low runoff years (relative to all non-low runoff years) differ with the number of years used to identify the anomalous low flows (three or five lowest flow years), by each time period and by region. When investigating WED anomalies during the three years of lowest runoff in each given period (Figure 2.12) periods 1 and 4 are dominated by positive WED anomalies with annual WED increasing by approximately 10% off the coast of Alaska and in the northern Pacific Ocean. Period 2 is dominated by negative WED anomalies of around 5 to 10% in the Alberta region and only period 3 exhibits positive WED anomalies on land with increased WED anomalies of around 15% in southern BC and on the East coast of Vancouver Island. Elsewhere in period 3 WED anomalies are negative (~-15%) throughout BC, Alberta and the Yukon. Period 5 exhibits composite characteristics of periods 1 to 4 and suggests positive WED anomalies (~7%) near the coast of Alaska and negative WED anomalies (-10 to 15%) along BC’s coast and the Rockies.

Using the five years of lowest runoff (Figure 2.13) suggests fewer positive WED anomalies in each of the five periods and throughout the study area. Period 1 demonstrates very few significant WED anomalies during the five years of lowest runoff and periods 2 to 4 are dominated by negative WED anomalies (-5 to -15%). Period 3 exhibits the most similar behaviour between the three and five year approaches and is again dominated by negative WED anomalies (~-12%) but exhibits some positive anomalies (5%) around the Vancouver Island and Alaskan coast regions. In the five-year approach, period 5 suggests a north/south divide with positive WED anomalies of around 5% appearing in southern BC and the US PNW. Notably, period 5 represents a 121-year period and selecting the 3 or 5 years of lowest runoff only represents around 2% of the total number of years. Additional analysis investigated the influence of testing 10, 20, 30 and 60 years of lowest flows on period 5 but the spatial patterns and magnitude of WED anomalies is not largely different from those exhibited in period 5 of the five-year approach (Figure 2.14).
Figure 2.12 Colour indicates significant positive (orange) or negative (blue) WED anomalies during the 3 years of lowest runoff. Dot size indicates average monthly WED over the length of each period. Only locations that show statistically significant ($p \leq 0.1$) relative differences from mean WED in non low-runoff years are shown.
Figure 2.13  Colour indicates significant positive (orange) or negative (blue) WED anomalies during the 5 years of lowest runoff. Dot size indicates average monthly WED over the length of each period. Only locations that show statistically significant ($p \leq 0.1$) relative differences from mean WED in non low-runoff years are shown.
Figure 2.14  WED anomalies during the 10, 20, 30 and 60 years of lowest runoff during period 5 (1979-2099).
2.5. Discussion

2.5.1. Trends in wind speed and WED

*Comparison of multiple datasets for period 1, 1979-2004*

The lack of consensus among these datasets is not surprising given the differences between each data source. In fact, previous, data-dependent differences in results have been used to advocate the use of multiple data sources as a means of distinguishing between the potential influences on wind behaviour (Pryor et al., 2009). For example, only the ISD data are likely to capture local-scale topographic influences on wind speeds, which may explain the lack of spatial consistency in WED trends observed among the ISD locations within BC's mountainous terrain. The high level of spatial variability may also be an artefact of pre-processing. Although we used strict validation criteria, we did not have the resources to undergo a full homogenization of the observed (ISD) wind speeds, which could account for step changes in wind speed time series and other data quality issues (Wan et al., 2010).

The decreasing WED trends observed for the majority of ISD locations north of 50° latitude (Figure 2.6) are consistent with the declining wind speed behaviour seen in recent studies of surface wind observations in Canada, and the continental US (McVicar et al., 2012; Pryor et al., 2009; Tuller, 2004; Vautard, Cattiaux, Yiou, Thépaut, & Ciais, 2010; Wan, Wang, & Swail, 2010). Unlike the ISD data, the NARR product and (to a lesser extent and with lower statistical significance) CRCM-ENSM simulations indicate significant, positive trends in WED throughout 1979-2004.

This study adds further support to previous work that has found substantial differences in trends obtained from surface station data and the NARR product (e.g. Pryor et al., 2009). The increases in WED (~10%/decade) are consistent with Cross et al. (2015), who observed increased monthly average wind speeds and monthly WED of 10%/decade over a similar study area using the NARR product.
Potential causes of multi-decadal variability between periods 2 to 4

As discussed in Section 2.2, large-scale climate oscillations such as the El-Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) influence wind speeds over multi-decadal timescales – such as the 30-year periods used in this study. The ECHAM5 climate model used to drive the CRCM-ENSM simulations has been shown to recreate large-scale climate oscillations (Lapp, St Jacques, Barrow, & Sauchyn, 2012) and as a result, oscillatory behaviour in the CRCM output likely explains some of the differences in WED trends between periods 2 to 4.

For this study our selection of discrete, 30-year periods has been somewhat arbitrary and therefore does not investigate how periodic trends (and correlations) may change with periods examined. Future research may develop these findings by investigating trends (and correlations) during periods based on the phase of large-scale climate oscillations such as the PDO. Selecting time periods that align more closely with the phasing of positive and negative PDO regimes could provide useful insights into longer-term systematic variability that accompanies the climatological behaviours of large-scale oscillations. Though we are not able to resolve the PDO signal in the CRCM output (due to the limited spatial extent of the simulation) future research may identify the PDO signal using the ECHAM5 output and investigate trends (and correlations) during periods of positive and negative PDO index respectively. Alternately, another useful way to investigate the influence of time on both the trend and correlation results would be to investigate a ‘sliding-window’ which may also identify systematic periodicity in trends and correlations while not relying on the ECHAM5 model output.

In addition to oscillatory behaviour, the period or length of time used in analysis can also affect the magnitude, and even the sign, of wind speed trends (Bylhouwer, Ianson, & Kohfeld, 2013; Vincent et al., 2012). As such, the differences in WED trends during periods 2, 3 and 4 emphasize the strategic value of examining different timescales for the useful insights they might provide. For example, wind energy installations with lifetimes of less than 30 years may experience very different trends depending on when they are constructed. The long-term (121-year) trend is useful for understanding general climatic changes but does not reveal how shorter-term (30-year) variations in the trends may affect renewable electricity investment. While the longer-
term (121-year) trend is important for the planning of a wind farm, the 30-year trends are important for investment and replacement purposes particularly when considering that the lifespan of a turbine is around 20 years (Martinez et al., 2009).

**Causes of long-term spatial patterns in wind speed trends and correlations between 1979 and 2099, period 5**

The most prominent feature in our trend results - the dipolar change in WED trends in the CRCM-ENSM (Figure 2.8) - is consistent with the expected impacts of climate warming (for a summary see (McVicar et al., 2012)). Climate model simulations that have been forced with increasing GHG concentration scenarios have been shown to exhibit increasing zonal wind speeds at higher latitudes as a consequence of poleward shifts in the jet stream, midlatitude westerlies, and Pacific storm tracks (McCabe, Clark, & Serreze, 2001; Yin, 2005). To determine if these mechanistic changes may be present in our results we examine changes of the mean sea level pressure (MSLP) between periods 1 (1979-2004) and 4 (2070-2099) (Figure 2.15) to identify the location and intensity of the Aleutian Low, which in turn manifests the position of storm tracks in the North Pacific Ocean. Although we are not able to resolve the location of the Aleutian Low in the CRCM output, our comparison suggests that MSLP decreases to the north and increases to the south of 52° latitude during period 4 relative to period 1, resulting in an intensification and/or northward shift of the Aleutian Low. Salathe (2006) identified a similar intensification and north/north-eastward shift in the position of the Aleutian Low, using a composite of 10 global climate models (GCM) to compare MSLP between 1950-2000 and 2050-2100. A northward shift of the Aleutian Low is likely to encourage a southwesterly airflow over the region and shift storm tracks to the northeast through time. Such a change in regional circulation is likely to stimulate orographic precipitation and pressure differences in the locale resulting in increasing wind speeds towards the northeast of our study region.
Figure 2.15  Mean sea level pressure output from the CRCM-ENSM simulations. Mean pressure is displayed for 1979-2004 in a) and panel b) presents the difference between 1979-2004 and 2070-2099.

We contend that the northerly shift in storm tracks is not only responsible for the dipole in wind speed trends, but also is the underlying cause of the similar pattern seen in the correlations of Figure 2.10 where we observe positive correlations between WED and runoff (Section 2.5.2). Our results showing increasing WED throughout the northern portion of the study area (e.g. increases of WED of up to 9%/decade (See section 3.4.1)), and on or near the coast, bode well for wind energy generation. Though any increase in wind energy infrastructure development will help to meet growing electricity demand, the timing of this energy availability can also contribute to its utility and so we focus on the temporal correlation between runoff and wind speeds during the validation period and into the future.

2.5.2. Complementarity of wind energy density and runoff

Comparison of data sets for period 1, 1979-2004

While we find little agreement between ISD, NARR, and CRCM-NRA with respect to significant WED trends (Figure 2.6), we find a higher degree of correspondence (similar spatial behaviour) when we consider patterns of correlation
between WED and runoff (Figure 2.9). We anticipate that this correspondence occurs because correlations rely on the temporal variability of wind speeds. Since the NARR and CRCM-NRA contain information from real observations, their temporal variability is likely to be similar. Though systematic differences may occur as a result of the re-analysis techniques and model parameterisations (which would lead to differences in wind speed magnitudes and trends) the overall temporal variability is likely to be similar, resulting in similarities in correlation.

Though one might expect that our observations of WED trends and WED-runoff correlations align with the similar analysis conducted by Cross et al. (2015), we observe certain key differences between them. For example, while both analyses observe negative correlations between wind speed and the proxy for reservoir conditions along the Pacific west coast, the current study shows a much more prominent, extensive area of negative correlations along the Pacific coast. However, we do not expect to find the same spatial pattern in WED-runoff correlations as Cross et al. (2015) for many reasons. First, Cross et al. (2015) use CUI instead of a runoff proxy for CUI, and though we demonstrate that runoff serves as a reasonable proxy for CUI (Spearman ρ = ~0.9) these time series are not identical. Second, we estimate correlations over the 1979-2004 time period whereas Cross et al., (2015) use the 1979-2010 time period. Correlating over fewer years will change correlation estimates. Third, Cross et al. (2015) used Pearson correlation coefficient instead of the Spearman rank correlation used here to identify correlations, and Cross et al. (2015) did not demonstrate the significance of the correlations. Fourth, Cross et al., (2015) use 10m wind density estimates not 80m wind energy density as used in the current study. Given the four systematic differences in correlation methodology we believe that the spatial patterns of correlation align reasonably closely with those of Cross et al. (2015). Notably, although the magnitudes are different, the spatial patterns of decadal trends in 80 m wind energy density (this study) and the 10 m wind density (Cross et al. 2015) are quite similar.

Although no regions show agreement between all four correlation analyses (Figure 2.9), we identify key areas of agreement between at least three analyses and suggest that investigating future complementarity in WED and runoff in these regions could be useful for future renewable electricity planning. Key regions include BC’s south
coast and the US PNW (NARR & CRCM-NRA & CRCM-ENSM), and BC’s Peace River region (ISD, NARR & CRCM-NRA). We also select BC’s northern coast as a region of interest because previous research has highlighted this area as one of the optimal places to consider for complementary climatic behaviour between wind speeds and streamflow.

**Complementarity from 2010 to 2099 and implications for development**

The variation in the correlation patterns of WED with runoff between the successive 30-year time periods is likely due to large-scale climate oscillations partially recreated by the ECHAM5 GCM (Lapp et al., 2012). Temperature and atmospheric circulation conditions established during different phases of ENSO and PDO will likely result in shifts in the Pacific storm track intensity and location (Lapp et al., 2012), which will, in turn, influence the complementarity between wind speeds and runoff over different timescales.

Different states of ENSO and PDO influence wind speed, precipitation, and streamflow in the PNW (Dettinger, Battisti, Garreaud, McCabe, & Bitz, 2001; Holt & Wang, 2012; Mantua et al., 1997) and perhaps most importantly for correlations, the influences of ENSO and PDO vary spatially across BC and the PNW (Section 2.2). The WED-runoff relationship likely reflects the spatially distinct responses of wind speed and streamflow to climate oscillations and consequent storm track behaviour. For example, low runoff years in the Peace River region are most likely to occur when ocean and atmospheric conditions are more similar to negative (cold) ENSO phases, which bring strong winds to coastal areas and weaker winds to interior areas. More generally, wind speed and precipitation are often closely linked, particularly during stormy periods, and therefore locations close to the Peace River region are more likely to have positive WED-runoff correlations. Locations where wind speed behaviour is influenced by factors other than large-scale climate cycles (for example due to location or local topography) are also more likely to exhibit low or negative WED-runoff correlations. Wind speed variability at these locations is less likely to be similar to runoff variability in the Peace River region, which is largely controlled by regional circulation patterns associated with different phases of ENSO and PDO. Finally, the complementarity between WED and runoff will also be influenced by the fact that our proxy for streamflow represents a small
area (9 grid cells) in the Peace River region with behaviour dominated by BC’s northern climate. We expect that the stationary position of the runoff proxy tends to result in higher correlations between WED and runoff in the northern portion of the study area (i.e. near the runoff location).

The results for period 5 indicate a persistent negative correlation between runoff and WED throughout southern BC and the US PNW and positive correlations in the north over the entire time period. We do not see a continuation of the negative correlations observed in period 1 on BC’s north coast in the NARR, CRCM-NRA and in the results of Cross et al., (2015) and suggest that once again, the northerly location of our runoff metric is likely to play a role in the decoupling of WED and runoff in the south and a coupling in the north east. In addition, these patterns of correlation align with the simulated changes in MSLP suggesting that storm tracks in BC may shift northward and increase the co-incident occurrence of higher winds and precipitation (due to stormy weather) in the northern part of the province (Figure 2.15).

Persistent negative correlations (\(\rho = -0.2\)) into the future in the southwest portion of the study area suggest that most wind farm sites in southwest BC and the US PNW and along the BC coast could have some moderating effect on the climate related variability in provincial electricity supply over the long term future – provided that identifying complementary (anti-correlated) behaviour in winds and runoff is the main criterion for site selection.

Although the southwest region of BC shows the most promise with regard to predominant negative correlations and thus complementarity, we acknowledge that complementarity is not the only consideration when developing a wind farm. Identifying optimal wind power development regions requires that optimal locations exhibit a suite of characteristics, such as: a) mean annual wind speeds that are greater than ~5m/s, which are needed for wind power development (National Renewable Energy Laboratory, 2014) b) positive trends in mean WED, c) complementary, negative correlations with runoff resources, and perhaps most importantly, d) an understanding of the economic and infrastructure-based feasibility of wind farm development (which is not addressed in this study). Although the region of southwest BC exhibits complementarity with runoff
behavior, we note that it does not exhibit a useful annual WED intensity, and WED trends are projected to decrease over the 1979-2099 time period.

2.5.3. Explaining correlations and characterizing wind energy density anomalies in low-runoff years.

Negative correlations in our study area are likely to be more beneficial for wind energy development if caused by more frequent high WED-low runoff conditions (as opposed to low WED-high runoff conditions). Our investigation into the cause of the negative correlations revealed a dominance of the less desirable low WED-high runoff conditions in periods 3 and 5 (Figure 2.11). The dominance of low WED-high runoff in these periods is likely a consequence of the combined increasing runoff and decreasing WED trends over the 2040 to 2099 period leading to more occurrences of higher runoff and fewer occurrences of high wind speeds. Despite that throughout period 5 the negative correlations are caused by predominantly low WED-high runoff conditions, the ratio between the two conditions is only around 1.2, suggesting that a large proportion of the correlations could be generated by reasonably frequent high WED-low runoff conditions. Therefore wind farms in southern BC and the US PNW could still have a moderating effect on the climate related variability in provincial electricity supply.

Where is WED higher in years of anomalously low runoff?

As discussed in Section 2.5.2, fluctuations in runoff (streamflow), particularly in periods of low-flow can place the electricity system under stress. When considering wind power generation, electricity produced during periods of extreme low runoff (high stress) may be more economically valuable than at other times (Voisin et al., 2006; Woo et al., 2011). The lack of spatially consistent WED anomalies between periods 1 and 4 suggests that no singular region will exhibit systematically higher mean WED during periods of low runoff (Figure 2.12 and Figure 2.13 respectively). As a result, we focus on the potentially more representative period 5. Period 5 in Figure 2.13 and Figure 2.14 suggest that between 1979 and 2099 we will observe positive WED anomalies of around 5% in southwestern BC and in isolated regions of the Alaskan coast during periods of low runoff. The Alaskan coast is also where Cross et al., (2015) identified positive median WED anomalies in years of low hydroelectricity availability. Of the two regions,
the Alaskan coast exhibits larger average annual WED resource and increasing WED trends (Figure 2.7), which may imply that this is a stronger location for wind power development than the southern region of BC where annual average WED values are lower and WED is projected to decrease. When considering occurrences of anomalously low runoff (between 1979 and 2099), wind power development in the Alaskan coast region and to some extent around the Eastern coast of Vancouver Island is most likely to provide a moderating effect on provincial electricity supply during low-flow years.

2.5.4. Limitations and future analysis

Despite our use of multiple sources of wind speed information, our findings are limited by sparse spatio-temporal meteorological station coverage in the PNW. A lack of dense spatio-temporal meteorological stations limits opportunities to monitor wind speeds over long time periods and also weakens the connection between reanalysis products and actual observations (Cross et al., 2015). The lack of a dense spatio-temporal meteorological station network may explain the inconsistencies seen between observational data and the NARR in our results and elsewhere (McVicar et al., 2008; Pryor et al., 2009). To compound the poor spatial sampling issue, both the NARR and CRCM simulations have a limited ability to capture small-scale topographical features (due to a finite spatiotemporal resolution of 32-45km) which may be an important influence on conditions at meteorological stations. We also acknowledge that the use of runoff as a proxy for hydroelectricity generation potential may be inferior to using streamflow projections from a basin specific (e.g. the Peace River basin) hydrological model as used by Schnorbus et al., (2014).

We denote two directions of interest for future analysis, each taking a different perspective on the issue of complementarity between wind power and hydroelectricity. First, we suggest investigating changes in the WED and runoff resources, and their relationships on a different timescale. Chapter 3 develops this idea by investigating the intra-annual changes in WED and runoff from 1979 to 2099 and considering the use of smaller-scale hydroelectricity that does not use storage. Second, we suggest investigating the economic feasibility of developing wind farms in regions exhibiting anti-correlation between WED and hydroelectricity availability. Linear optimization (linear
programming) models present a technique capable of considering the cost effective dispatch of different sources of electricity. Through linear optimization, it may be possible to identify regions with anti-correlated wind and hydroelectricity resources, which are also economically desirable – should they exist. This economic approach must be performed as a first step in quantifying the true value of anti-correlated resources.

2.6. Conclusions

Previous research suggests that long-term (multi-decadal) relationships between wind speed and reservoir inflow behaviour can be examined together to improve wind power site selection and that in British Columbia (BC), the northwest part of the province shows promise for wind power development (Cross et al., 2015). We develop this research further by: a) examining the strength of the relationships between wind speed and runoff using four different sources of wind field information; and b) investigating the relationships between wind energy density (WED) and runoff behaviour under projected future climate conditions. We use runoff as a proxy for cumulative useable inflow, which is a measure of hydroelectricity availability provided by BC Hydro (BC’s electric utility). We investigate trends and relationships between 1979-2099 using the state-of-the-art Canadian Regional Climate Model (CRCM).

Over the long-term (1979-2099), the CRCM projects increasing 80m WED (2%/decade) throughout BC’s northern and coastal regions but decreasing (-2%/decade) WED further south and inland. While spatial trends in WED display considerable variability on the multi-decadal time scale, correlations between WED and runoff are projected to be somewhat spatially consistent between 2010 and 2099. Persistent negative correlations between WED and runoff are projected in southern BC and the US Pacific northwest (PNW) during most of the 30-year time windows between 1979 and 2099 as well as for our analysis of the entire time series (1979-2099). Negative correlations ($\rho = -0.2$) are also prevalent in 3 out of the 4 datasets during the period of 1979 to 2004 suggesting that they are relatively robust.

Although persistent negative correlations are more frequently due to low WED and high runoff conditions, which may be less desirable in hydroelectricity dominated
systems, there are some regions where WED is higher during years of anomalously low runoff. Regions of the Alaskan coast and the eastern coast of Vancouver Island exhibit positive WED anomalies (+15%) during periods of low flow, which could have a moderating effect on climate related variability in provincial electricity supply.

This research focuses on complementarity between resources but we acknowledge that multiple factors should be considered when choosing where to develop wind farm infrastructure. Identifying regions optimal for wind farm development requires an understanding of the wind resource and the trade-offs between mean annual wind speeds, the trend in mean wind speeds, as well as the complementarity between wind speed and runoff behaviour. Furthermore, aspects external to the wind resource are also important in developing wind farm infrastructure. For example, aspects such as the economic feasibility of the project, the accessibility of the electricity grid, and also the potential environmental impact of the project are also key influences in identifying regions for wind energy development. In this research, do not find a location that exhibits optimal behaviour for all three characteristics of the wind resource, e.g., high wind speed magnitudes, positive WED trends, and optimal timing. We do note, however, that BC’s northern coast is a region of strong and increasing wind speeds, and BC’s southern coast is a region with consistent inverse correlations with available hydroelectric resources. These insights can inform the wind planning process.

### 2.7. References


### 2.8. Supplementary Tables

**Table A.1** Integrated Surface Dataset Wind Speed Observation Locations.

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Chapter 3. Projected changes in the intra-annual relationship between British Columbia’s wind and runoff resources in regions of future wind farm development.

3.1. Abstract

British Columbia’s (BC) demand for electricity is projected to increase by as much as 40% in the next two decades (BC Hydro, 2013). BC’s Clean Energy Act legislation mandates that increasing electricity demand must be met by production within BC and that 93% of provincial electricity generation must be from clean or renewable sources. As a result, the adoption of renewable sources of electricity is likely to increase in the coming decades (Government of British Columbia, 2010a). Understanding the climatic drivers behind BC’s renewable resources is key to long-term electricity resource planning. This is particularly true when considering that increasing concentrations of greenhouse gases are projected to affect the magnitudes and seasonal patterns of wind speeds and hydrological resources, and thus renewable electricity generation in the future (IPCC, 2014).

We investigate the future of BC’s 80m-wind energy density (WED) and runoff resources at six locations that have been identified for future wind farm development to understand how BC’s WED and runoff resources may contribute to BC’s future electricity demand. We investigate the correlations between the WED and runoff resources, which is valuable because anti-correlated resources may help to provide a more balanced supply of electricity. Identifying wind farms where wind speeds are anti-correlated with the hydrological resource facilitates co-management of hydropower and wind power so that they provide a more balanced supply of electricity. In other words, if one resource is available when the other is not, then the supply of electricity is less variable.
Comparing differences in the output from the Canadian Regional Climate model (CRCM) between 1980-2009 (Present) and 2070-2099 (Future) we find increased WED of around 9% in BC’s northwestern Stikine region in the Future period. Sites in central BC exhibit a relatively stable WED resource, and sites in southern BC (the Okanagan) exhibit decreases in WED of ~8% between the Present and Future periods. We observe significant increases of 10%-15% in the magnitude of the annual cycle (standard deviation) of WED at four of the six locations, but despite these changes, the overall WED resource remains relatively unchanged. The most substantial changes are observed in the runoff resource where all locations exhibit increases in mean monthly flow (7%-19%) and most exhibit a shift towards rainfall-dominated regimes. The timing of peak runoff shifts earlier by one month in three of six locations. Spearman $\rho$ correlations between WED and runoff are projected to increase at all sites, which may reduce the potential for the supply of one resource (e.g. wind power) to offset reductions in the other (e.g. hydroelectricity). The Stikine location in northwest BC shows the most promise for future wind power infrastructure because of consistently negative correlations between runoff and increasing WED through time.

### 3.2. Introduction

In an effort to reduce anthropogenic greenhouse gas (GHG) emissions, many governments are developing renewable electricity resources, which can reduce emissions relative to fossil-fuel based electricity generation whilst meeting increasing demand for electricity (Weisser, 2007). Many forms of renewable electricity are intermittent and depend on the seasonal and inter-annual variability in regional weather and climate, which influence wind speeds and precipitation. Because anthropogenic climate change is expected to affect the magnitudes and patterns of hydroclimatic resources such as wind speeds, runoff, and streamflow (Stocker et al., 2013), we expect climate change to influence renewable electricity generation in future.

Changes in water availability are particularly important in the western Canadian province of British Columbia (BC) because of BC’s commitments to clean renewable electricity and increasing demand for electricity. BC Hydro (BC’s only electric utility) has projected an increase in electricity demand of up to 40% by 2030 (BC Hydro, 2013), and
BC’s Clean Energy Act mandates that 93% of electricity supply in the province must be from clean or renewable sources (Government of British Columbia, 2010a). As a result, the Clean Energy Act is likely to increase the need for clean or renewable electricity sources in BC.

At present, BC’s water resources produce hydropower in two different ways. The first is to store water behind large dams and release water through dam turbines when electricity is needed. This is known as large-scale storage-based hydropower and accounts for ~90% of BC’s electricity generation. The second is to run flowing water through a pipe to generate electricity in real time, without storage. This is known as run-of-river hydropower (ROR) and accounts for less than 4% of BC’s electricity generation (BC Hydro, 2014b). The supply of electricity from ROR is not controllable and potentially intermittent. However, ROR may have a reduced environmental impact relative to large-scale storage-based hydropower (Abbasi & Abbasi, 2000; Evans et al., 2009). In BC, the need for increased electricity generation coupled with a continued reliance on storage-based hydropower is likely to spur the development of lower quality sites which may cause unnecessarily large environmental and social costs including flooding, road construction and changes in streamflow (Robinson, 1997). In addition, because the Clean Energy Act’s self-sufficiency mandate requires a greater generation capacity than is needed, costly new facilities could end up relatively underused.

One way to increase the resilience of the electricity system and reduce the need to expand large storage-based hydropower facilities is to diversify the electricity supply mix, e.g., by including different sources of electricity such as wind power and run-of-river hydropower (Molyneaux, Wagner, Froome, & Foster, 2012). One consequence of the BC Clean Energy Act has been the rapid development of wind energy and ROR hydropower to supplement existing storage-based hydropower. As of October 1 2014, wind and ROR independent power producers (IPPs) provided ~5500 GWh of electricity in 2014 (BC Hydro, 2014b), with projects under development expected to provide an additional ~4000 GWh/year (BC Hydro, 2014b). When fully completed in 2015, these ROR and wind IPPs will supply around 16% of BC Hydro’s total annual electricity generation (BC Hydro, 2013).
In addition to diversification, strategic selection of sites for development based on historical hydroclimatic behaviour is also important. Understanding the complementary behaviour of different climate variables has been examined previously (Fischer & Knutti, 2013; Tencer, Weaver, & Zwiers, 2014), though only recently has the idea of investigating wind speeds and streamflow been suggested. Recent work has suggested that identifying sites with complementary (anti-correlated) patterns of low- and high-energy production periods can help to mitigate climate related intermittency in electricity supply (Cross et al., 2015). For example, wind farms with above-average generation during months of low streamflow may have greater value than similar sites where most electricity generation occurs during high flows. In this work we show how time series of wind speed, streamflow, and runoff behaviour can help identify sites where wind availability is anti-correlated with runoff (a proxy for streamflow), either locally from ROR hydropower sites (hereafter referred to as “local hydropower”) or in large watersheds associated with large-scale storage-based hydropower (hereafter referred to as “central hydropower”).

In Chapter 2, we investigated the long-term, multi-decadal trends in the relationships between observed and modeled wind speeds and modeled runoff. In this Chapter, we focus more specifically on the intra-annual behaviour of the wind speed and runoff resources and identify how the characteristics of these resources (e.g. annual mean, annual 90th percentiles, magnitude of annual cycle, and the month in which maximum values occur) are projected to vary into the future. We investigate how the seasonal complementarity (Spearman ρ) of the wind speed and runoff resources is projected to change and infer the consequences of changes in resource characteristics on the future of renewable electricity generation in BC.

Understanding current wind speed and runoff relationships is useful for strategic selection of sites for wind power and ROR development in BC, but analysis of hydroclimatic data suggests that wind speed (Cross et al., 2015; Holt & Wang, 2012; Pryor et al., 2009; Pryor & Ledolter, 2010; St George & Wolfe, 2009; Tuller, 2004), runoff, and streamflow (Kiffney et al., 2002; Rood, Samuelson, Weber, & Wywrot, 2005; Stewart, Cayan, & Dettinger, 2005; Whitfield & Cannon, 2000; Yue, Pilon, & Phinney, 2003) resources have been changing over the past 30 years. Likewise, wind speeds (H.
Bailey, Kohfeld, Curry, Cross, & Cooper, In Preparation; Pryor & Barthelmie, 2011; Sailor et al., 2008), runoff and streamflow (Lapp et al., 2012; Morrison, Quick, & Foreman, 2002; Music et al., 2012; Schnorbus et al., 2014) are projected to change in future, and so understanding intra-annual interactions between wind speed and runoff behaviour is of critical importance to the development of BC’s clean electricity grid. We seek to understand if different spatio-temporal changes in wind speeds and runoff resources could change the complementarity of wind power and hydroelectricity in BC.

3.3. Methods

3.3.1. Locations of interest and methodology

We focus on monthly mean wind energy density (WED) and monthly mean runoff behaviour at six locations in BC that have been identified as potential sites of wind farm development (Figure 3.1 and Table 3.1). The potential sites of wind farm development have been identified by BC’s government and BC Hydro as regions where new wind farms have recently been developed, are under-development, or may be developed, comprising: (1) Stikine in northwestern BC, (2) Kitimat in central coastal BC, (3) The northern tip of Vancouver Island, (4) Williston in the northeastern interior of BC, (5) Peace in the central interior of BC, and (6) Okanagan in the southern interior of BC (Government of British Columbia, 2010b).

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Lat, Long</th>
<th>Wind Speed (m/s)</th>
<th>WED (Wm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stikine</td>
<td>57.0,-129.0</td>
<td>7.56</td>
<td>923</td>
</tr>
<tr>
<td>Kitimat</td>
<td>53.8,-129.6</td>
<td>7.73</td>
<td>987</td>
</tr>
<tr>
<td>Vancouver Island</td>
<td>50.7,-128.0</td>
<td>6.04</td>
<td>470</td>
</tr>
<tr>
<td>Williston</td>
<td>57.4,-125.8</td>
<td>5.84</td>
<td>424</td>
</tr>
<tr>
<td>Peace</td>
<td>55.0,-122.0</td>
<td>5.23</td>
<td>306</td>
</tr>
<tr>
<td>Okanagan</td>
<td>50.0,-120.0</td>
<td>4.23</td>
<td>162</td>
</tr>
</tbody>
</table>

Table 3.1 The six locations from the Canadian Regional Climate Model (CRCM) used in our study, along with their annual mean wind speeds and annual mean WED.
Solid blue points represent the potential wind resource sites identified by the BC government in 2010. Solid green points represent the centre locations of the sites used in our study. The Williston location (purple) is used in this study to represent central hydropower in BC because streamflow from the Williston region represents 40% of BC’s large hydro electricity generation (BC Hydro, 2014a). Vancouver is shown for reference.

3.3.2. Climate model description

For each location, we obtained 10m height, 6-hourly model-simulated wind speeds and surface runoff from the Canadian Regional Climate Model (CRCM) version 4.2 (Mladjic et al., 2011), developed from previous versions of the model originally described by Caya and Laprise (1999). The CRCM is a state-of-the-art model of regional climate based on gridded finite-difference techniques (Caya & Laprise, 1999; Laprise et al., 1998). The CRCM horizontal grid is uniform in a polar stereographic projection, and is used operationally at a 45km grid mesh, which allows a good representation of the processes important for the regulation of hydrological regimes at a regional scale.
We used three ensemble members from the CRCM generated with boundary forcing information from the German Coupled Global Climate Model (ECHAM5 at approximately 1.87° latitude-longitude horizontal resolution; (Jungclaus et al., 2006)). Both global and regional simulations were performed using the IPCC SRES A2 GHG and aerosol projected evolution after the year 2000 (Nakicenovic et al., 2000). The A2 scenario equates to global GHG emissions of approximately 17 gigatons of carbon dioxide per year (Nakicenovic et al., 2000) and evolves similarly to the IPCC’s more recently adopted relative concentration pathway 8.5 (Rogelj et al., 2012).

In this circumstance we do not attempt to validate wind and runoff behaviour in these historical model simulations with observed or reanalysis data for a few reasons. First, the CRCM version 4.2 is a relatively new model product and detailed validations of wind speeds and runoff parameters from the model have not been published in the literature. Second, comparing CRCM output to observed (measured) data is difficult in BC because of a lack of spatially and temporally dense monitoring stations. Third, the observed data that is available is often limited by inconsistencies and has not been homogenised to account for differences in recording methodology. Finally, this is an initial investigation into regional WED and runoff behaviour and because of the 45km grid output of the CRCM, we do not expect local scale observations to match the CRCM closely. Notwithstanding, the CRCM will provide useful initial insights into the relationships between WED and runoff over the 1980-2009 and 2070-2099 time periods.

Despite the fact that we do not seek to validate wind and runoff behaviour in the CRCM historical model simulations we find evidence suggesting that simulations from the CRCM reflect historical climate reasonably well. First, the high correlation (Spearman $\rho=\sim0.8$) between CUI and our runoff-based proxy suggests that the temporal variability of runoff from the CRCM matches historical behaviour very well. Second, previous research has compared output from versions 3.6 (the previous version) and 4.2 (our version) of the CRCM to observed hydro-climatological variables and demonstrated reasonably good agreement. Specifically, comparisons of precipitation and water budgets (Music, Caya 2007, Mearns et al. 2012) and streamflow discharge estimated by downscaling CRCM output (Troin et al. 2015) suggest a reasonable reflection of temporal variability in past hydrological behaviour relative to other climate models.
Though wind speeds are often less frequently validated, 50m WED outputs from the CRCM match well with observations from the National Renewable Energy Laboratory (Pryor, Barthelmie & Schoof 2012) and has been shown to be particularly good at characterizing wind speeds on the upper end of the Gaussian distribution (Pryor, Barthelmie 2011).

To generate results that are relevant for the renewable energy planning community, we converted 10m wind speed time series into 80m WED time series because 80m is representative of typical wind turbine hubs. We used Hueging et al., (2013) and Manwell et al., (2010) to extrapolate 10m wind speeds $U(z_r)$ up to wind speeds at typical hub heights of 80m $U(z)$ where $z_r$ is the original reference height of 10m (equation 1) and $z$ is the new height (80m). In equation (2), we estimate monthly mean WED from the time series of wind velocities within a given month, where $U$ is wind speed at a height of 80m, $i$ represents the beginning of the summation index and $N$ is the time period (1 month). We assume a constant air density ($\rho$) of 1.225g/m$^3$ and a power law exponent ($\alpha$) of 0.2 as suggested by the International Electrotechnical Commission for areas over land (IEC, 2005).

$$\frac{U(z)}{U(z_r)} = \left(\frac{z}{z_r}\right)\alpha$$

$$\text{WED} = \left(\frac{1}{2}\right)\rho \frac{1}{N} \sum_{i=1}^{N} U_i^3$$

To represent streamflow available for hydroelectricity generation, we used the monthly mean runoff from each of our three CRCM ensemble members for the nine grid points in the Williston region of BC. Chapter 2 demonstrated a strong correlation (Spearman $\rho=0.8$) between BC Hydro’s hydroelectricity generation potential and simulated runoff from these nine grid points, over the time period (1979-2004) in these CRCM simulations (Chapter 2). From the outset, we recognize that the CRCM does not capture glacial behaviour, and so our results do not reflect the impact of glaciers on runoff regimes.
3.3.3. Analysis methods

For each location and ensemble member, we generated a climatology of average monthly WED (Figure 3.2) and monthly mean runoff (Figure 3.3) for the Present (1980-2009) and the Future (2070-2099) periods. For each of the six locations, we generated time series by averaging all land-based model grid points that fell within one degree latitude and one degree longitude of the centre locations (~10 grid points) identified in Figure 3.1 and Table 3.1. We take monthly mean runoff at the six locations to represent the availability of local-scale ROR hydroelectricity generation. Runoff at the Williston location was used to represent the availability of central-scale large hydroelectricity generation. Runoff at this location has been shown to correlate well (Spearman $\rho$=~0.8) with BC Hydro’s measure of hydroelectricity generation potential over the period 1979 to 2004 (Chapter 2).

For each ensemble member we calculated the annual mean, annual 90$^{th}$ percentile, and the magnitude of annual cycle (as reflected in intra-annual standard deviation) for WED and runoff at each location for each year in the Present and Future periods (Appendix Figure A.1). The annual 90$^{th}$ percentile was chosen as a measure of extreme winds because these represent time periods of largest potential for wind energy generation and they were chosen in preference over max WED values to avoid investigation of results from anomalously extreme periods. We examined changes in seasonal timing of runoff and WED between the Present (1980-2009) and Future (2070-2099) by estimating the median month of maximum WED and runoff for each location (for all ensemble members and years in each period). We identify significant differences between the populations of annual mean, annual 90$^{th}$ percentiles and magnitude of annual cycle samples, using the Student’s t-test function in the base package of the statistical software R (R Core Team, 2014). We tested for significant differences in WED and runoff behaviour between time periods, by grouping results from all three ensemble members. Furthermore we identify significant differences between the populations of month of maximum WED using the Mann-Whitney U test function in the exactRankTests package of the statistical software R (R Core Team, 2014).

We also investigated the seasonal complementarity between WED and runoff resources for each time period, considering both the "local-hydropower" relationships
(i.e. WED and ROR) as well as the "central-hydropower" relationships between WED and the estimate of runoff at Williston. We investigated both the central-hydropower and local-hydropower complementarity to infer potential changes in correlations with a) BC’s current large-scale storage-based hydropower resource, and b) BC’s potential future local-scale ROR resource.

We first computed the correlation (Spearman $\rho$) between WED and the central runoff estimate. Our analysis produced three correlation estimates (one for each ensemble member) for each model year and location, giving a total of 90 correlations for each location and each period (Present and Future). We repeated this procedure, for the local-hydropower assumption. That is, for each ensemble member, we generated a single correlation between the monthly means of WED with the respective monthly mean of runoff at each location for every year within the time period. The subsequent population of 90 correlation values was compared (Student’s t-test) to the population of correlation values in the Future period.

3.4. Results

3.4.1. Projected changes in WED and runoff

At each site, WED is lowest in the summer months and greatest through the winter (Figure 3.2). Westerly sites (Stikine, Kitimat and Vancouver Island) exhibit larger seasonal variability and annual mean WED values (Present-period mean = 1180 Wm$^{-2}$) compared to inland easterly regions (Present-period mean = 297 Wm$^{-2}$). Differences between the Present and projected Future WED values are small, exceeding the inter-ensemble spread only in winter when Future WED shows a slight increase compared to the Present. Within both periods and most sites (except perhaps Williston), the three ensemble members display consistent seasonal behaviour and exhibit the largest spread in the winter months.
During the Present period, the Stikine, Williston, Peace, and Okanagan regions all exhibit the typical snowmelt-dominated peak that occurs in spring (Figure 3.3). The Vancouver Island site exhibits a pluvial (rainfall-dominated) regime where the majority of runoff occurs in the winter months as a result of rainfall. Kitimat exhibits hybrid behaviour with characteristics of both pluvial and nival (snowmelt-dominated) regimes. Kitimat also exhibits two runoff peaks of roughly equal magnitude, one in early spring and one in early winter.
Between the Present and Future periods, the annual distribution of runoff changes considerably at most locations. Largest changes are seen at the coastal Kitimat site, where the spring runoff peak is projected to decrease and the peak in late fall / winter is projected to increase. In terms of annual distribution, in the Future period, Kitimat shifts towards a runoff regime more similar to that of Vancouver Island. The spring freshet peaks in runoff at the Okanagan, Stikine and Williston sites shift earlier in the season, moving from around May-June towards April-May. All ensemble member simulations suggest that fall and winter runoff will increase at all locations during the Future period compared with the Present period.
Figure 3.3  Monthly mean runoff (per 45km\(^2\) grid) at each location for the Present and Future periods.

### 3.4.2. Significant differences between periods

Visual inspection of the annual WED distributions (Figure 3.2) did not imply large changes in the resource in the Future but statistical analysis suggests some significant differences (Table 3.2). Annual mean WED is projected to increase significantly in the northwesterly sites of Kitimat and Stikine. For example, the average of the ensemble WED means at the Stikine location is projected to increase by 9% between the Present and Future periods. In contrast, annual mean WED is projected to decrease significantly in the Okanagan (-8%), and no significant change is projected in the other locations. The 90\(^{th}\) percentile of WED is projected to increase at the Stikine, Kitimat and Williston
locations, and the WED in the Okanagan is likely to experience significantly reduced 90\textsuperscript{th} percentile WED values. Likewise, the magnitude of the annual WED cycle (average intra-annual standard deviation of all ensemble members) is projected to increase between the Present and Future at all sites (average increase 12.5\%) apart from the Vancouver Island and Okanagan locations.

**Table 3.2** Percent change in the metric mean between Present and Future. Bold values represent statistically significant differences (p < 0.05), as determined using a Student’s t-test.

<table>
<thead>
<tr>
<th>Resource</th>
<th>Annual Statistic</th>
<th>Location</th>
<th>Stikine</th>
<th>Kitimat</th>
<th>Van. Island</th>
<th>Williston</th>
<th>Peace</th>
<th>Okanagan</th>
</tr>
</thead>
<tbody>
<tr>
<td>WED</td>
<td>Mean WED</td>
<td>9%</td>
<td>10%</td>
<td>-2%</td>
<td>3%</td>
<td>1%</td>
<td>-8%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>90\textsuperscript{th} Percentile WED</td>
<td>11%</td>
<td>13%</td>
<td>0%</td>
<td>9%</td>
<td>5%</td>
<td>-7%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Std. Dev</td>
<td>10%</td>
<td>15%</td>
<td>5%</td>
<td>15%</td>
<td>10%</td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>Runoff</td>
<td>Mean runoff</td>
<td>16%</td>
<td>10%</td>
<td>7%</td>
<td>19%</td>
<td>14%</td>
<td>15%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>90\textsuperscript{th} Percentile runoff</td>
<td>-5%</td>
<td>10%</td>
<td>11%</td>
<td>-7%</td>
<td>-6%</td>
<td>-3%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Std. Dev</td>
<td>-3%</td>
<td>9%</td>
<td>15%</td>
<td>3%</td>
<td>-15%</td>
<td>-27%</td>
<td></td>
</tr>
</tbody>
</table>

At all locations, the CRCM projects increases in annual mean runoff between the Present and Future periods. Increases in annual mean are accompanied by significant increases in annual 90\textsuperscript{th} percentiles of runoff only in the westerly locations of Kitimat and Vancouver Island. Magnitude of the annual cycle is projected to increase significantly at the Kitimat and Vancouver Island locations and to decrease significantly at the Okanagan and Peace locations. In the Stikine, Williston and Okanagan locations, the month of peak runoff is expected to shift significantly towards earlier in the year, while this characteristic was unchanged in Future at the other locations (Table 3.3).

**Table 3.3** Median (over each 30-year period) month of max runoff. Bold values represent statistically significant (p < 0.05) differences between the Present and the Future, as determined using a Mann-Whitney U test.

<table>
<thead>
<tr>
<th>Resource</th>
<th>Stikine</th>
<th>Kitimat</th>
<th>Van. Island</th>
<th>Williston</th>
<th>Peace</th>
<th>Okanagan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present</td>
<td>7</td>
<td>10</td>
<td>11</td>
<td>6</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Future</td>
<td>6</td>
<td>10</td>
<td>11</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

WED is omitted due to no significant differences observed.
3.4.3. Correlations between wind energy density and runoff

In addition to investigating the resource statistics, we examined the correlation between WED and runoff resources under the two assumed scenarios (i.e. central-versus local-hydropower) in the Present and Future periods.

![Figure 3.4](image)

**Figure 3.4** The cumulative density functions (CDF) of correlations at each location for the Present and Future periods. The upper panel shows Spearman $\rho$ correlations between WED at each location and runoff at the Williston location (central-hydropower). The lower panel shows correlations between WED and runoff at each respective location (local-hydropower).

As shown in the upper panels of Figure 3.4, under the central hydropower condition, WED-runoff correlations are negative (average $\rho \sim -0.58$) at the westerly (of which two are coastal) sites throughout the Present period. At the inland locations, negative correlations occur between 93-100% of the time and exhibit an average correlation of -0.45 (Table 3.4). Average correlations were calculated using the mean of
the correlations corresponding to a cumulative density of 0.5 (i.e. median) over the three stations in question. In the Future period, the distribution of correlations in each location becomes less negative with increases in mean Spearman $\rho$ of 0.17 for the westerly sites and 0.2 for the easterly sites. Notably, in the Peace location the percentage of negative correlations decreases from 97% in the Present period, 97% to 80% in the Future period and corresponds to an increase in average Spearman $\rho$ from -0.44 to -0.22.

Under the local-hydropower scenario shown in the lower panels of Figure 3.4, the monthly correlations between WED and runoff vary much more according to location and range from a median $\rho$ of -0.56 (Stikine) to a median $\rho$ of 0.72 (Vancouver Island). Although most cumulative density functions (CDF) indicate that the bulk of the correlations are negative with a distribution around zero or less, Kitimat and Vancouver Island feature more positive correlations (88% and 100% respectively) between WED and runoff. Irrespective of the local- versus central-hydropower assumption, the CDFs at all locations shift to the right in Figure 3.4, indicating that intra-annual correlations between WED and runoff become more positive in the future (Table 3.4). Despite this, under the central-hydropower condition, at least 80% of the correlations at each site remain negative. Under the central-hydropower condition, the Kitimat, Okanagan, Peace and Stikine sites are almost always negatively correlated, even in the Future period as such these locations could be the most preferred candidates for the future development of BC’s wind energy infrastructure – assuming that complementarity is a priority. By contrast, under local-hydropower, the Okanagan correlations shift from mostly negative (73% negative correlations) to mostly positive (15% negative correlations) with large changes in the same direction also seen in the Kitimat and Peace locations.

Table 3.4  
**Comparison of Present and Future periods. All differences in average $\rho$ are significant.**

<table>
<thead>
<tr>
<th>Hydropower Scenario</th>
<th>Metric</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Stikine Kitimat Van. Island Williston Peace Okanagan</td>
</tr>
<tr>
<td>Central</td>
<td>Period 1 Average $\rho$</td>
<td>-0.56 -0.57 -0.58 -0.33 -0.44 -0.59</td>
</tr>
<tr>
<td></td>
<td>Difference (P-F) of average $\rho$</td>
<td>-0.19 -0.17 -0.12 -0.16 -0.22 -0.22</td>
</tr>
<tr>
<td></td>
<td>Period 1 Percentage of Negative $\rho$</td>
<td>100% 100% 100% 93% 97% 100%</td>
</tr>
<tr>
<td></td>
<td>Difference in Percentage of Negative $\rho$</td>
<td>-4% -2% 0% -20% -17% -4%</td>
</tr>
<tr>
<td>Local</td>
<td>Period 1 Average $\rho$</td>
<td>-0.57 0.19 0.73 -0.33 -0.36 -0.16</td>
</tr>
</tbody>
</table>
### 3.5. Discussion and implications for wind power development

Although each location has been identified as a candidate for wind farm development, the range between sites in annual mean WED is high. While the easterly locations such as the Okanagan and Peace exhibit reduced mean WED values relative to the westerly locations, the smaller seasonal variability of the easterly locations may provide a more consistent supply of renewable electricity.

Few of the WED statistics exhibit significant differences between Present and Future periods. The significant decreases exhibited at the Okanagan location align with projected decreases in wind speeds in southern BC and the contiguous US (Breslow & Sailor, 2002; Pryor et al., 2012; Sailor et al., 2008). Specifically, reductions in surface wind speeds of between 1.5%-4.5% over the next 100 years as projected by Breslow and Sailor (2002) are similar to the projected reductions in mean WED seen at the Okanagan location (-8%). Projections from the CRCM identify increasing wind speed trends in the northern regions of BC (as projected in the Kitimat and Stikine locations) but decreasing wind speeds in the south (as projected in the Okanagan) and this north–south divide has been identified elsewhere in this thesis (see Section 2.4.1) and potential reasons for this divide have been demonstrated by Salathe (2006) who identified a projected intensification and north/north-eastward shift in the position of the Aleutian Low (using a composite of 10 global climate models (GCM) to compare MSLP between 1950-2000 and 2050-2100). A northward shift of the Aleutian Low is likely to encourage a southwesterly airflow over the region and shift storm tracks to the northeast through time. Such a change in regional circulation is likely to stimulate orographic precipitation and pressure differences in the locale resulting in increasing wind speeds towards the northeast of our study region.

<table>
<thead>
<tr>
<th>Difference (P-F) of average $\rho$</th>
<th>-0.17</th>
<th>-0.48</th>
<th>-0.05</th>
<th>-0.16</th>
<th>-0.36</th>
<th>-0.36</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period 1 Percentage of Negative $\rho$</td>
<td>100%</td>
<td>24%</td>
<td>0%</td>
<td>93%</td>
<td>92%</td>
<td>73%</td>
</tr>
<tr>
<td>Difference in Percentage of Negative $\rho$</td>
<td>-3%</td>
<td>-24%</td>
<td>0%</td>
<td>-20%</td>
<td>-41%</td>
<td>-58%</td>
</tr>
</tbody>
</table>

P = present period, F = future period. 'Difference in percentage of negative $\rho$' compares the percentage of correlations that are negative between the present and future periods. E.g. in the Central scenario at the Stikine location, only 96% of the correlations are negative (100% - 4%) in the Future period.
Unlike WED, most runoff statistics are projected to be significantly different between the Present and Future periods. Projected increases in mean annual runoff, a tendency towards earlier peak runoff (freshet) and shifts towards a warmer more pluvial dominated regime align with previous research (Clair, Ehrman, & Higuchi, 1998; Merritt et al., 2006; Morrison et al., 2002; Schnorbus et al., 2014; Whitfield et al., 2002). We observe no annual decreases in runoff in southern BC as suggested by Hamlet and Lettenmaier (Hamlet & Lettenmaier, 1999) but our results at the Okanagan location do indicate reduced freshet peak runoff. Increases in winter runoff (which occur for around 4 months of the year) observed in the CRCM negate the decreased peak freshet runoff (which occurs for around 1 month of the year) and so annual mean runoff is still increasing.

The projected 10-11% increase in annual 90th percentile runoff at the Kitimat and Vancouver Island locations could be a result of two factors. First, the predominantly snow-dominated regimes may undergo a more intense period of melting, releasing moisture stored as snow water equivalent more rapidly. Second, areas that are currently designated as rainfall or hybrid rainfall-snow regimes may receive increasingly intense precipitation. Annual precipitation on BC’s North Coast is projected to increase by at least 10% by 2070 (Rodenhuis et al., 2007). In contrast, in locations where the annual 90th percentile runoff is projected to decrease slightly (e.g. ~3 to -6% Okanagan and Peace) the eventual disappearance of snowpack likely plays a large role in reducing runoff. Although beyond the scope of this thesis, future research will investigate the relative contributions of rainfall and snowmelt to the runoff in these cases. The earlier onset of the spring freshet suggested in previous research using observed data, basin-scale hydrological models and global climate models (Clair et al., 1998; Merritt et al., 2006; Morrison et al., 2002; Schnorbus et al., 2014; Whitfield et al., 2002) is also projected by the CRCM at the Okanagan, Stikine and Williston locations, and so this hypothesis would align with previous research.

Significant changes in the spatial and temporal behaviour of WED and runoff separately will lead to a change in their spatiotemporal relationships. We focus on these relationships because of their potential to delay grid system expansion and facilitate the optimal supply of renewable sources of electricity. Correlations between WED and runoff
are expected to become significantly more positive in both the central- and local-hydropower conditions. We attribute the increased correlation to the increasing temperatures and increased rainfall-based precipitation that are projected for BC’s future (Rodenhuis et al., 2007). Instead of being stored as snow water equivalent, whose release is delayed until the spring, winter rainfall results in almost instantaneous runoff. Since WED is largest in winter and it exhibits little or no change in seasonality (Figure 3.2), increased winter runoff leads to more frequent positive correlations between WED and runoff.

Stikine stands out as a location with optimally negative correlations in both the local- and central-hydropower conditions. Wind power generation at the Stikine location is probably most appropriate in the central-hydropower scenario, given that most streamflow will be stored as ice or snow during the winter months under the local hydropower condition due to high latitude. Stikine provides a suitable WED resource (annual mean WED ~920 Wm⁻²) with increasing WED in future, and a small change in the proportion of negative correlations compared to other sites. In both generation conditions at least 96% of the correlations remain negative in the Future period at the Stikine location. Under the central-hydropower condition, all locations are almost always negatively correlated - even in the Future period (where the proportion of negative correlations ranges from 73%-100%). The persistent negative correlations exhibited at the Stikine location are optimal for providing a more reliable energy supply.

The predominant negative correlations (under the central-hydropower scenario) exhibited at the Stikine location align well with the results in Cross et al. (2015) who observed predominantly negative correlations between WED and CUI over the 1979-2010 period in northwestern BC and the Alaskan coast. Despite differences in methodology, the time period analysed, and the fact that Cross et al. (2015) do not identify the significance of the correlation, the correspondence between the findings of Cross et al. (2015) and the persistent negative correlations in the Stikine location is likely due to the seasonal approach to correlating WED and runoff time series. In this chapter and in the work of Cross et al. (2015) the WED and hydrological time series were not deseasonalised and so both capture shorter-term seasonal complementarity between WED and the corresponding hydrological time series.
This same deseasonalisation process creates differences in the relationships estimated for WED and runoff behaviour in Chapters Two and Three. In Chapter Two, we identified negative correlations in regions of BC south of 53° latitude and predominant positive correlations north of 53° latitude. This result is in contrast to the strong negative correlations found the Stikine location in northwestern BC in Chapter Three. The differences in methodological approach have implications for resource planning since both studies can be used in different ways. Resource planners working on timescales of 5-20 years who seek to develop infrastructure now may benefit more by using the results from Chapter Three to inform shorter-term energy infrastructure development since broadly speaking, long-term climate oscillations such as the PDO are unlikely to be of concern and seasonal relationships will dominate complementarity. Likewise, long-term systematic planning such as planning BC’s energy grid beyond 2050 may benefit from the findings of Chapter Two. Over longer-term 30-year periods, seasonal behavior may be relatively less influential on the renewable electricity generation system than larger scale climate oscillations. Notwithstanding, no single approach is ‘better’ than another and both approaches are inextricable and consulting both Chapters Two and Three may help to inform resource planning more than when consulting a single chapter.

These findings are based on outputs from the CRCM, which is one of many models capable of projecting BC’s future hydroclimatology and we recognize that model selection can have a significant effect on the estimates of BC’s hydroclimatological future (Music et al., 2012). However, we have attempted to account for internal climate variability by using three ensemble members from the CRCM 4.2 in our analysis. We recommend future studies employ other regional climate model – global climate model combinations to address the robustness of our findings and suggest that an ideal next step may be to investigate the impact of higher spatiotemporal model output on the results presented in Section 3.4. Recent versions of the CRCM 4.2 available at 15km resolution could be statistically downscaled to generate input for macro-scale hydrology models (such as done by Schnorbus et al., (2014)), which may provide higher resolution projections of BC’s WED-runoff future and serve as a detailed tool for BC’s future renewable electricity resource planning.
3.6. Conclusions

We investigate the future of British Columbia’s (BC) wind energy density (WED) and runoff resources in regions identified as key in future wind farm development. In comparing the Present (1980-2009) to the Future (2070-2099), we observe significant changes in different features of the WED and runoff resources, which are likely to impact future electricity generation potential. Annual mean WED is projected to increase by around 9% in the northernmost locations of BC but to decrease by around 8% in BC’s southern interior. Likewise, the 90th percentiles of annual WED are projected to increase in BC’s northwesterly regions (~11%) and decrease in the southern interior (~7%). Overall, the seasonal distribution of WED does not appear to shift significantly, suggesting that BC may have a relatively stable wind power resource into the long-term future.

We also observe significant changes in the seasonal distribution and magnitude of runoff between the 1980-2009 and 2070-2099 periods. In almost all potential wind farm development regions, annual mean and 90th percentile monthly mean runoff estimates are projected to increase significantly. For example, in all potential wind farm development regions annual mean runoff increases by 7%-19% between the Present and Future periods. In three locations (Stikine, Okanagan, Williston), the month of maximum flow is significantly earlier suggesting an earlier onset of the spring freshet in response to increasing temperatures in BC, which agrees with previous research using a range of streamflow observations, basin scale hydrological models and global climate models. Widespread increases in annual runoff likely occur due to corresponding projected increases in winter rainfall, which compensate for reduced snowpack in the future.

Such changes in WED and runoff are expected to change the temporal correlations between the WED and runoff resources. In both storage-based central-hydropower and run-of-river local-hydropower conditions we observe a shift towards increasingly positive correlations between WED and runoff. For example, in the local-hydropower scenario, average Spearman $\rho$ at all sites is projected to increase from -0.081 to 0.18. We hypothesise that the increasing contributions of winter rainfall to
annual runoff budgets in our study locations are responsible for this shift. Even northern interior sites where the spring freshet dominates runoff become increasingly rainfall dominated in the winter months, resulting in higher correlations with stronger winds in winter. Because negative correlations indicate optimal conditions for complementarity between wind power and hydropower generation, increasingly positive correlations are unlikely to be favourable for the electricity generation industry. Notwithstanding positive correlations within BC’s borders, should electricity transactions between states close to BC (e.g. Alberta, Washington and Idaho) develop; there may be opportunities to investigate complementarity between different regions developing the possible benefits of complementarity elsewhere.

However, despite increasing correlations, we identify the Stikine location in northwest BC as exhibiting consistent negative correlations in both hydropower conditions and in both periods. Should BC develop sufficient transmission capabilities, findings from our research suggest that Stikine would provide the best wind power resource when considering timing and seasonal WED magnitudes. Finally, when comparing WED behaviour at each location with, runoff under the central-hydropower condition, most sites have relatively consistent negative correlations between WED and runoff into the later part of the 21st century. This consistent complementarity between WED and the central-hydropower runoff scenario bodes well for the development of a more stable combination of wind and hydropower for BC given that large-scale hydropower will likely remain a substantial contributor to BC’s electricity supply in the coming decades.

3.7. References


BC HYDRO, 2014b. *Independent Power Producers (IPPs) currently supplying power to BC Hydro*. BC Hydro.


3.8. Supplementary Tables

Figure A.1  A summary of how the 90 values in Period 1 (e.g. a mean value for each year, for each ensemble member) are compared to the 90 values in Period 2.
Chapter 4. Anticipating PEV buyers' acceptance of utility controlled charging

4.1. Abstract

Utility controlled-charging (UCC) of plug-in electric vehicles (PEVs) could potentially align vehicle charging with the availability of intermittent, renewable electricity sources. We investigated the case of a nightly charging program where the electric utility can control home PEV charging. To explore consumer acceptance of this form of UCC, we implemented a web-based survey of new vehicle buyers in Canada (n = 1470). The survey assessed interest in PEVs, explained UCC, and elicited openness to UCC through attitudinal questions and a stated choice experiment. We find potential for UCC support among one-half to two-thirds of respondents interested in purchasing a PEV, depending on the scenario. However, some respondents expressed concerns with privacy and loss of control. To quantify preferences for UCC, we estimated a latent class choice model where respondents chose between different PEV charging programs. The model identified four distinct respondent segments (or classes) that varied in their acceptance of UCC, as well as their valuation of renewable electricity, saving money on their electrical bill, and undergoing charging inconvenience. The overall sample was more sensitive to cost incentives than to renewable incentives, where cost-based UCC programs garnered 63-78% enrollment while renewable-based programs garnered only 49-59% enrollment. Overall, we observe the potential for widespread acceptance of UCC programs among Canadian PEV buyers, but program design and deployment will

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need to carefully acknowledge the various motivations and concerns of different vehicle buyer segments.

4.2. Introduction

Utility controlled charging (UCC) occurs when an electric utility (or an appointed third party) controls the charging of plug-in electric vehicles (PEVs) in some way. For example, one form of UCC, vehicle-to-grid (V2G), allows plugged-in PEVs to provide power to the electrical grid (Kempton and Tomić, 2005a). However, UCC is a broader term referring to an electric utility’s ability to control the charging of a given PEV or fleet of PEVs to manage charge times, charging rates and/or vehicle-to-grid (V2G) discharge.

UCC can be designed or framed according to a number of benefits; it has the potential to facilitate load management (Kempton and Tomić, 2005a, Druitt and Früh, 2012), reduce electricity system costs (Fernandes et al., 2012, Tomić and Kempton, 2007) subsidize the PEV market (Kempton and Tomić, 2005a, Kempton and Tomić, 2005b) and increase the use of renewable sources of electricity (renewables) (Lund and Kempton, 2008, Tomić and Kempton, 2007, Weis et al., 2014). Our research primarily explores the potential of UCC to facilitate the uptake of intermittent renewable electricity sources, e.g. wind, solar and run-of-river hydroelectricity, where intermittency inherently presents a challenge for grid management. In theory, UCC could be used to influence the timing and rate of PEV charging to better align electricity demand with the intermittent availability of renewable electricity. More advanced versions of UCC, namely V2G, can further use a larger fleet of PEVs that stores the excess electricity produced by renewables when supply exceeds demand, and then send some or all of that electricity back to the grid when demand is present. In either case, such alignment of demand and supply could reduce the need for expensive energy storage or additional backup that goes with intermittent renewables, thus reducing the costs of using renewables, increasing renewables uptake, and lowering the cost of abating greenhouse gas emissions in a given region.

The uptake of renewable electricity is of interest to governments with greenhouse gas (GHG) emission reduction and air quality targets and may present an incentive for
some consumers interested in PEVs. Although the benefits associated with intermittent renewables vary with grid system, location, PEV penetration and renewable energy penetration, there is evidence that UCC has the potential to support environmental goals in a range of locations. As examples, grid modeling studies demonstrate that V2G or other UCC charging schemes can help increase the use of intermittent wind and solar and cut GHG emissions in the Texan grid (Sioshansi and Denholm, 2009), the Californian and German electricity grids (Dallinger et al., 2013), and in Denmark (Lund and Kempton, 2008).

Of course, UCC can also be designed to achieve cost minimization goals, which may or may not align with GHG reduction goals, depending on the region. The cost savings of such a UCC program could, in part, be transferred to PEV owners to incentivize their enrolment in such a program (e.g. through reduced electricity bills, subsidized home charger installation, or other incentives). For example, previous modeling research suggests that UCC cost savings could allow electric utilities to pay PEV owners between ~$85 USD and ~$2500 USD annually to partake in UCC (Druitt and Früh, 2012, Schuller and Rieger, 2013).

For this study, we assume that the primary goal of UCC is to facilitate the efficient use of intermittent sources of renewable electricity, which may also correspond with cost savings. We recognize that some electricity grids may present different tradeoffs between GHG reductions, cost minimization and other objectives, but leave those considerations to future research and to the individual mandate established by a given region or electric utility.

To assess the potential for UCC to support the deployment of renewable electricity, we must understand how potential PEV owners perceive UCC and under what conditions they might accept it. Therefore, we investigated consumer acceptance of UCC for nightly residential PEV charging because most current PEV owners charge their vehicles during this time (US DOE, 2012). We used empirical data to address the following research objectives:

1) Characterize consumer attitudes towards UCC, including perceptions of renewable energy sources, charging inconvenience, and privacy.
2) Quantify consumer preference for enrolment in a UCC program, including tradeoffs between usage of renewable sources of electricity, impacts on the electricity bill, and charging inconvenience.

3) Anticipate how different segments of consumers might react to different UCC programs, using a latent class (LCM) choice model.

Note that our definition of PEV includes both ‘pure’ electric-vehicles (EV) that are powered by electricity, as well as plug-in hybrid electric vehicles (PHEVs) that can be powered by electricity for a given charge-depleting range of around 20-70km, and which can be powered solely by gasoline after that. Both types of PEV require a connection to the grid for recharging, with an EV typically requiring more time to fully charge than a PHEV. We focus exclusively on potential UCC acceptance among household buyers of light-duty passenger vehicles—particularly those that are most likely to be the “Early Mainstream” buyers of PEVs.

4.3. Background

No research has explored consumer acceptance of UCC as we define it here. However, we start by drawing from two studies that explore consumer perceptions of PEVs and how PEVs might be connected to the electricity grid.

Axsen and Kurani (2013a) explored the idea of pairing the sale of a PEV with consumer enrollment in a renewable electricity program. Through a web-based survey of 1502 American new vehicle buyers (1064 conventional vehicle owners, 364 hybrid owners, and 74 PEV owners), the authors elicited respondents’ interest in combining a PEV purchase with enrollment in a renewable electricity program. Among the conventional vehicle owners, offering a green electricity program to accompany a PEV purchase increased stated interest in PEVs by 23%. Although this increase is substantial, not all survey respondents were motivated by the availability of renewable energy to fuel a PEV, suggesting some degree of heterogeneity in preferences. To further explore heterogeneity, the authors identified significant differences between the motivations reported by samples of conventional vehicle owners, HEV owners and PEV owners. For example, PEV buyers were more likely to be motivated by environmental concerns and an interest in technology relative to HEV and conventional vehicle buyers.
A second related study by Parsons et al. (2014) investigated consumer preferences for V2G, a complex type of UCC where power stored in PEVs may be discharged back to the electric grid. The authors conducted a stated choice experiment and estimated latent-class choice models using web-survey data from 3029 US residents to quantify the compensation required by consumers to enroll in a V2G program. The study focused on cost savings and the “guaranteed minimum charge” — defined as the electric powered range that would be guaranteed for the V2G participant at any time. The study did not address the potential for V2G to support renewable energy sources, or how consumer might value that aspect of a V2G program. Further, this study only focused on valuation of V2G among potential owners of EVs, whereas Axsen and Kurani (2013a) also included PHEVs, which by definition are not range limited. Overall, Parsons et al. (2014) find that potential EV drivers would require a high degree of annual compensation to enroll in some form of V2G program, ranging from $2000 to over $8000 per year. Respondents generally preferred higher levels of charge (guaranteed minimum range) across various V2G scenarios; for example, reducing guaranteed minimum charge from 175 miles to 125 miles was valued as a loss of about $500 in upfront value (instantaneous repayment), while the reducing the charge to 75 miles is equivalent to a loss of $4000.

These two studies yield different insights into the potential for consumer enrollment in UCC programs. Some consumers may be motivated by cost savings (and thus will require financial compensation), while some consumers may be motivated by the potential to facilitate the uptake of renewable sources of electricity. Further, the amount of guaranteed minimum charge provided to consumers seems to be an important factor for many consumers. The present study seeks to quantify consumer tradeoffs among these three attributes when considering a UCC program, while representing the heterogeneity in valuation across potential PEV buyers.

In addition to the limited consumer research surrounding UCC, we draw from broader literature on consumer preferences for PEVs and renewable energy to anticipate the characteristics of consumers potentially interested in UCC. Consumers who are more interested in PEVs tend to be younger (Dagsvik et al., 2002, Hidrue et al., 2011), more highly educated, and more environmentally oriented (Bunch et al., 1993,
Ewing and Sarigöllü, 2000). The role of income seems uncertain; some studies find that those with higher incomes are more likely to be willing to pay more for renewables (Bergmann et al., 2006, Wiser, 2007) although the opposite has also been found (Ek, 2005). Consumers who demonstrate the highest affinity for renewables tend to have relatively high biocentric values (value for living things) (Clark et al., 2003), relatively strong pro-environmental values (Ozaki, 2011), and to be more knowledgeable about renewables (Salmela and Varho, 2006). Although respondents generally favour renewable sources such as solar and wind, studies also find that respondents support a non-specific mix of renewable sources (Borchers et al., 2007, Cicia et al., 2012, Greenberg, 2009).

4.4. Methods

To explore consumer acceptance of UCC, we implemented the 2013 Canadian Plug-in Electric Vehicle Survey (CPEVS) between April and October 2013. The target population was new vehicle buyers in Canada. We define “new vehicle buyers” as households who purchased a new vehicle in the past five years and use a vehicle regularly. Rather than survey current PEV owners, we intentionally focused the CPEVS on the target population of new vehicle buying households to identify the “potential early PEV mainstream” consumers who are most likely to be the next buyers of PEVs. We contracted a market research company to recruit a representative sample of new vehicle buying households and individuals whom completed all three surveys received a $20 gift card for a chosen Canadian retail outlet. Participants were also entered into a draw to win $500. CPEVS was a three-part Internet based survey that elicited details about respondents (Part 1), encouraged respondents to learn about their own interest in PEVs and how the technology may relate to their lifestyle (Part 2), and explored respondents’ interest in buying a PEV and how they may recharge it under various conditions (Part 3). Figure 4.1 depicts the flow of the three-part survey.
A detailed account of the full 2013 CPEVS methodology is available in Axsen et al., (2013). The following sections detail components of the survey that are relevant to our research questions: 1) a PEV and green electricity “buyers’ guide”, 2) PEV design space exercises 3) attitudinal questions regarding UCC, 4) UCC discrete choice experiments, and 5) individual characteristics. These components are ordered differently in Figure 4.1 but we discuss them as listed above for simplicity.
4.4.1. Informing respondents about PEVs and UCC

We assumed that most respondents have almost no experience with PEVs or the notion of UCC prior to survey completion. Part 2 of the survey included exercises to help respondents consider their potential usage of a PEV, including a home recharge assessment questionnaire and three-day driving and parking diary. We also included a “PEV Buyers’ Guide” document explaining how different vehicle technologies function using language tailored to non-experts. The guide discussed vehicle charging and described renewable energy sources that a PEV owner might charge with—preparing respondents for later survey questions about UCC. This buyers’ guide is based on similar documents used in consumer research for PHEVs in the U.S. (Axsen and Kurani, 2009) and PEVs in San Diego, California (Axsen and Kurani, 2013b), and was extensively pre-tested to maximize respondents’ ability to comprehend survey questions whilst attempting to minimise bias.

Table 4.1 Different design configurations available in the design space exercise and their associated incremental prices

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Higher price scenario</th>
<th>Lower price scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compact</td>
<td>Sedan</td>
</tr>
<tr>
<td>HEV</td>
<td>$1380</td>
<td>$1740</td>
</tr>
<tr>
<td>PHEV-16</td>
<td>$2230</td>
<td>$2720</td>
</tr>
<tr>
<td>PHEV-32</td>
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<td>$3230</td>
</tr>
<tr>
<td>PHEV-64</td>
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</tr>
<tr>
<td>EV-80</td>
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<td>$7880</td>
</tr>
<tr>
<td>EV-120</td>
<td>$8940</td>
<td>$10690</td>
</tr>
<tr>
<td>EV-160</td>
<td>$11380</td>
<td>$13500</td>
</tr>
<tr>
<td>EV-200</td>
<td>$13820</td>
<td>$16310</td>
</tr>
<tr>
<td>EV-240</td>
<td>$16260</td>
<td>$19130</td>
</tr>
</tbody>
</table>

4.4.2. Identifying the potential early mainstream PEV market: Design space exercise

For this research, it was important to identify what we call the “potential early mainstream market” for PEVs. We defined this as a broad segment of new vehicle buyers that may purchase a PEV in the near-term, provided the incremental price is
relatively low, and that a variety of PEV design options are available. We focused exclusively on this consumer segment to elicit perception of and attitudes towards UCC; we assumed that only this segment was relevant to UCC potential in any initial rollouts of UCC programs (e.g. within the next 10 to 15 years). As noted above, we did not investigate the preferences of existing PEV owners.

We consider three broad classifications of potential PEV buyers:

1) “PEV Pioneers” are the first buyers of PEVs. These buyers are a relatively small, extreme group and are generally different from “potential early mainstream” buyers.

2) Potential “Early Mainstream” PEV buyers are the focus of this study. They represent a much larger segment than the PEV pioneers, and generally have characteristics more in line with mainstream values and interests.

3) The “Late Mainstream” PEV buyers (or non-buyers) represent the larger segment of new vehicle buying households who are not interested in buying a PEV. These households may become buyers, but considerable changes will be required, e.g. changes in policy, costs, technology, or cultural norms.

PEV Pioneers (current PEV owners) tend to have more extreme socio-demographic characteristics and preferences relative to the general population of new vehicle buyers (Axsen and Kurani, 2013b) and do not necessarily represent the larger group of potential Early Mainstream PEV buyers. For example, PEV Pioneers are more likely to reside in detached homes and tend to have higher incomes, be older, be more highly educated, and own more vehicles per household. Further, PEV Pioneers are motivated by interests in new technology and the environment rather than fuel and vehicle cost savings which are more common amongst conventional vehicle purchasers (Axsen and Kurani, 2013a).

To identify the “Early Mainstream” PEV market segment, we used a PEV design space exercise. The design exercise allowed respondents to personalize a vehicle (or other product or behavior) to match their preferences under different price contexts. The PEV design space exercise is consistent with theories of constructed preferences that view consumer preferences as outcomes of, not inputs to, decision contexts and processes (Bettman et al., 1998). We provided respondents with a “space” or design
envelope—a series of design options that respondents could select to create their preferred design given a particular context. Such design exercises and games have been pioneered for use in transportation behavior research by Lee-Gosselin (1990), Kurani et al., (1994), and Turrentine and Kurani (1998) and more recently applied to market research on PHEVs and PEVs (Axsen and Kurani, 2009, Axsen and Kurani, 2013b).

In the design space exercise, each respondent first selected a currently available ‘base’ vehicle (conventional gasoline powered) that represented the vehicle they would buy next if they were limited to a conventional vehicle. The respondent indicated the body type, price, and fuel economy of this vehicle. Subsequently, respondents completed “higher price” and “lower price” scenarios for the vehicle design exercises. The design exercises presented the respondent with four vehicle types: (i) their base conventional vehicle; (ii) a hybrid version (with 33% improved fuel economy over the base); (iii) a PHEV version powered with electricity for the first 16, 32, or 64 kilometres (achieving the same 33% increase in fuel economy until the battery is recharged); and (iv) an EV version powered only by electricity for 80, 120, 160, 200, or 240 kilometres of range. The only difference between the price scenarios was the cost of vehicle upgrades; the design options in the exercises remained constant. The incremental prices for each vehicle type and electric driving range differed by vehicle body size (Table 4.1). See Axsen and Kurani (2013a) for discussion of the derivation and limitations of the incremental prices.

We identify the “Early Mainstream” as the respondents who designed some form of PEV (PHEV or EV) in the lower price design space exercise. We focused only on this Early Mainstream sub-sample when reporting UCC attitudes and estimating preferences for UCC.
4.4.3. Eliciting respondent attitudes towards UCC

After identifying the Early Mainstream respondents, we characterized their preferences for UCC through attitudinal questions and discrete choice experiments. Attitudinal questions elicited sentiment towards the notion of UCC, the sources of renewables used for PEV charging and the acceptability of having a vehicle that may not be fully charged in the morning (the concept of guaranteed minimum charge). We asked general questions first because UCC is a novel subject and we wanted to understand how it was perceived. We then assessed general support for different electricity sources to enable comparison between attitudinal questions and a tradeoff-based discrete choice response. Each of these three questions provided Likert–type response scales. We used previous survey literature (Axsen and Kurani, 2009, NHTS, 2009, NRCan, 2009, Axsen and Kurani, 2013a) and the principles outlined in Dillman and Groves (2011) to inform the crafting of all questions. Details of these questions can be found in Axsen et al., (2013).

Table 4.2 Attributes and levels used in the choice experiment

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Status Quo</th>
<th>UCC Style 1</th>
<th>UCC Style 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of Green Electricity: Percentage of current electric supply powering the respondents’ home and vehicle.</td>
<td>Current Green Electricity%</td>
<td>25%</td>
<td>25%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>75%</td>
<td>75%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Source of Green Electricity: The source of the green electricity to supply the respondents’ home and vehicle.</td>
<td>Existing grid supply mix</td>
<td>Wind</td>
<td>Wind</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solar</td>
<td>Solar</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Small Hydro</td>
<td>Small Hydro</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mixed</td>
<td>Mixed</td>
</tr>
<tr>
<td>Guaranteed Minimum Charge: The amount of charge that the vehicle’s battery would have ‘the next morning’. Displayed to respondent as both percentage charge and electric range in km.</td>
<td>100% charge</td>
<td>50% charged</td>
<td>50% charged</td>
</tr>
<tr>
<td></td>
<td></td>
<td>70% charged</td>
<td>70% charged</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90% charged</td>
<td>90% charged</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100% charged</td>
<td>100% charged</td>
</tr>
<tr>
<td>Monthly Electricity Bill: Current bill or with green electricity, user’s current electric bill plus the expected</td>
<td>Current bill provided by respondent</td>
<td>60% of current bill</td>
<td>60% of current bill</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80% of current bill</td>
<td>80% of current bill</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100% of current bill</td>
<td>100% of current bill</td>
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</tbody>
</table>
4.4.4. **UCC Discrete choice experiments (DCE)**

To provide an additional perspective on consumer perceptions of and preferences for UCC, respondents completed a discrete choice experiment. A choice experiment allowed us to quantify the tradeoffs consumers made between the different potential attributes of a UCC program. Discrete choice experiments estimate the utility that an individual perceives when considering different multi-attribute alternatives (Akiva and Lerman, 1985, McFadden, 1974). We estimated a multinomial logit model (MNL) and a latent class model (LCM) to help identify heterogeneity in consumer preferences. To address heterogeneity, a LCM assumes that respondents can be discretely grouped according to different patterns of preferences. The latent class specification allows for the inclusion of individual specific variables such as socio-demographic, attitudinal, and value based variables. These individual variables facilitate the interpretation of class membership (Strazzera et al., 2012). Since there are no previous examples of discrete choice experiments investigating UCC preferences, we took care when generating the experimental design. Attributes and levels were extensively pre-tested to assess respondent understanding of the concept (after reading the PEV Buyers’ Guide as described in 4.4.1).

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Status Quo</th>
<th>UCC Style 1</th>
<th>UCC Style 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>cost of charging a vehicle multiplied by a scalar.</td>
<td></td>
<td>110% of current bill</td>
<td>110% of current bill</td>
</tr>
</tbody>
</table>
We used four attributes to represent the UCC charging decision. Each attribute was assigned four levels that varied between the alternatives depicted in each choice set (Figure 4.2 and Table 4.2). To represent the inconvenience associated with UCC (due to the integration of intermittent sources of renewable electricity), we used the attribute ‘guaranteed minimum charge’ (GMC). This GMC attribute aligns closely with the guaranteed minimum range attribute used by Parsons et al., (2014) in their V2G choice experiment. We informed respondents that, as a part of a UCC program, their electric utility might delay charging of the PEV until later in the evening or take electricity from the vehicle battery when it is plugged-in. The GMC was described as: “the minimum level of charge that your battery would have after a night of being plugged-in. For example, if your GMC were 50%, then in the morning your battery would be at least half full. There is a chance that the level of charge could be higher than this.” We represented this GMC attribute as a percentage of charge (e.g. 90% charged), and informed respondents of their consequent electric driving range in km (dependent on their vehicle design); GMC did not affect the gasoline-powered driving range of a PHEV design.

**Figure 4.2   Illustrative UCC choice set (screenshot from survey)**

We used four attributes to represent the UCC charging decision. Each attribute was assigned four levels that varied between the alternatives depicted in each choice set (Figure 4.2 and Table 4.2). To represent the inconvenience associated with UCC (due to the integration of intermittent sources of renewable electricity), we used the attribute ‘guaranteed minimum charge’ (GMC). This GMC attribute aligns closely with the guaranteed minimum range attribute used by Parsons et al., (2014) in their V2G choice experiment. We informed respondents that, as a part of a UCC program, their electric utility might delay charging of the PEV until later in the evening or take electricity from the vehicle battery when it is plugged-in. The GMC was described as: “the minimum level of charge that your battery would have after a night of being plugged-in. For example, if your GMC were 50%, then in the morning your battery would be at least half full. There is a chance that the level of charge could be higher than this.” We represented this GMC attribute as a percentage of charge (e.g. 90% charged), and informed respondents of their consequent electric driving range in km (dependent on their vehicle design); GMC did not affect the gasoline-powered driving range of a PHEV design.
Given our research focus on the potential for UCC to increase the uptake of intermittent, renewable sources of electricity, two attributes used in the experiment were ‘percentage of green electricity’ and ‘source of green electricity’. We set the ‘percentage of green electricity’ attribute as 25%, 50%, 75% or 100%, where lower percentages were not viewed as attractive among pre-testers. The PEV Buyers’ Guide explained “green” electricity as zero or near-zero greenhouse gas emissions sources of electricity, such as solar, wind, small-scale hydroelectric and geothermal. We excluded large-scale hydroelectricity due to the potential land-use impacts of this type of electricity generation—and lack of intermittency. In the experiment, we focused on popular sources of intermittent energy currently available and realistic for use in UCC. We also included the idea of using a ‘mixed’ source of green electricity, as done by Borchers et al. (2007).

To represent the cost of PEV charging, we designed a monthly electricity bill attribute (Canadian dollars). We customized the experiment for respondents with their reported monthly electricity bill, and the estimated additional cost of charging the PEV vehicle design used for the choice set. For example, if the respondent’s electrical bill was $100/month, and they designed a compact PHEV with 64km of range, we adjusted their “current electricity” bill to be $123/month. The additional $23 represented the approximate monthly cost of charging a 64km PHEV given electricity prices in the respondent’s province. The choice experiment then included this bill level, as well as potential bills of 110, 80 and 60 percent of this value.

Each choice set presented the respondents’ current home electricity situation and two hypothetical UCC alternatives that they might enroll in. Respondents repeated the choice sets with two different PEV scenarios. In the first PEV scenario, the respondent considered a UCC program for the PEV that they designed in the lower-price PEV design space exercise (as if the respondent owned this vehicle, and chose whether to adopt a UCC program). The second PEV scenario choices sets were framed as if the respondent owned a 240km range EV version of their base vehicle (i.e. all Early Mainstream respondents considered this same vehicle design). We anticipated that respondents may respond differently to a UCC program if they were to imagine driving their PEV design (which may be a PHEV) versus a pure EV.
For each of the two PEV scenarios (user designed or EV-240 each respondent was shown six randomly assigned choice sets. The original experiment featured a 4^4 full factorial design. We used SAS’s choice mktEx macro function (Kuhfeld, 2005) to generate a main-effects fractional factorial version of this experimental design, reducing the total number of choice sets to 48. The mktEx macro attempts to optimize D-efficiency, which is a standard measure of the goodness of the experimental design. As D-efficiency increases, standard errors of parameter estimates in the model decrease—see Rose et al., (2008) for details.

4.4.5. Understanding heterogeneity through individual characteristics

To aid our identification and characterization of latent classes (segments), the survey collected individual information about respondents. Supplementary to collecting demographic information, we used a series of scales relating to: values (biospheric and altruistic), lifestyle (technology orientation) and attitudes (privacy concern). We chose value and lifestyle scales because they relate to PEV (Ewing and Sarigöllü, 2000) and renewable energy preferences (Clark et al., 2003). The value scales were based on Stern et al.’s (1998) “brief” values inventory. The technology-orientated lifestyle scale was measured as a composite of five lifestyles practice questions from Part 1 of the survey—previous research suggests that this scale can help understand heterogeneity in consumer interest in pro-environmental technologies (Axsen et al., (2012)). The privacy concern scale was a likert-type scale that was uniquely developed for the present study (as no previous versions exist).

4.4.6. UCC acceptance under policy scenarios

Since we expected heterogeneity in preferences for UCC, we sought to understand how consumer acceptance of UCC may change given different policy scenarios. Consequently, we embedded the class-specific utility coefficients that we estimated through the LCM into a simple policy analysis tool. Using the tool, we estimated the impact of changes in the levels of attributes on the acceptance of UCC within each class (or segment) of respondents.
The utility function for each respondent class can estimate the probability of respondents in that class accepting a given UCC program, and this probability can be interpreted as a market share or forecasted UCC program enrollment rate for a particular respondent segment. In other words, we predicted how specific UCC program designs (represented as changes in attributes) might impact the acceptance of UCC across the Early Mainstream sub-sample.

4.5. Results

4.5.1. The sample

In total, representing new vehicle buyers across Canada (excluding Quebec because funds were not available for a full French translation), 1,470 respondents completed all three parts of the CPEVS survey. British Columbia, Alberta, and Ontario were intentionally oversampled to permit regional comparisons. Initially, 3,179 respondents completed Section 1, and at the time of this data analysis, 1,470 had finished Section 3 (note that by the completion of CPEVS, 1754 respondents had completed Part 3). Table 4.3 compares our full respondent sample (n = 1470) and our “Early Mainstream” sub-sample (n = 530) to the Canada Census data. All analyses using the Early Mainstream sample were weighted to account for the provincial oversamples. Our sample is generally older, more highly educated, and more likely to own a home relative to the general population, as has been found in previous studies (Axsen and Kurani, 2010; Busse et al., 2013; Harris-Decima, 2013). Overall, we are confident that the sample is representative of new-vehicle buying households in English-speaking Canada and that it provides enough breadth in consumer households to facilitate the objectives of this study—that is, exploring potential general acceptance of UCC programs.

Figure 4.3 depicts the distribution of vehicle designs in the lower price PEV design exercise. We categorize as the Early Mainstream sub-sample the 36% (n=530 / n=1470) of respondents that designed either a PHEV or EV. Amongst the Early Mainstream, PHEV designs were selected more frequently than EV designs. Axsen and Kurani (2013a) observed a similar interest in PHEVs using the design exercises survey.
implemented in San Diego, California. The remainder of this paper focuses on this Early Mainstream sub-sample, which we refer to as survey “respondents.”

**Figure 4.3** Selected vehicle designs from the “lower price” PEV design space (full sample, n=1470)

**Table 4.3** Demographic comparison of our sample with the Canadian census data

<table>
<thead>
<tr>
<th>Sample Size</th>
<th>All respondents(^a)</th>
<th>Early Mainstream(^b)</th>
<th>Census (Canada)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household Size</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>13.1%</td>
<td>13.5%</td>
<td>27.6%</td>
</tr>
<tr>
<td>2</td>
<td>40.0%</td>
<td>40.4%</td>
<td>34.1%</td>
</tr>
<tr>
<td>3</td>
<td>20.8%</td>
<td>20.3%</td>
<td>15.6%</td>
</tr>
<tr>
<td>4+</td>
<td>26.2%</td>
<td>25.7%</td>
<td>22.7%</td>
</tr>
<tr>
<td>Sex (of person filling out the survey)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>58.4%</td>
<td>56.8%</td>
<td>51.0%</td>
</tr>
<tr>
<td>Male</td>
<td>41.6%</td>
<td>43.2%</td>
<td>49.0%</td>
</tr>
<tr>
<td>Age (of person filling out the survey)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-24</td>
<td>7.0%</td>
<td>5.4%</td>
<td>13.0%</td>
</tr>
<tr>
<td>25-34</td>
<td>23.0%</td>
<td>22.8%</td>
<td>12.9%</td>
</tr>
<tr>
<td>35-44</td>
<td>18.2%</td>
<td>18.9%</td>
<td>13.4%</td>
</tr>
<tr>
<td>45-54</td>
<td>19.5%</td>
<td>19.6%</td>
<td>15.9%</td>
</tr>
<tr>
<td>55-64</td>
<td>19.2%</td>
<td>19.9%</td>
<td>13.1%</td>
</tr>
<tr>
<td>65+</td>
<td>13.1%</td>
<td>13.4%</td>
<td>14.8%</td>
</tr>
</tbody>
</table>

**Work Status** (of person filling out the survey)
<table>
<thead>
<tr>
<th>Employment Status</th>
<th>2011 (%)</th>
<th>2012 (%)</th>
<th>2013 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Employed</td>
<td>60.9</td>
<td>61.2</td>
<td>62.3</td>
</tr>
<tr>
<td>Retired</td>
<td>21.0</td>
<td>21.6</td>
<td>33.1</td>
</tr>
<tr>
<td>Student</td>
<td>4.0</td>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td>Family caregiver</td>
<td>6.8</td>
<td>6.7</td>
<td>0.2</td>
</tr>
<tr>
<td>Presently unemployed</td>
<td>5.6</td>
<td>5.3</td>
<td>4.4</td>
</tr>
<tr>
<td>Not applicable</td>
<td>1.8</td>
<td>1.8</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**Highest level of education completed** (of person filling out the survey)

<table>
<thead>
<tr>
<th>Level of Education</th>
<th>2011 (%)</th>
<th>2012 (%)</th>
<th>2013 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than high school</td>
<td>1.8</td>
<td>2.7</td>
<td>23.8</td>
</tr>
<tr>
<td>High school certificate or equivalent</td>
<td>16.6</td>
<td>16.8</td>
<td>25.5</td>
</tr>
<tr>
<td>Apprenticeship, trades certificate or diploma</td>
<td>6.2</td>
<td>5.9</td>
<td>10.9</td>
</tr>
<tr>
<td>College, CEGEP, or other non-univ. diploma</td>
<td>24.3</td>
<td>24.6</td>
<td>17.3</td>
</tr>
<tr>
<td>Some university</td>
<td>12.5</td>
<td>11.8</td>
<td>4.4</td>
</tr>
<tr>
<td>University degree (Bachelor)</td>
<td>26.2</td>
<td>26.0</td>
<td>13.5</td>
</tr>
<tr>
<td>Graduate or professional degree</td>
<td>12.4</td>
<td>12.3</td>
<td>4.6</td>
</tr>
</tbody>
</table>

**Household income** (pre-tax)

<table>
<thead>
<tr>
<th>Income Range</th>
<th>2011 (%)</th>
<th>2012 (%)</th>
<th>2013 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than $40,000</td>
<td>14.8</td>
<td>13.9</td>
<td>24.9</td>
</tr>
<tr>
<td>$40,000 to $59,999</td>
<td>20.5</td>
<td>20.4</td>
<td>19.3</td>
</tr>
<tr>
<td>$60,000 to $89,999</td>
<td>27.8</td>
<td>28.4</td>
<td>24.3</td>
</tr>
<tr>
<td>$90,000 to $124,999</td>
<td>24.6</td>
<td>24.9</td>
<td>16.8</td>
</tr>
<tr>
<td>Greater than $125,000</td>
<td>12.3</td>
<td>12.3</td>
<td>14.7</td>
</tr>
</tbody>
</table>

**Residence ownership**

<table>
<thead>
<tr>
<th>Ownership Type</th>
<th>2011 (%)</th>
<th>2012 (%)</th>
<th>2013 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Own</td>
<td>77.9</td>
<td>77.9</td>
<td>68.7</td>
</tr>
<tr>
<td>Rent</td>
<td>22.1</td>
<td>22.1</td>
<td>31.3</td>
</tr>
</tbody>
</table>

**Residence type**

<table>
<thead>
<tr>
<th>Type</th>
<th>2011 (%)</th>
<th>2012 (%)</th>
<th>2013 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detached House</td>
<td>66.7</td>
<td>65.3</td>
<td>61.9</td>
</tr>
<tr>
<td>Attached House (e.g. townhouse, duplex, triplex, etc.)</td>
<td>15.3</td>
<td>14.9</td>
<td>17.0</td>
</tr>
<tr>
<td>Apartment – “low-rise” (&lt;5 storeys/levels)</td>
<td>10.0</td>
<td>9.5</td>
<td>13.2</td>
</tr>
<tr>
<td>Apartment – “high-rise” (≥5 storeys/levels)</td>
<td>6.4</td>
<td>6.8</td>
<td>6.8</td>
</tr>
<tr>
<td>Mobile Home</td>
<td>1.6</td>
<td>1.4</td>
<td>1.2</td>
</tr>
</tbody>
</table>

---

*Overall Canada sample is unweighted. Survey data includes only English-speaking Canada – Quebec was excluded due to language translation costs. Census data includes Quebec.*

*This is 530 out of the 1470 pre-close sample which represents a slight subset of the all respondents final sample.*

**Note.** Data on household size, sex, age, and residence type are from the 2011 Canada Census. Data on work status, education, and income are from the 2006 Canada Census. Data on home ownership are from the Canadian Mortgage and Housing Corporation:

4.5.2. Attitudes towards UCC

We asked respondents attitudinal questions about the characteristics of UCC (Figure 4.4). We provided respondents with a brief description of UCC as outlined in 4.4.1. The survey included several statements about UCC, where respondents indicated their agreement or disagreement using a five-point likert-type scale. We asked if respondents perceive UCC as an invasion of privacy to which 24% agreed or strongly agreed. The survey also asked if respondents believed that UCC would “take control away from me in a way that I would not like” to which 39% of respondents agreed or strongly agreed. Generally, respondents perceived that UCC can benefit the environment and most (68%) believed that the government should support UCC.

We also asked respondents for their opinions on the sources of electricity used to charge PEVs (Figure 4.5). Solar, wind, geothermal, and run-of-river hydro all received strong support, with minimal opposition. Except for geothermal, each of these sources is an intermittent source of electricity that may be complemented by UCC of a large fleet of PEVs. Coal and nuclear were the least supported with only 15% and 38% of respondents supporting them, respectively.

![Figure 4.4 Perceptions of utility controlled charging among potential early mainstream PEV buyers (Early Mainstream only, n=530)](image-url)
To represent the intermittency in renewables and the inconvenience of having a utility control PEV charging, we elicited respondents’ opinions on the frequency and level of guaranteed minimum charge (GMC) that their PEV would receive after a night of charging. Respondents were asked to imagine owning a 240km EV version of their base vehicle (Figure 4.6). Respondents were then asked: “if there was a chance that your battery would only be 90% charged in the morning, how often (out of 5 days) would you be ok with this?” (where the other mornings would have 100% state of charge). This question was repeated for 70% and 50% GMC in the morning. Most respondents were comfortable with allowing a 90% GMC some of the time—96% would allow this for at least 1 day out of 5, and 43% would allow this GMC every morning. This suggests that the majority of respondents may allow their electric utility to have some degree of charging control of their PEV through a UCC program. There was less support for a 50% GMC, where 32% of respondents would not allow a GMC of 50% on any day. We used the discrete choice model to further investigate tradeoffs and heterogeneity in preferences for GMC and other UCC attributes.

**Figure 4.5** Perceptions of different electricity sources among potential early mainstream PEV buyers (Early Mainstream only, n=530)
4.5.3. The discrete choice model

To demonstrate how results differ when accounting for heterogeneity in preferences, we present the latent class specification alongside a multinomial logit (MNL) (Table 4.4). We estimated discrete choice models using Latent Gold (Vermunt and Magidson, 2005). When we estimated separate models for the two different PEV design scenarios (user design and EV-240), we did not find substantial differences in model coefficients. For the sake of parsimony, we opted to combine data from both scenarios into a single model. Our model provides insights regarding how UCC preferences vary with PEV type by interacting PEV type (PHEV and EV) with the guaranteed minimum charge coefficient and by interacting PEV type with the UCC alternative specific constant.

The alternative specific constants indicate that, on average, UCC with a PHEV design is perceived as a disutility relative to uncontrolled charging with all attributes held equal, as indicated by the negative and statistically significant constant estimate. This same constant is not significant for an EV design except in the case of the Renewables-focused class. We attribute the significant alternative specific constants throughout the MNL and latent-class models to the fact that some respondents may accept or reject enrollment in a UCC program based on attributes other than those specified in our experimental design (and that some of those differences are unique to PHEVs versus EVs). In most discrete choice experiments that assess demand for complex products, it is not possible to capture every attribute that a consumer may consider when selecting an option in each choice set. For example, when considering a UCC program, some respondents might consider things such as potential for battery degradation, trust in their electric utility, the potential for loss of control or invasion of privacy (as we discussed in Section 4.4.3) or other potential attributes of UCC that we might not have considered. For the estimated models, these “lurking variables” are captured by the alternative specific constant estimates (Hensher et al., 2005).

In addition to the constant term, the MNL model’s coefficient estimates for the electrical bill, GMC and percentage of renewables are all of the expected sign, and are all statistically significant at a 99% confidence level. On average, respondents value an additional km of PHEV range over an additional km of EV range (even when accounting
for non-linearity in their valuation), though we do identify heterogeneity in the latent class model (discussed next). While we cannot be sure why one km of PHEV range is valued more highly than EV range in the context of UCC, one explanation may be that PHEV range is more limited (and drivers want to maximize the electric powered portion), whereas respondents might select EV range with an extra “buffer” that is not typically needed. The dummy coefficients for wind and solar energy are negative relative to the base of “mixed sources” and wind was least desirable among the green electricity sources depicted. Interestingly, this ranking of preferred renewable sources differs from our findings in section 4.5.2; one explanation is that the choice contexts in each case are very different—the survey question asked how respondents “feel” about each source of electricity, whereas the choice experiment presented different UCC program packages for the respondent to enroll in. Further, there could be some instability in respondent preferences, as the valuation of renewable electricity is likely to be a novel exercise for most respondents.

The bottom of Table 4.4 translates the coefficient estimates into willingness to pay (WTP) values. WTP values can be estimated as the ratio between the negative of any given parameter coefficient and the monthly bill coefficient. Because of the logarithmic (non-linear) transformation of the GMC coefficients, we used a base vehicle to estimate the incremental WTP for GMC in the PHEV and EV cases. We chose a PHEV-64 and an EV-120 (similar to the Chevy Volt and Nissan Leaf respectively) as our base vehicles. To represent the initial state of charge of the PEV on a given evening we subtract the median daily driving distance (36km) estimated in CPEVs (Axsen et al., 2013) from the electric range of each PEV type. This meant that our base PHEV vehicle started its evening charge with 28km of charge, and our base EV started with 84km of charge. On average, respondents were willing-to-pay an additional $239/year to increase their morning PHEV GMC by 10km, $59/year to increase their morning EV GMC by 10km, and $16/year to increase the amount of renewable electricity used to power their PEVs by 10%. For each WTP calculation, we also present standard error estimates generated using the delta method, which uses a first-order Taylor expansion around the mean value of the variables used in the WTP calculation and computes the variance for this expression (Hole, 2007).
“How frequently (days out of 5) would you be willing to wake up to a vehicle that was only X% charged?”

Figure 4.6  Respondent acceptance of guaranteed minimum charge assuming a pure EV with 240 km range (Early Mainstream only, n=530)
### Table 4.4

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Multinomial Logit</th>
<th>Latent Class Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coeff</td>
<td>s.e.</td>
</tr>
<tr>
<td>Interacted Alternative specific constants</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UCC x PHEV</td>
<td>-0.241*** (0.067)</td>
<td></td>
</tr>
<tr>
<td>UCC x EV</td>
<td>0.119 (0.130)</td>
<td></td>
</tr>
<tr>
<td>Model attributes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monthly electric bill (CAD)</td>
<td>-0.030*** (0.001)</td>
<td></td>
</tr>
<tr>
<td>Log (GMC x PHEV (km))</td>
<td>1.669*** (0.089)</td>
<td></td>
</tr>
<tr>
<td>Log (GMC x EV (km))</td>
<td>-0.433 (0.266)</td>
<td></td>
</tr>
<tr>
<td>Percentage of green electricity (%)</td>
<td>0.004*** (0.001)</td>
<td></td>
</tr>
<tr>
<td>Type of green electricity (base = &quot;mixed sources&quot;)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dummy - 1 if wind.</td>
<td>-0.3230*** (0.060)</td>
<td></td>
</tr>
<tr>
<td>Dummy - 1 if small hydro.</td>
<td>-0.006 (0.059)</td>
<td></td>
</tr>
<tr>
<td>Dummy - 1 if solar.</td>
<td>-0.058*** (0.057)</td>
<td></td>
</tr>
<tr>
<td>Class membership probability model (with Class 2 as the base)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>-2.327*** (0.754)</td>
<td></td>
</tr>
<tr>
<td>Demographics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age: Continuous</td>
<td>0.020*** (0.007)</td>
<td></td>
</tr>
<tr>
<td>Dummy - 1 if Bachelors or higher.</td>
<td>-0.771*** (0.233)</td>
<td></td>
</tr>
<tr>
<td>Dummy - 1 if income &gt; 80k/yr.</td>
<td>0.144 (0.216)</td>
<td></td>
</tr>
<tr>
<td>Lifestyle &amp; Attitudes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technologically oriented lifestyle: Scale (0-25)</td>
<td>0.048** (0.024)</td>
<td></td>
</tr>
<tr>
<td>Biopsychic values: Relative scale (0-12)</td>
<td>0.047 (0.063)</td>
<td></td>
</tr>
<tr>
<td>Altruistic values: Relative scale (0-12)</td>
<td>0.008 (0.008)</td>
<td></td>
</tr>
<tr>
<td>Privacy concern: Likert (-2 – 2)</td>
<td>-0.050 (0.092)</td>
<td></td>
</tr>
<tr>
<td>Annual WTP ($CAD)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10km increase in PHEV-64 GMC / yr</td>
<td>$239 (13.38)</td>
<td>$202 (128.52)</td>
</tr>
<tr>
<td>10km increase in EV-120 GMC / yr</td>
<td>$59 (12.08)</td>
<td>$755 (244.08)</td>
</tr>
<tr>
<td>For a 10% increase in % of renewables / yr</td>
<td>$16 (2.78)</td>
<td>-$34 (-29.75)</td>
</tr>
<tr>
<td>To adopt UCC with a PHEV-64 / month</td>
<td>-$8 (-2.21)</td>
<td>-$164 (27.75)</td>
</tr>
<tr>
<td>To adopt UCC with an EV-120 / month</td>
<td>$4 (4.37)</td>
<td>-$42 (31.79)</td>
</tr>
<tr>
<td>Class membership probabilities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class 1</td>
<td>0.21</td>
<td>0.33</td>
</tr>
<tr>
<td>Class 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall Pseudo R²</td>
<td>0.156</td>
<td>0.561</td>
</tr>
</tbody>
</table>

**Significant to 99%, **Significant to 95%, *Significant to 90%

*Example vehicle is a PHEV-64 (e.g. Chevy Volt) which has been driven 36km. Range at end of day is 28km.

**Example vehicle is an EV-120 (e.g. Nissan Leaf) which has been driven 36km. Range at end of day is 84km.
The MNL estimates assume homogeneous preferences amongst the respondents. To represent variability in preferences for UCC, we tested various latent class model specifications. Table 4.5 reports the model selection statistics for models containing up to 5 classes. When fitting models, increasing the log-likelihood by adding parameters is possible, but doing so may result in overfitting where the model describes random error instead of the underlying relationship. The Akaike Information Criteria (AIC) and Consistent Akaike Information Criteria (CAIC) resolve overfitting by introducing a penalty for additional model parameters. As such, the AIC and CAIC are measures of the relative quality of a statistical model, and they provide a means for model selection. Although the 5-class model represented the optimal AIC and values, many of the coefficient estimates in this model were statistically insignificant. The 4-class model represented the next best AIC and the best CAIC values and the incremental increase in Pseudo $R^2$ from 3 classes to four was large. Further, the 4-class model had significant parameters and was the most logically interpretable. Overall, we found that the 4-class model (Table 4.4) provided the best combination of interpretability and mathematical rigor which Louviere et al., (2000) describe as important criteria for model specification.

We also varied model specification through different combinations of socio-demographic and attitudinal covariates. The final model (Table 4.4) only included significant covariates for parsimony. Generally, class specification and model parameter estimates appeared relatively stable under different covariate combinations.

We name the four classes based on differences in preferences, as indicated by different coefficient estimates. Specifically, these classes are: “Anti-UCC”, “Charge-focused,” “Cost-motivated” and “Renewable-focused.” The class membership probability model in Table 4.4 shows how average individual characteristics of respondents differ between classes. Membership coefficients for each class are reported relative to the base class (Charge-focused) where positive values signify that class members are more likely to have a given characteristic relative to respondents in the base class. The class membership probability model also reports the estimated size of each class. The “Charge-focused” class is the largest and is estimated to represent 33% of respondents.
Following this, class sizes decrease from the Cost-motivated (27%) to the Anti-UCC (21%) and Renewable-focused classes (19%) respectively.

The Anti-UCC class was so named because of negative and significant (in the PHEV case) estimates for the UCC alternative specific constants and also for the negative and significant renewable electricity coefficient. These respondents are highly sensitive to changes in GMC compared to other groups and this is particularly true for the case of the EV. The negative estimate for the UCC alternative specific constants and the high WTP for GMC suggest that the Anti-UCC class was not open to the potential inconvenience associated with UCC. Respondents in this class are the only ones to value GMC more for EVs than for PHEVs. Respondents in the Anti-UCC class are more likely to be significantly older and less highly educated than members of the other classes.

Respondents in the remaining classes express more positive preferences for UCC with either PHEVs or EVs, as evidenced by positive, and in three cases, statistically significant UCC alternative specific constants. Only the Renewable-focused class expressed significant and positive preferences for UCC with both PHEVs and EVs. Respondents in the Charged focused class are primarily sensitive to changes in the GMC and monthly electricity bill attributes. These respondents do not have a significant UCC constant estimate, nor is the renewable electricity coefficient significant but they value additional PHEV range most highly. As noted above, these respondents represented the base group in the class probability model and, as such, all other class estimates were presented relative to this class.

Respondents in the Cost-motivated class have a significant positive parameter estimate for increases in GMC and renewable sources of electricity. These respondents are the most sensitive to increases in costs and, accordingly, were willing to pay the least for additional units of renewables and GMC relative to the other pro-UCC classes. Also, these respondents are significantly more likely to live technologically-oriented lifestyles and are less likely to have altruistic values relative to other classes.

Respondents in the Renewable-focused class represent individuals that value UCC and renewable electricity most highly. These respondents are less cost sensitive
than the other pro-UCC classes and are the only class to have significant parameter estimates for all sources of renewable electricity. These individuals prefer mixed sources of renewable electricity to small hydro, solar and wind respectively. These respondents are significantly more likely to be highly educated and have a higher level of biospheric values than the other classes and significantly less likely to perceive UCC as an invasion of privacy relative to all other classes.

Table 4.5 Summary statistics for the range of latent class models tested

<table>
<thead>
<tr>
<th>No. of classes</th>
<th>No. of parameters (k)</th>
<th>Log-likelihood (LL)</th>
<th>AIC(^a)</th>
<th>CAIC(^b)</th>
<th>Pseudo R(^2c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
<td>-5980.4</td>
<td>11978.8</td>
<td>12032.5</td>
<td>0.156</td>
</tr>
<tr>
<td>2</td>
<td>26</td>
<td>-4855.2</td>
<td>9762.4</td>
<td>9917.5</td>
<td>0.444</td>
</tr>
<tr>
<td>3</td>
<td>43</td>
<td>-4656.3</td>
<td>9398.5</td>
<td>9655.0</td>
<td>0.510</td>
</tr>
<tr>
<td>4</td>
<td>60</td>
<td>-4493.2</td>
<td>9106.5</td>
<td>9464.4</td>
<td>0.561</td>
</tr>
<tr>
<td>5</td>
<td>77</td>
<td>-4428.1</td>
<td>9010.1</td>
<td>9469.5</td>
<td>0.588</td>
</tr>
</tbody>
</table>

\(^a\)Aikaike information criterion = -2(LL - k).
\(^b\)Consistent Aikaike information criterion = -2LL + k(Ln\(n_{obs}\) + 1), \(^c\)Pseudo R\(^2\) = 1 - (LL/LL (0)).

\(^c\)Pseudo R\(^2\) = 1 - (LL/LL (0)).

*Note. N.Individuals = 530, N Observations N = 6360

4.5.4. Policy simulation

As a final step in this analysis, we used the latent-class model results from Table 4.4 to conduct a simple, illustrative simulation of consumer acceptance of (or voluntary enrollment in) different UCC programs. Specifically, we can set the attribute levels for hypothetical UCC programs that a utility (or third party) might offer, then use the estimated coefficients to simulate the probability of UCC acceptance within each class of Early Mainstream respondents (which could be interpreted as the percentage of respondents that would enroll in the UCC program). The “baseline” is a UCC program that does not use any renewables (0%), has a 100% guaranteed minimum charge, and does not affect the respondent’s monthly electricity bill. We then simulated respondent support for four additional UCC program scenarios:

1) 20% savings on the electrical bill with 100% GMC
2) 20% savings on the electrical bill with 80% GMC
3) 100% usage of “green” electricity with 100% GMC (no bill savings)
4) 100% usage of “green” electricity with 80% GMC (no bill savings)
These scenarios were selected to illustrate different respondent class priorities. UCC programs designed for financial-savings versus programs designed to support renewable electricity.

Results for these scenarios are presented in Figure 4.7, where overall respondent support for (or enrollment in) a UCC program varies from a low of 49% to a high of 78%. Figure 4.7 depicts support differently for a PHEV-based scenario, and for an EV-based scenario. The PEV design scenarios are based on a PHEV-64km and an EV-120km.

Under a “base” scenario with no incentives, there was clear heterogeneity in the level of acceptance among classes. The simulation suggested that, even without renewable electricity content or bill savings, the 80% of respondents in the Renewable-focused and 71% of the Cost-motivated classes would accept or enroll in a UCC program. Generally, the overall sample was more sensitive to cost incentives than to renewable incentives, where simulation of programs with cost savings garnered 61-70% enrollment while programs with more renewable content garnered only 46-57% enrollment.

Although our baseline estimate appears to show a consecutive order of acceptance rates across respondent classes (i.e. Anti-UCC < Charge-focused < Cost-motivated < Renewable-focused), this does not hold throughout. For example, under UCC program scenario 1, the model simulated higher support amongst the Cost-motivated class relative to all others. Clearly, specific UCC programs are likely to impact different classes in different ways. We also observed that the combined rate of acceptance varies under different scenarios. Of those UCC program designs depicted here, scenario 1 represents the situation with greatest acceptance among the Early Mainstream respondents (78%). Importantly, the 100% GMC played a large role in the acceptance among the Charge-focused class which represented 33% of the sample (the largest class). For example, under the 20% bill subsidy simulation, a reduction of GMC by 20% reduced acceptance among the Charge-focused class by 20 percentage points in the PHEV case and 7 percentage points in the EV case.
Figure 4.7 Estimated rates of UCC enrollment for different latent classes under different program design scenarios. Standard error bars have been calculated using the delta method

4.6. Discussion

There is very little previous research that explores consumer acceptance of UCC programs for PEVs. We noted two related stated-preference studies—one that looked at how the availability of green electricity might impact PEV demand (Axsen et al., 2013), and one that quantified the payment that PEV owners might require to enroll in a V2G program (Parsons et al., 2014). Our present effort blends elements of both studies by assessing consumer valuation of renewable electricity and cost savings in relation to UCC programs for PEVs.

We acknowledge that this is an exploratory study that assessed potential UCC interest and enrollment in a particular context. To focus our study, we restricted this initial exploration to new, light-duty vehicle buyers in Canada that expressed interest in purchasing a PEV—what we call the potential Early Mainstream PEV buyers. Further, we only investigated voluntary enrollment in UCC programs for nightly residential charging. Although nightly charging currently represents the majority of charging among...
PEV owners (US DOE, 2012), we neglect the potential for daytime and non-home charging elsewhere. Further, all stated preference studies are limited by consumer understanding of the subject matter and, since the idea of UCC is not straightforward, we strived to simplify the concept. We view this as an empirical exercise that can be used to assess patterns of consumer interest and preferences for UCC and to infer the potential role of UCC in facilitating the deployment of renewable electricity, as well as potentially reducing grid costs and increasing reliability.

We used a PEV design space exercise (4.4.2) to identify that 36% (530 of 1470) of our total sample could be best characterized as the Early Mainstream PEV buyers - representing consumers that have not yet purchased a PEV, but are most likely to do so in the near term (10 to 15 years). Using this subsample, we assess the potential acceptance of (or enrollment in) some form of UCC program. We discuss these results according to our research objectives (see section 4.2).

### 4.6.1. What are consumer perceptions of utility-controlled charging?

Overall, about two-thirds of Early Mainstream respondents indicate that some form of UCC should be supported by government. Further, the vast majority (96%) would “be okay with having a guaranteed minimum charge” of 90% for one day out of five (with 100% on other days). However, acceptance dwindles to 43% if a 90% guaranteed minimum charge were imposed on a daily basis (five out of five days), while acceptance is reduced to 67% if this guaranteed minimum charge were 50% on one day in five. Clearly, some consumers are willing to have some degree of intervention imposed on their charge availability, but this varies greatly by scenario and by respondent—as also indicated by Parsons et al. (2014).

As indicated by Axsen and Kurani (2013), some potential PEV buyers are interested in renewable electricity. Among our Early Mainstream sample, solar, wind and small hydro were the most commonly supported sources of electricity. These results largely align with those of Borchers et al., (2007) Greenberg (2009) and Cicia et al., (2012) who also found that solar and wind were typically preferred by electricity consumers.
Minorities of Early Mainstream respondents were concerned about privacy (24%) and “loss of control” (39%) in relation to a UCC program. These concerns over privacy and control are likely to be a consequence of consumer understanding, consumer trust towards UCC programs, and trust towards the electric utility. Other research finds that consumers often express a lack of understanding regarding how renewable sources of energy are generated and how electricity is distributed throughout a grid system (Salmela and Varho, 2006). We hypothesize that providing clear and accessible information about UCC may help increase understanding and reduce levels of concern. Further, electric utilities may want to test their customers’ reactions to different framing of a UCC program according to bill savings, renewable content, and guaranteed charge—as well as the perception effects of opt-in, opt-out or mandatory UCC programs. Electric utilities that have experienced trust issues with customers might consider use of a neutral third party for the implementation of a UCC program.

To quantify consumer tradeoffs in preferences for these different attributes, we estimated discrete choice models. We first estimated a simple multinomial logit model, which represents the aggregated preferences of the entire sample. As expected, the model estimated positive, significant coefficients for percentage of renewable electricity and guaranteed minimum charge (GMC), and a negative, significant coefficient for monthly bill. Using these coefficient estimates, we calculated an average willingness to pay of $16/year for a 10% increase in renewable electricity—which is lower than findings of Borchers et al., (2007) who estimated a mean WTP of ~$100/year for a mandatory program supplying 10% green electricity amongst US households, though this study does not consider PEVs.

Increasing guaranteed minimum charge by 10% was valued at $47/year for potential EV buyers, and $95/year for potential PHEV buyers. Similarly, Parson et al. (2013) found that a 28% decrease was valued at about $115/year (when annualized). Interestingly, on average, guaranteed minimum charge was valued more highly in PHEVs than in EVs, whereas we expected the opposite may be true. One explanation for this result could be that PHEV owners would place a greater value on their more limited range (which was 16 to 64km), whereas the EV scenario designs had 240km of range. Another explanation may be that respondent preferences are unstable when
considering a novel product attribute (PEV range) that the vast majority have no direct experience with.

4.6.2. **How might consumer segments differ in preferences for UCC?**

To further understand the heterogeneity preference and motives among our respondents, we estimated a latent class discrete choice model. We identify the following four classes (or segments) of the sample:

1) **Renewable-focused (19% of the Early Mainstream sample):** these respondents are likely to have strong positive preferences for increasing renewables in their UCC program. Members of this class are willing to pay $98/year to increase their supply of renewables by 10%. They are more likely to have higher than average biospheric values, and be less concerned with the privacy implications of UCC than other classes.

2) **Cost-motivated (27% of the Early Mainstream sample):** these respondents are the most sensitive to cost, expressed the least willingness to for increases in GMC ($49/year for a 10km increase in PHEV GMC), and also expressed a relatively low valuation of renewables (at $6/year for a 10% increase in renewables). These respondents are more likely to be technologically oriented and less altruistic than members of the other classes.

3) **Charge-focused (33%):** respondents in this class place a relatively high value on GMC, with a WTP of $317/year for a 10km increase in PHEV GMC. They place no significant value on the environmental benefits of the UCC program.

4) **Anti-UCC (21%):** respondents in this class have a negative preference for adopting UCC and using renewables. These respondents are more likely to be older and less likely to have a bachelor's degree than members of the other classes.

Generally, preference for specific sources of green electricity was not statistically significant in the choice models. Rather, concerns over cost, GMC and the amount of renewable electricity were consistently significant across classes and models. Our overall findings suggest that the specific source of renewables is not a necessary focus for the policy maker or utility when presenting UCC programs to consumers—whereas having some degree of support of renewable electricity (of any type) is attractive to some consumer segments.
The socio-demographic and attitudinal characteristics of pro-UCC consumers were largely consistent with the literature on related goods such as PEVs and renewable sources of electricity. Those that were more biospheric (Clark et al., 2003), younger (Dagsvik et al., 2002, Hidrue et al., 2011) and more highly educated (Bunch et al., 1993, Ewing and Sarigöllü, 2000) were more likely to adopt UCC. We did not identify any significant relationship between respondent income and acceptance of UCC and we did not find significant differences in respondent preferences when the UCC choice experiment was framed according to their own PEV design versus a pure EV with 240km of range—other than slightly different valuations of GMC as reported above.

4.6.3. How might different UCC program designs affect consumer enrollment?

Previous research on utility controlled charging and V2G programs tends to assume that all PEV owners are willing to (or are forced to) enroll in the program, e.g. Weis et al., (2014). As a final step in this study, we used the estimated latent class choice model to simulate overall acceptance of different UCC programs across the sample. Our estimates of respondent enrollment varied considerably by class. It is here that we can directly compare the tradeoffs potential PEV buyers might make between two aspects of UCC that they may value: green electricity (as indicated by Axsen and Kurani, 2013), and cost savings (as indicated by Parsons et al., (2014)). For brevity, we discuss only the PHEV-design case since results from the EV case are similar (Figure 4.7).

Overall in the PHEV-64km design case, simulated enrollment varied from 49-71% by program scenario. Across UCC program scenarios, the Anti-UCC class had a relatively low probability of enrollment (2 to 9%). The Renewable-focused class had a consistently high enrollment rate (79 to 94%), even with a UCC program that includes 0% renewable electricity—showing that this class is largely in favor of UCC in general. The Charge-focused class was fairly sensitive to UCC program designs, ranging from a low of 26% for scenario 4, to a high of 80% for scenario 1. The Cost-motivated class also varied in program enrollment across scenarios, ranging from a low of 71% in the baseline scenario to a high of 100% in scenario 1.
For the entire sample (including all classes), 53% of the potential early mainstream PEV sample are simulated to be open to enrolling in a UCC program in a baseline scenario where the program provides no additional renewable electricity, no cost savings, and guarantees a 100% state of charge each morning. Simulated consumer enrollment was highest in scenario 1 (20% bill savings 100% GMC) at 71%, and lowest in scenario 4 (100% renewables, 80% GMC, no bill savings) at 49%. Overall UCC program enrollment appears to be highly influenced by cost savings—seemingly even more than the percentage of renewables. For example, reducing the electricity bill from 100% to 80% increases overall enrollment by 18 percentage points, while increasing the percentage of renewables from the status quo to 100% increases enrollment by only 6 percentage points. This pattern may be explained by the tendency for the renewable-focused class to be in favor of green electricity (i.e. having a high, positive renewable electricity coefficient) and UCC programs in general (i.e. having a high, positive alternative specific constant for UCC). Thus, simulated UCC enrollment is already high in this class in the baseline (no renewables) scenario so increasing the percentage of renewables has little influence on overall simulated enrollment. Potentially, some respondents may have perceived the UCC program as efficient or “green” in general (say, by contributing to overall grid efficiency or conservation). While it still seems wise for an electric utility to communicate the environmental benefits of a UCC program, we find evidence that the provision of an electricity bill subsidy might be a particularly powerful means of incenting consumer enrollment.

We also observe that the guaranteed minimum charge (GMC) attribute had a strong effect on simulated UCC enrollment overall, and in the Charge-focused class in particular. GMC is our chosen metric for potential UCC inconvenience, but can also serve as a proxy for an electrical utility’s capacity to have increased flexibility and control over the timing of PEV charging. Although providing a GMC of 100% minimizes the flexibility available to the utility, it still allows the utility to control the timing of PEV charging, and could still facilitate the uptake of renewables. Consequently, we suggest that initial deployment of UCC programs ought to consider the guarantee of 100% PEV charge at the time of day agreed upon with customers.
The Anti-UCC class demonstrates strong and consistent opposition to program enrollment. In this exploratory study, we cannot be sure of the primary concerns of this class, though respondents in this class do indicate stronger concerns regarding privacy than the Renewable-focused and Cost-motivated classes. These respondents may also have lower levels of trust in their electric utility—though we did not directly assess this.

In summary, our exploratory empirical research and UCC program enrollment simulation exercise suggests that without incentives (neither cost savings nor direct support of renewable electricity), around 53% of the potential Early Mainstream PEV buyers are likely to be open to UCC. To put this number in perspective, given that 36% (n=530 / n=1470) of our total sample is identified as the “potential early mainstream” PEV market, about 22% of our total sample of new vehicle buying households demonstrated the potential to enroll in a UCC program.

4.7. Conclusion and policy implications

For this research, we defined utility controlled charging (UCC) as any system where an electric utility somehow controls the charging of plug-in electric vehicles (PEVs). Through UCC, utilities have the potential to facilitate the efficient deployment of intermittent renewable sources of electricity, improve load management, subsidize PEV operation, and reduce electricity system costs. In this research we explore the potential acceptance of UCC among household buyers of light-duty passenger vehicles. Future research ought to explore the additional cases of vehicle fleets and medium- and heavy-duty vehicles.

Previous research on UCC charging programs (including proposed Vehicle-to-Grid systems which would involve two-way electricity flow between the vehicle and utility) typically focuses on technical feasibility and tends to assume that all PEV owners would be willing to (or would be forced to) enroll in a program, which may lead to unrealistic estimates regarding the acceptability or eventual scale of UCC. The goal of our present study is to elicit consumer preference and in turn anticipate acceptance of UCC and explore how consumers perceive the notion of UCC in general. We used the case of nightly PEV charging to frame the stated preference survey exercises because
this represents the majority of charging amongst PEV owners (US DOE, 2012). Future research should also explore UCC perceptions for daytime and non-home charging to fill in gaps left by our study.

We used a web-based survey to explore consumer acceptance of UCC. Using this survey, we identified the 36% of the total sample of new vehicle buying households that are most likely to be part of the “early mainstream” market for PEVs. Overall, 53% of these early mainstream respondents stated that they would voluntarily enroll in a UCC program. Some respondents expressed concerns with privacy (24%) and loss of control (38%) associated with UCC programs. Through a latent class discrete choice model, we found that different segments of respondents are motivated to adopt UCC through different incentives (environmental versus financial benefits), which may be used to increase acceptance of UCC. Across the sample of potential early mainstream PEV buyers, cost incentives (reduced electricity bill) were more effective at incentivizing consumer enrollment in a UCC program than environmental benefits (increased use of renewable electricity), though environmental incentives were attractive for some segments of respondents.

Although our study is exploratory, we believe the results hold important implications for utilities and policymakers. We demonstrate that there could be widespread acceptance of a voluntary UCC program among early market PEV buyers—even in the absence of offering financial benefits and without framing UCC according to environmental benefits. Careful design of a UCC program could further increase enrollment, most notably by providing cost subsidies to the PEV owners. Enrollment may also be boosted if the electric utility can clearly frame UCC as a means of supporting the deployment of intermittent, renewable electricity sources, and thus as a means of providing environmental benefits. Further, although many consumers may accept some level of charging “inconvenience” – such as occasionally being provided less than 100% of a full charge on a given morning—it seems advisable for the utility to provide a 100% state of charge if possible. To maximize the acceptability of UCC programs, utilities will also want to maintain and foster a high degree of trust with consumers, in order to alleviate concerns about loss of control, and potential or perceived threats to consumer privacy. One strategy might be for the utility to administer a UCC program through a
more trusted third-party. Of course, given the high degree of consumer heterogeneity that we demonstrate in our latent class analysis, a given utility ought to employ market research in order to optimize the uptake of the UCC program for the consumer segments within their particular jurisdiction.

Our results also hold implications for climate policy more generally. Other studies have established the potential GHG reductions benefits of controlling the charging of PEVs. We further demonstrate the market potential for UCC programs. To realize widespread GHG reductions from PEVs and renewables, policymakers will need to coordinate the strategies and policies implemented in both the transportation and electricity sectors. For example, standards enacted in each sector may be interdependent, such as a renewable portfolio standard for electricity and a zero-emissions vehicle standard. Actively developing UCC programs could create clear linkages between the feasibility of the two policies—having PEV buyers enroll in UCC programs could facilitate the uptake of renewables, and the planned deployment of renewables could increase the desirability of PEVs among some consumer segments. The design and success of UCC programs would also impact policies that follow a “life-cycle” method of GHG accounting, such as California’s low-carbon fuel standard. For example, if a UCC program is successfully increasing the amount of renewable electricity being used to charge PEVs in a given jurisdiction, then electricity should be given credit as a transportation fuel with a relatively low carbon intensity. Such an accounting method may also provide incentives for other fuel providers regulated by the low carbon standard to help incentivize UCC programs (if that is a lower cost means of policy compliance).

4.8. Acknowledgements

This research has been funded by: Social Sciences and Humanities Research Council of Canada, the BC Ministry of Energy and Mines, BC Hydro and the Pacific Institute of Climate Solutions. We thank George Kamiya and Paulus Mau for their thorough contributions, along with Jeff Rambharack, Steven Groves and all who helped with survey development. We also thank Ryan Trenholm for assistance in applying the delta method.
4.9. References


Chapter 5. Is awareness of public charging associated with consumer interest in plug-in electric vehicles?²

5.1. Abstract

Policymakers often seek to increase the visibility of plug-in electric vehicle (PEV) chargers in public locations in an effort to build familiarity and interest in PEVs. However, it is not clear if the visibility of public charging stations actually has an impact on PEV demand. The purposes of the present study are to (1) assess the current levels of visibility for public PEV charging infrastructure within Canada and (2) identify whether or not a statistically significant relationship exists between consumer awareness of public charging infrastructure and interest in purchasing a PEV. We use data collected from a sample of 1739 Canadian new-vehicle buyers in 2013. About 18% of Canadian respondents have seen at least one public charger, while the proportion is highest in British Columbia (31%). We find a significant bivariate relationship between public charger awareness and PEV interest. However, when controlling for multiple explanatory variables in regression analyses, the relationship is weak or non-existent. While perceived existence of at least one charger exhibits no significant relationship with PEV interest, perceived existence of multiple chargers can have a weak but significant relationship. Thus, public charger awareness is not a strong predictor of PEV interest; other variables are more important, such as the availability of level 1 (110/120-volt) charging at home.

² This Chapter was published as: Joseph Bailey, Amy Miele, Jonn Axsen, Is awareness of public charging associated with consumer interest in plug-in electric vehicles? Transportation Research Part D: Transport and Environment, Volume 36, May 2015, Pages 1-9, ISSN 1361-9209, http://dx.doi.org/10.1016/j.trd.2015.02.001.
5.2. Introduction

Policymakers are increasingly promoting the adoption of plug-in electric vehicles (PEVs) to help combat the global rise in CO$_2$ emissions. Despite the potential environmental benefits of PEVs, several structural, social, and cultural challenges may need to be overcome before PEVs can be widely adopted (Egbue and Long, 2012). One of these challenges is thought to be the limited availability of non-home PEV charging infrastructure, i.e. chargers at work, public and commercial locations. In reality, however, the relationship between the availability of non-home charging infrastructure and the uptake of PEVs is not currently well understood.

Using consumer data from a survey of Canadian new vehicle buyers (the Canadian Plug-in Electric Vehicle Survey, CPEVS 2013) we assess consumer awareness of non-home vehicle charging locations and seek to identify if this awareness is associated with interest in purchasing PEVs. Specifically, our main objectives are to (1) assess the current levels of visibility for public PEV charging infrastructure within Canada and (2) identify if there is a statistically significant relationship between awareness of public charging infrastructure and consumer interest in purchasing a PEV. We introduce and explore the importance of two unique concepts of charger awareness: perceived charger existence as having seen a public charger in at least one location type, and perceived charger abundance as having seen PEV chargers in at least two location types, e.g. at a workplace and in a mall. For convenience, we refer to “public charging” as PEV chargers at any location other than the consumer’s home, including workplace and commercial charging locations. Our definition of PEVs includes pure electric vehicles (EVs), and plug-in hybrid electric vehicles (PHEVs) that can be powered by grid electricity and/or gasoline.

5.3. Background

Increasing the availability of PEV charging (home and public) is associated with two main social benefits. The first is to support the use of PEVs among current owners, allowing them to use their PEVs more extensively and ideally offsetting more gasoline-
powered kilometres with electric-powered kilometres. The second benefit is to help promote PEV ownership in the first place. The idea is that widespread availability of PEV chargers will increase general awareness of PEV technology, increase perceptions of PEV functionality, and potentially allow for the development of green, innovative, and progressive “cultural branding” (Community Energy Association, 2013). It is this second benefit that we focus on here—the potential of public chargers to increase the uptake of PEVs by stimulating demand.

There is some evidence that the uptake of PEVs may depend on the availability of home charging infrastructure. Amongst PEV owners in the US in 2012, more than 80% of vehicle charging occurred at home (Smart, 2013). Home recharging can also be an important factor for those considering potential PEV ownership. A survey of 508 new vehicle buying households in San Diego, California in 2011 found that interest in PHEV and EV designs was much higher among respondents whom had identified recharge potential at their home (Axsen and Kurani, 2013). Further, home charging availability is already fairly widespread. One US survey found that over 50% of new-vehicle buying households are likely to already have Level 1 (110/120-volt) PEV charging access within 25 feet of where they park their vehicle at home, while just under one-third of households in one U.S. city (San Diego) have access to Level 2 charging (Axsen and Kurani, 2012). Although Level 1 charging may not be optimal for the operation of larger battery PEVs, it is likely to be functional for many PHEV designs.

Evidence supporting the necessity of public charging access in stimulating consumer uptake is less common and results are generally inconsistent. One well-known study was conducted by the Tokyo Electric Power Company (TEPCO), which studied the driving and charging habits of PEV users in Japan both before and after the addition of a public charger. TEPCO found that, although PEV drivers made very little use of the new public charging facility following its implementation, the cumulative distance travelled by PEV users increased more than sevenfold (Bakker, 2011). TEPCO also found that drivers returned from their trips with significantly less stored battery power than they had previously (Anegawa, 2010 and Bakker, 2011). Both results suggest that the awareness of public charging infrastructure could give PEV drivers
confidence to travel further on electric power, thus positively impacting those who feel limited by the range of their PEVs. This study is very limited, however, in that it only involved a small sample of PEV owners and operators. The study did not investigate changes in consumer interest, perception, or acceptance of the technology among non-PEV users.

Over the past decade, a variety of surveys have attempted to measure consumer valuation of recharge infrastructure as one of several PEV-related attributes. In particular, research with stated preference choice models suggests that consumers are willing to pay more for PEVs if public charging is widely available (Batley et al., 2004 and Hackbarth and Madlener, 2013). Amongst a nationwide panel of 711 German new car buyers, willingness to pay values for a one percent expansion of refueling infrastructure have been estimated to range from $65-$134 CAD (Hackbarth and Madlener, 2013). In contrast, UK households have been estimated to value a 10% increase in fuel availability at $1960 CAD - slightly higher than the estimates in Germany (Batley et al., 2004). Other stated preference studies simulate the impacts of public charging availability on interest in PEVs. Using a panel of 598 German potential car buyers, Achtnicht et al. (2012) estimate that increasing charger availability from 10% to 33% could increase demand for EVs by up to 50%. Further, when the authors used respondent data to simulate a tenfold increase in charger availability, demand for EVs increased roughly four times with estimated market share increasing from 2.2% to 8.9%. In another European study of 1903 car owners, Hoen and Koetsse (2014) demonstrate that increasing recharge availability increases willingness to pay for a new vehicle by $165 CAD for each minute of avoided detour time—in other words, reducing time in search of charging infrastructure increases individual utility and the likelihood that someone may purchase a PEV. One drawback of the stated preference studies cited here is that they rely on hypothetical scenarios of charger availability, such as asking the respondent to imagine a world where 33% of gasoline stations also had PEV chargers (Achtnicht et al., 2012).
More closely aligned with our present research are two studies that used a large sample size of vehicle buyers, and also included a measure of survey respondents’ awareness of actual public PEV chargers to look for a statistical association with PEV interest. Both studies use data drawn from the same 2011 nationwide survey implemented with a sample of 2030 US drivers. One study found that 12% of respondents recall seeing public charging infrastructure in their community and that these respondents with charger awareness were 9% more likely to be interested in PEVs when controlling for a variety of factors (Carley et al., 2013). However, the second study used the same survey dataset and found that the awareness of public chargers was not a significant predictor of interest when considering interest in PHEVs and EVs separately (2013). Clearly, this association is still not well understood.

To further explore the relationship between awareness of public chargers and interest in PEVs, we presently use data from a large sample survey in Canada (CPEVS, 2013). Our study is unique in that we explore the role of two different types of awareness: perceived charger existence and perceived charger abundance. We defined perceived existence as occurring when a consumer has seen a public PEV charger in at least one location where they are likely to park. We define perceived abundance as occurring when the consumer has seen PEV chargers in at least two different types of locations, e.g. seeing a public charger at a gym and seeing a public charger at a mall. Our present study is also unique in exploring the importance of charger awareness in the Canadian context.

5.4. Methods

5.4.1. Data Collection

We implemented the Canadian Plug-In Electric Vehicle Survey (CPEVS 2013) between April and October of 2013. The target population was new vehicle buyers in Canada, which we defined as households who have purchased a new vehicle in the past five years and use a vehicle regularly. We contracted a market research company to recruit a representative sample of new vehicle buying households. To avoid preferential
selection of individuals interested in PEVs we framed the survey as a “household vehicle survey” and did not discuss PEVs until later in the survey.

We intentionally oversampled respondents from the Province of British Columbia (BC) where a Clean Energy Vehicle Program was initiated in 2011. The goal of the program was to provide residents of BC with more affordable clean energy transportation solutions. Specifically, the program included funding for: point-of-sale incentives for PEVs, residential rebates for PEV charging equipment and a Community Charging Infrastructure Deployment Fund. The deployment fund targeted the placement of up to 570 Level 2 (220/240-V) public charging stations across BC with the greatest emphasis in the Metro-Vancouver region—the most densely populated urban region of the province. Since the implementation of the program, the number of public chargers in BC has dramatically increased, and by September 2013, at least 456 chargers had been installed (Fraser Basin Council, 2014).

The CPEVS survey design was web-based and included three parts:

1) Part 1 elicited personal respondent details including awareness of PEVs and other energy-using technologies, awareness of and access to PEV recharge infrastructure, details of the household’s vehicle fleet (including number of and model types) and socio-demographic information.

2) Part 2 informed respondents about PEV terminology and asked respondents to complete an assessment of PEV charging potential at their home. Respondents that had a reliable and consistent parking location at home were asked to locate outlets (110/120 V and 220/240 V) and electrical panels, noting their proximity to their vehicle’s typical parking location, as well as any barriers (e.g. walls) that could restrict access.

3) Part 3 explored respondents’ interest in buying a PEV and how they may recharge it under various conditions.

A detailed account of the full 2013 CPEVS methodology, including the recharge questionnaire and findings regarding home recharge availability is provided in Axsen et al. (2013).

We used data from all three parts of the survey to address our present research questions. Of particular relevance for this study was the concept of public charger
visibility elicited in Part 1. This section first described and provided examples of what public charging infrastructure can look like and then asked if the respondent had “seen any electric vehicle recharge stations at the following parking spots or spaces you use?” We provided seven broad categories with checkbox responses including: Grocery Stores, Retail Stores, Shopping Malls, Gyms or Recreation Centres, Religious or Spiritual Centres, Workplace parking lots, as well as “Other” (for which respondents provided a custom response). Because we focus on the importance of awareness of chargers that the respondent may actually use, the few responses that specified sightings at locations other than these categories were removed from our analysis (e.g. sightings in other countries, on the internet, outside of the respondent’s province, etc.).

We assessed interest in adopting a PEV using data from Part 3 of the survey. We asked respondents to indicate their PEV interest using PEV “design exercises”. From these design exercises, respondents selected a vehicle type that they would be most willing to purchase under particular price conditions. In contrast to discrete choice models, these design space exercises are consistent with theories of constructed preferences that view consumer preferences as outcomes of, not inputs to, decision contexts and processes (Bettman et al., 1998). Such design exercises and games have been pioneered for use in transportation behaviour research by Lee-Gosselin, 1990 and Kurani et al., 1994, and Turrentine and Kurani (1998) and more recently applied to market research on PHEVs and PEVs (Axsen and Kurani, 2009 and Axsen and Kurani, 2013).

The PEV design exercises were completed by every respondent and so all individuals had the option of completing a PEV design. In the design exercise, each respondent first selected a currently available “base” vehicle that represented the conventional (gasoline) vehicle they would most likely buy next (if they could only buy a conventional vehicle). Respondents provided the make and model, body type, price, and fuel economy of this vehicle. Subsequently, the design exercises presented the respondent with four vehicle types: (i) their base conventional vehicle, (ii) a hybrid version (with 33% improved fuel economy over the base), (iii) a PHEV version that could be powered with electricity for the first 16, 32, or 64 kilometres and then a gasoline
engine for the remaining kilometers (achieving the same 33% increase in fuel economy until the battery is recharged), and (iv) an EV version powered only by electricity for 80, 120, 160, 200, or 240 kilometres of range.

The incremental prices for each vehicle type and electric driving range differed by vehicle body size (Table 5.1). Respondents completed “higher price” and “lower price” scenarios for the vehicle design exercises. The higher-price scenario was meant to approximate the modern-day cost of these vehicle technologies at the time of the survey, and the lower-price situation represented subsidized vehicle costs. If a respondent selected a PEV design in the lower price design game—either a PHEV or “pure” EV design—we considered the respondent to be interested in purchasing a PEV. In other words, this is our present measure of “PEV interest.” Respondents did not have to design a PEV if they did not choose to—they could have stayed with the conventional vehicle or selected a hybrid version. For discussion of the derivation and limitations of the incremental prices see Axsen and Kurani (2010).

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Higher price scenario</th>
<th>Lower price scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compact</td>
<td>Sedan</td>
</tr>
<tr>
<td>HEV</td>
<td>$1380</td>
<td>$1740</td>
</tr>
<tr>
<td>PHEV-16</td>
<td>$2230</td>
<td>$2720</td>
</tr>
<tr>
<td>PHEV-32</td>
<td>$2680</td>
<td>$3230</td>
</tr>
<tr>
<td>PHEV-64</td>
<td>$3560</td>
<td>$4260</td>
</tr>
<tr>
<td>EV-80</td>
<td>$6500</td>
<td>$7880</td>
</tr>
<tr>
<td>EV-120</td>
<td>$8940</td>
<td>$10690</td>
</tr>
<tr>
<td>EV-160</td>
<td>$11380</td>
<td>$13500</td>
</tr>
<tr>
<td>EV-200</td>
<td>$13820</td>
<td>$16310</td>
</tr>
<tr>
<td>EV-240</td>
<td>$16260</td>
<td>$19130</td>
</tr>
</tbody>
</table>

Table 5.1 Different design configurations available in the design space exercise and their associated incremental prices.
5.4.2. Data analysis

To achieve our first research objective, we portray respondents’ awareness of public chargers and compare this awareness by region, namely: Metro-Vancouver (with a relatively strong PEV infrastructure initiative), the Province of BC, and the rest of Canada; as well as urban versus rural respondents across the full sample.

To investigate the relationship between charger awareness and PEV interest we began with a bivariate test using Chi-Squared tests of association. We constructed two categories representing awareness of public chargers: the respondent has “perceived charger existence” if they state that they are aware of a public charger in at least one location type, and the respondent has “perceived charger abundance” if they are aware of a public charger in at least two location types. We conducted Chi-Square tests with both variables.

We subsequently developed our investigation with binary logistic regression to control for socio-demographics and variables relating to respondent readiness for a PEV, and see if the relationships observed in the Chi-Squared tests remained when controlling for other relevant variables. Socio-demographic variables included income, age, education, household size, and geographic location. PEV-readiness variables included home charger availability because this has previously been shown to be influential in PEV preferences (Axsen and Kurani, 2013)—specifically if the respondent can park their vehicle within 25 feet of an electrical outlet (110/120-volt or Level 1), and if the respondent’s home recharge assessment questionnaire indicated that it would be feasible to install a Level 2 charger (220/240-volt) at home.

We believe it is important that we control for respondents having prior interest in PEVs. Individuals with prior interest may be more likely to notice and remember PEV infrastructure. In other words, any significant bivariate relationship we observe between charger awareness and PEV interest might be spurious if pre-existing PEV interest is the true explanation. We thus deemed it important to add an explanatory variable to control for “pre-existing PEV interest” —that is, PEV interest that existed prior to the respondent completing the survey. We did not directly ask this question on the survey, so we used
two different questions that we believe serve as proxies for pre-existing interest. Our first proxy is a dummy variable indicating if the respondent stated that they had previously researched at least one of the following specific vehicle models: a Chevrolet Volt or a Nissan Leaf. Our second, alternate proxy is a dummy variable indicating if the respondent stated that they were “familiar” or “highly familiar” with either of these vehicle models. The survey questions specified these two relatively popular PEV models rather than refer to “electric vehicles” or “plug-in hybrid vehicles” more generally—we believe that reference to specific models would produce more reliable results.

5.5. Results

5.5.1. Sample

In total, of the 4111 individuals that initiated the survey, 1739 respondents (42% of the recruited sample) completed all three parts of the survey with valid responses. We did not weight or adjust our final sample, as the realized sample appears to be representative of our target population of new vehicle buying households in Canada. The recruited sample (Table 5.2) tended to be slightly older than those in the general Canadian census and have higher levels of education and income. Respondents were more likely to own their home (as opposed to rent) and more likely to live in a single-family detached house (rather than in townhouses, low-rise and/or high-rise apartment complexes) compared to the Canadian census. These differences are typical of new-vehicle buying households when compared to the general public (Axsen and Kurani, 2010, Busse et al., 2013 and Harris-Decima, 2013).

<table>
<thead>
<tr>
<th>Table 5.2</th>
<th>Demographic summary of the sample and comparison with the Canadian census</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Survey(^a) (n = 1739)</td>
</tr>
<tr>
<td>Household Size</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>13.1%</td>
</tr>
<tr>
<td>2</td>
<td>40.0%</td>
</tr>
<tr>
<td>Age of person filling out the survey</td>
<td>Percent</td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>15-24</td>
<td>7.0%</td>
</tr>
<tr>
<td>25-34</td>
<td>23.0%</td>
</tr>
<tr>
<td>35-44</td>
<td>18.2%</td>
</tr>
<tr>
<td>45-54</td>
<td>19.5%</td>
</tr>
<tr>
<td>55-64</td>
<td>19.2%</td>
</tr>
<tr>
<td>65+</td>
<td>13.1%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Work Status of person filling out the survey</th>
<th>Percent</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Employed</td>
<td>60.9%</td>
<td>62.3%</td>
</tr>
<tr>
<td>Retired</td>
<td>21.0%</td>
<td>33.1%b</td>
</tr>
<tr>
<td>Student</td>
<td>4.0%</td>
<td>1.4%</td>
</tr>
<tr>
<td>Family caregiver</td>
<td>6.8%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Presently unemployed</td>
<td>5.6%</td>
<td>4.4%</td>
</tr>
<tr>
<td>Not applicable</td>
<td>1.8%</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Highest level of education completed of person filling out the survey</th>
<th>Percent</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than high school</td>
<td>1.8%</td>
<td>23.8%</td>
</tr>
<tr>
<td>High school certificate or equivalent</td>
<td>16.6%</td>
<td>25.5%</td>
</tr>
<tr>
<td>Apprenticeship, trades certificate or diploma</td>
<td>6.2%</td>
<td>10.9%</td>
</tr>
<tr>
<td>College, CEGEP, or other non-univ. diploma</td>
<td>24.3%</td>
<td>17.3%</td>
</tr>
<tr>
<td>Some university</td>
<td>12.5%</td>
<td>4.4%</td>
</tr>
<tr>
<td>University degree (Bachelor)</td>
<td>26.2%</td>
<td>13.5%</td>
</tr>
<tr>
<td>Graduate or professional degree</td>
<td>12.4%</td>
<td>4.6%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Household income (pre-tax)</th>
<th>Percent</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than $40,000</td>
<td>14.8%</td>
<td>24.9%</td>
</tr>
<tr>
<td>$40,000 to $59,999</td>
<td>20.5%</td>
<td>19.3%</td>
</tr>
<tr>
<td>$60,000 to $89,999</td>
<td>27.8%</td>
<td>24.3%</td>
</tr>
<tr>
<td>$90,000 to $124,999</td>
<td>24.6%</td>
<td>16.8%</td>
</tr>
<tr>
<td>Greater than $125,000</td>
<td>12.2%</td>
<td>14.7%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Residence ownership</th>
<th>Percent</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Own</td>
<td>77.9%</td>
<td>68.7%</td>
</tr>
<tr>
<td>Rent</td>
<td>22.1%</td>
<td>31.3%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Residence type</th>
<th></th>
<th></th>
</tr>
</thead>
</table>
### Awareness of public charging infrastructure

A total of 18% of respondents in the Canada-wide sample reported seeing at least one public charger – which we defined as seeing a public charger in at least one of the specified location categories, i.e. shopping malls, grocery stores, retail stores, gyms or recreation centres, religious or spiritual centres, workplace parking lots, or other. Only five percent of respondents had reported perceived public charger abundance, i.e. that they had seen chargers in at least two of the location categories. Less than two percent of respondents reported seeing chargers in three or more of the specified categories.

Knowledge of public charging infrastructure varied both geographically and by charger location type. Overall public charger awareness (having seen at least one or more chargers) was higher among respondents in the BC sample (31%) than the rest of Canada sample (13%). The Metro-Vancouver sub-sample reported the highest level of awareness (36%). We also assessed consumer awareness of charging stations for urban versus rural locations (Figure 5.1). Perceived charger existence (having seen a charger in at least one location type) was significantly higher \( p < 0.001 \) among residents of urban areas (23%) relative to residents of rural areas (12%). Similarly, perceived abundance (having seen PEV chargers in at least two different locations) was higher among residents of urban areas, though this finding was not statistically significant at a 90% confidence level.
Figure 5.1  Charging station awareness: urban (n=1002) vs. rural (n=737).
Perceived existence refers to those that have seen at least one public charger. Perceived abundance refers to knowledge of PEV chargers in at least two or more different locations. ***significant at the 99% level.

Awareness also varied by types of charger location. All sub-samples reported the highest awareness of public chargers at shopping malls (Figure 5.2). Seven percent of the total sample reported seeing PEV charging infrastructure at a mall and over a third of respondents who had seen one public charging station were aware of infrastructure at a mall. Amongst the Canada wide sample, retail stores and grocery stores were the next most commonly sighted charging location types, respectively.
To investigate our second research objective, we first identify respondents that state interest in purchasing a PEV. According to the PEV design exercise described in Section 5.4.1, 36% of respondents expressed interest in purchasing a PEV (Figure 5.3) with PHEV designs (32%) being preferred to EV designs (4%).
Figure 5.3  Respondent vehicle designs (n=1739).

According to our bivariate analysis, the level of PEV interest is associated with awareness of public chargers at a 99% confidence level. Figure 5.4 compares stated PEV interest among respondents with different levels of charger awareness. About 43% of respondents with perceived public charger existence stated PEV interest, compared to 35% of those with no public charger awareness. However, this bivariate analysis does not control for other potentially important explanatory variables.
5.5.3. Regression analysis of PEV interest

To further explore the relationship between consumer interest in PEVs and awareness of charging locations we performed binary logistic regression analysis, allowing us to control for other explanatory variables. As noted in Section 5.4.2 there are reasons why the observed relationship between charger awareness and PEV interest might be spurious. For example, respondents with pre-existing PEV interest might be more likely to have become aware of public chargers, and more likely to have stated PEV interest in the survey—where the observed statistical association is not actually causal. To test for this particular pattern, we attempted to control for “pre-existing PEV interest” with two different explanatory variables: prior research into one of two specific PEV models and stated familiarity with either of these PEV models. We also controlled for several demographic variables, including age, income and education. We estimated the five regression models shown in Table 5.3:
(i) with charger awareness variables (perceived existence and abundance) only,

(ii) with all socio-demographic variables and “PEV research” as the proxy variable for pre-existing PEV interest,

(iii) a reduced version of model (ii).

(iv) with all socio-demographic variables and “PEV familiarity” as a proxy variable for pre-existing PEV interest, and

(v) a reduced version of the model (iv).

Table 5.3  Regression models summarizing influence of PEV readiness and socio-demographics on interest in PEVs

<table>
<thead>
<tr>
<th>Public charger awareness variables only (i)</th>
<th><em>PEV research</em> as proxy</th>
<th>Full (ii)</th>
<th>Reduced (iii)</th>
<th><em>PEV familiarity</em> as proxy</th>
<th>Full (iv)</th>
<th>Reduced (v)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PEV Readiness</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perceives public charger “existence”</td>
<td>0.180</td>
<td>0.004</td>
<td></td>
<td>-0.076</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perceives public charger “abundance”</td>
<td>0.700 ***</td>
<td>0.454**</td>
<td>0.488**</td>
<td>0.311</td>
<td>0.349</td>
<td></td>
</tr>
<tr>
<td>“Has researched” a Volt or Leaf (or both)</td>
<td></td>
<td>0.542***</td>
<td>0.567***</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>“Familiar with” a Volt or Leaf (or both)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Has Level 1 (110/120-volt) access at home</td>
<td>0.807***</td>
<td>0.857***</td>
<td></td>
<td>0.792***</td>
<td>0.825***</td>
<td></td>
</tr>
<tr>
<td>Has Level 2 (220/240-volt) potential at home</td>
<td>0.156</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Socio-Demographics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resident of British Columbia (Base = other)</td>
<td>0.373***</td>
<td>0.359***</td>
<td></td>
<td>0.220**</td>
<td>0.204</td>
<td></td>
</tr>
<tr>
<td>Resident of urban location (Base = other)</td>
<td></td>
<td>-0.041</td>
<td></td>
<td>-0.043</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bachelor’s degree (Base = less than Bachelor’s)</td>
<td></td>
<td>0.173</td>
<td></td>
<td>0.200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graduate Degree (Base = less than Bachelor’s)</td>
<td></td>
<td>0.402**</td>
<td>0.333**</td>
<td>0.439**</td>
<td>0.352*</td>
<td></td>
</tr>
<tr>
<td>Income $50-99k/yr (Base = &lt; $50k/yr)</td>
<td></td>
<td>-0.038</td>
<td></td>
<td>0.019</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Income $100-149k/yr (Base = &lt; $50k/yr)</td>
<td></td>
<td>-0.079</td>
<td></td>
<td>-0.010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Income &gt;$149k/yr (Base = &lt; $50k/yr)</td>
<td></td>
<td>-0.034</td>
<td></td>
<td>-0.099</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In our multiple-regression results, perceived charger existence was only determined to have a statistically significant association with interest in PEV uptake when we used a single independent variable (not shown). Perceived charger abundance however, was significant in models (i), (ii) and (iii). Perceived abundance was estimated to be a significant predictor at the 95% confidence level in both models where we used “PEV research” as a proxy to represent prior interest in PEVs. In contrast, perceived abundance was not estimated to be a significant predictor in models (iv) and (v), where we used the “PEV familiarity” as a proxy for prior interest in PEVs.

Across all four models that control for socio-demographic factors, PEV interest is higher for residents of BC, respondents with a graduate degree, and for younger individuals. Also, individuals that exhibited prior interest in PEVs by either proxy were more likely to be interested in PEVs. We also see that having access to Level 1 charging at home is a reliable and highly significant predictor of PEV interest.

We also tested regressions where the location category of the charger was used as an independent dummy variable (not shown), for example “aware of charger at a mall” vs “aware of charger at workplace.” When separated this way, the locations were not significant in predicting interest in PEVs. Further, we estimated separate models where the dependent variable was interest in a PHEV and interest in an EV, respectively, as done by Krause et al. (2013). Results for the PHEV interest model were very similar to those found in our present analysis using overall PEV interest as the dependent variable (Table 5.3). In the models with EV interest as the dependent variable, very few explanatory variables were significant; these results were likely due to

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**Table 5.3**

<table>
<thead>
<tr>
<th>Model</th>
<th>Perceived Charger Existence</th>
<th>Perceived Charger Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.106*</td>
<td>0.508***</td>
</tr>
<tr>
<td>2</td>
<td>0.137***</td>
<td>0.392***</td>
</tr>
<tr>
<td>3</td>
<td>0.092</td>
<td>0.484***</td>
</tr>
<tr>
<td>4</td>
<td>0.114*</td>
<td>0.409**</td>
</tr>
</tbody>
</table>

*Significant at 90% confidence level, **Significant at 95% confidence level, ***Significant at 99% confidence level
having insufficient observations of EV designs—only about 5% of the sample selected an EV design in the design space exercises.

5.6. Discussion and conclusions

Our results show that as of 2013, when this survey data was collected, 18% of Canadian respondents reported being aware of at least one public charger. For comparison, a 2011 US survey found that 12% of respondents had seen public charging locations in their community (Carley et al., 2013). If we exclude the Province of British Columbia, levels of awareness of at least one charger in the rest of Canada (13%) are very similar to those in the US. Awareness of at least one charger was much higher in BC (31%) which is likely a consequence of the Clean Energy Vehicle Program initiated in 2011 which drastically increased the number of public chargers in the region. We also found evidence that across Canada, charger awareness was higher in urban areas relative to rural areas, and that public chargers were most likely to have been seen in shopping mall, retail store, or grocery store parking lots.

Our primary analyses focused on the association between PEV interest and public charger awareness—specifically the role of perceived charger existence (having seen a public charger in at least one location type) versus perceived charger abundance (having seen a public charger in at least two locations). Simple bivariate analysis indicated that respondents with either perceived existence or abundance were statistically more likely to have PEV interest, relative to respondents with no public charger awareness. However, when controlling for other explanatory factors through regression analysis, we found that perceived charger existence did not have a statistically significant relationship with consumer interest in PEVs. Perceived charger abundance had a statistically significant relationship with PEV interest in some models, but this association was weak at best, and non-existent in the other models. Thus, our measures of public charger awareness did not serve as robust predictors of PEV interest. The significant associations we saw in the bivariate analyses may actually be spurious, as the relationships diminish or disappear when other explanatory factors are introduced. Though, we do demonstrate that our distinction between perceived public
charger existence and abundance provides a unique perspective on the potential association with PEV interest relative to previous studies (Carley et al., 2013 and Krause et al., 2013). Indeed, the notion of “abundance” might be more likely to serve as a significant factor in PEV interest, which should be further tested and refined in future research.

Results from our logistic regression also suggest that other factors, besides perceived charger abundance, are statistically related to PEV interest. Residents within the province of BC are more likely to express interest in PEV technology than those in the rest of Canada and interest was also higher among those who possess a graduate degree, and those that are younger. The findings relating to respondent age and level of education align well with previous stated preference research (Achtnicht et al., 2012 and Hackbarth and Madlener, 2013) and with the studies that use a similar methodology to ours (Carley et al., 2013 and Krause et al., 2013). Like the studies of Carley et al. (2013) and Krause et al. (2013) we do not find income to be a significant predictor of interest in PEVs.

In terms of PEV readiness, respondents with Level 1 (110/120-volt) charger access at home and respondents whom have previously researched PEV technology are more likely to be interested in PEVs – which also supports previous findings in Germany (Hackbarth and Madlener, 2013). In particular, Level 1 charger access seems to be a key predictor of interest in PEVs, being a significant predictor at a high significance level (99%) in all regression models. This finding suggests that policies aimed at investment in home recharge accessibility could have a greater impact on PEV adoption than those that focus on public charging infrastructure—such as subsidies for home charger installation or building regulations that require or facilitate charger installation. Development of home charging availability may be particularly effective among residents of apartment buildings and in housing situations where respondents are less likely to already have some form of home charger access.

Future research is required to better understand the potential importance of different types of non-home charger locations, such as workplace charging, as well as
the specific charger details that may make PEVs more attractive, e.g. charging speed (Level 1, Level 2 or DC fast charging), location in parking lot, the cost charged to the driver, and the aesthetics of charger design. In addition, future research ought to investigate the differences between awareness of chargers in different locations relative to awareness of an overall large amount of chargers (regardless of location). Because consumers are also learning about their own interests and preferences as PEV technology and infrastructure are introduced to the market, this research should likely consult both PEV buyers and non-buyers as regional markets gain PEV-related experience over time.

For now, we can say that public charger awareness does not seem to be the most significant determinant of PEV interest. Policymakers ought to carefully consider how they direct resources aimed to support PEV adoption, including tradeoffs between public charging, home charging, vehicle subsidies, R&D funding and other PEV-related policies.

5.7. Acknowledgements

This research has been funded by: The Social Sciences and Humanities Research Council of Canada, BC Hydro and Natural Resources Canada. We would like to thank George Kamiya and Paulus Mau for their thorough contributions to this work, along with Jeff Rambharack, Steven Groves and all those who helped us to test and implement the survey.

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Chapter 6. Key Findings & Conclusions

This thesis addresses the goal of greenhouse gas (GHG) emission reduction by investigating the complementarity of intermittent renewable sources of electricity such as wind and hydropower and by examining ways to mitigate intermittency in the supply of renewably sourced electricity (renewable electricity) by creating demand for renewable electricity when it is available. Systematic development of the energy and transportation sectors has the potential to buffer intermittency in renewable electricity while reducing the need for storage technologies, increasing the use of renewable electricity and reducing GHG emissions. Optimizing connections between the energy and transportation sectors relies on understanding the supply and demand sides of the problem of intermittency in renewable electricity. This thesis focuses on the supply and demand aspects of intermittency in renewable electricity by addressing the following research goals:

1) Demonstrate how the multi-decadal and seasonal behaviour of British Columbia’s (BC) wind speed and runoff (a proxy for hydropower) resources have changed in the past 30 years, and how they are projected to change between 1979 and 2099.

2) Examine the projected complementarity (anti-correlation) between BC’s wind speed and runoff resources on seasonal and multi-decadal timescales, between 1979 and 2099.

3) Identify regions of BC where wind power development is likely to be optimal given projected relationships between BC’s wind speed and runoff resources.

4) Investigate the scope for utility controlled charging (UCC) of plug-in electric vehicles (PEVs), which may match electricity demand with the supply of intermittent renewable electricity in BC.

5) Establish if increased public charging infrastructure for PEVs may lead to increased uptake of PEVs, which would in-turn increase the potential of UCC in the future.

The following summarizes the key findings of Chapters Two-Five of this thesis, which together address the five research goals.
6.1. Key Findings


In Chapter 2, we investigated the long-term relationships between wind speed and runoff behaviour in BC. Previous research has proposed that wind farm planning and development can be better integrated within an electricity grid system if wind farms are chosen based on their complementary availability with hydropower resources (Cross et al., 2015). For example, if wind power is available when hydropower is not, then the overall supply of renewable electricity may be less intermittent and wind power and hydropower may be considered complementary. To build on previous work, this research investigated the stability of complementary relationships between wind speeds and runoff by examining how they are projected to change throughout BC over the 1979-2099 period. This paper used a state-of-the-art Canadian regional climate model (CRCM) and investigated wind energy density (WED) and runoff relationships into the future.

CRCM simulations forced with a GHG emission scenario equating to twice the global emissions of 2000 by 2055 (Nakicenovic & Swart, 2000) for the period 1979-2099 and examined for 5 periods between 1979 and 2099 project trends of increasing WED (~2%/decade) throughout BC’s northern and coastal regions, but decreasing (~-2%/decade) WED further south and inland. Despite geographically clear trends over the 1979-2099 timescale, the CRCM projected high variability between the five ~30 year periods. When considering that the average lifespan of a wind turbine is ~20 years (Martinez et al., 2009), the high inter-period variability is likely to have large implications for wind resource development.

While spatial patterns of trends in WED change depending on the 30-year time period considered, the Spearman $\rho$ correlations between WED and our proxy for hydroelectricity (runoff) are projected to be reasonably spatially consistent between 1979 and 2099. Persistent negative correlations ($\rho$=-0.2) between WED and runoff are projected in southern BC and the US Pacific Northwest. The negative correlations
between WED and runoff in southern BC are persistent in the long-term (1979-2099) as well as in most of the 30-year time windows between 1979 and 2099. The negative correlations were also prevalent in 3 out of the 4 datasets used over the comparison period of 1979-2004, which adds to the robustness of the correlation pattern. Despite a dominance of positive correlations ($\rho=0.2$) between WED and runoff in BC’s northern regions, analysis of WED behavior suggests that regions on the Alaskan coast may exhibit increased WED (~+5%) during years of extreme low runoff. Over the long-term and when prioritizing negative correlations between resources, results suggest that the Alaskan coast and BC’s southwest region could be potentially valuable locations for future energy planning efforts.

6.1.2. **Chapter 3 – Projected changes in the intra-annual relationship between British Columbia’s wind speed and runoff resources in regions of future wind farm development.**

In addition to the long-term relationships addressed in Chapter 2, understanding the within-year (intra-annual) characteristics of BC’s wind speed and runoff resources at areas of potential wind farm development is important in resource planning and the subsequent production of renewable electricity. Understanding intra-annual behaviour in future is particularly important in areas marked for wind farm development. Sites currently designated for wind farm development are likely to be some of the best sites available for electricity generation and may be expanded in the future. In Chapter 3, we investigated the projected seasonal behavior (comparing the 1979-2009 and 2069-2099 periods) of BC’s WED and runoff resources at six locations identified as key in future wind farm development. The six locations included (1) Stikine in northwestern BC, (2) Kitimat in central coastal BC, (3) The northern tip of Vancouver Island, (4) Williston in the northeastern interior of BC, (5) Peace in the central interior of BC, and (6) Okanagan in the southern interior of BC (Government of British Columbia, 2010b). Characterizing changes of WED and runoff in these areas and projecting the relationships between BC’s WED and runoff resources is key in understanding the role of future developments in providing reliable renewable electricity.

We compared seasonal cycles of WED with runoff-based proxies for run-of-river and large-scale hydropower for the Present (1980-2009) to the Future (2070-2099) and
identified significant changes in the WED and runoff resources. First, while the annual distribution of WED is not projected to shift significantly, monthly mean WED is projected to increase (~10%) in the northernmost regions of BC and decrease by around 8% in the southernmost regions of BC. The mean monthly 90th percentiles of WED (wind speeds that contribute heavily to wind electricity generation) are projected to increase in magnitude (~10%) in BC’s northern regions and the four most northerly sites exhibit increased intra-annual standard deviation. Overall, the relative consistency in WED behavior supports the notion that BC may have a stable wind power resource into the future and that declines in WED should not be of concern.

The CRCM simulations suggest that the monthly mean runoff is likely to increase (7%-16%) at all locations by 2070-2099, when compared with the 1980-2009 time period. At most of the six locations, monthly mean and monthly 90th percentile runoff values are projected to increase significantly. At three locations (Stikine, Williston and Okanagan), the month of maximum flow is projected to shift a month earlier, shifting from early spring to late winter, likely in response to a shift in the spring freshet. We attribute both the earlier freshet and the increases in monthly 90th percentiles of runoff to a shift from snow-dominated to rain-dominated systems by the end of the century, likely in response to warmer temperatures (1.8°C to 4°C (1961-1990 to 2050s)) (Environment Canada, 2015a).

When observing complementarity, we see a shift towards increasingly positive correlations between WED and runoff at all locations, likely as a result of the shift in the runoff maxima towards the late winter season when they coincide with higher wind speeds. The increase in correlations is less optimal for the electricity generation industry since anti-correlation implies a less variable supply of electricity. However, although CRCM projections suggest a shift towards increasingly positive correlations between WED and runoff, mean correlations between WED and a proxy for large-scale hydropower remain negative at all six locations. As a result, integration of our six potential wind farm locations within a grid system supported by large-scale central hydropower may remain a favourable option for reliable electricity generation even during the future.
Of all sites, we identify the Stikine location in northwest BC as having consistently negative correlations in both local and central runoff scenarios and consistently high WED. Should BC develop sufficient transmission capabilities, findings from our research suggest that Stikine would provide the best wind resource when considering timing and annual WED magnitudes in the future. Finally, we note that the Kitimat (central coast), Okanagan (southern interior) and Peace (northeast) locations also suggest relatively consistent negative correlations between WED and runoff into the later part of the 21st century. Negative correlations implying that the WED resource at these locations could mitigate intermittency in BC’s electricity supply.

6.1.3. Chapter 4 - Anticipating PEV buyers’ acceptance of utility controlled charging

Chapter 4 examines solutions to intermittency in renewable electricity supply by investigating consumer acceptance of utility controlled charging (UCC) of plug-in electric vehicles (PEVs). UCC broadly refers to an electric utility’s ability to control the charging of a given PEV or fleet of PEVs to manage charge times, charging rates and even perhaps discharge of electricity back to the grid. As a result, UCC could be used to influence the timing and rate of PEV charging and better align electricity demand with the intermittent availability of renewable electricity. Chapter 4 explored consumer acceptance of UCC by implementing a web-based survey of new vehicle buyers in Canada (n = 1470) and using econometric analysis methods to investigate consumer acceptance of UCC. Specifically, Chapter 4 used discrete choice methods, which quantify consumer tradeoffs and in this case, establish what aspects of UCC (e.g. cost, inconvenience) are most important to consumers.

Thirty-six percent of respondents were likely to be early adopters of PEV technology, and of these, around half stated that they would voluntarily enroll in a UCC program. However, some of the early adopter respondents expressed concerns with the privacy (24%) and loss of control (38%) associated with UCC programs. Using a latent class discrete choice model to characterize consumer tradeoffs, we found that providing cost incentives (reduced electricity bill) was more effective than environmental benefits (increased use of renewable electricity) at motivating early mainstream PEV buyers to
enroll in UCC programs. However, environmental incentives were attractive for the environmentally oriented segment of respondents.

Results from Chapter 4 hold important implications for utilities and policymakers. Results suggest widespread acceptance of a voluntary UCC program is possible among early market PEV buyers, even in the absence of financial benefits and without framing UCC according to environmental benefits. Careful design of a UCC program could further increase enrollment, most notably by providing cost subsidies to PEV owners. Enrollment may also be boosted if the electric utility could frame UCC as a method for supporting the deployment of intermittent, renewable electricity, and thus as a means of providing environmental benefits. Furthermore, although many consumers (44%) may accept some level of charging "inconvenience," such as being provided a 90% charge on any given morning, only 18% were likely to find a UCC program acceptable if only a 75% state of charge was guaranteed. To maximize the acceptability of UCC programs, utilities will also want to maintain and foster a high degree of trust with consumers, in order to alleviate the concerns of those surveyed about loss of control and/or perceived threats to consumer privacy. One strategy might be for the utility to administer a UCC program through a more trusted third-party, though third party control is not currently done. Given the high degree of consumer heterogeneity that we demonstrate in our latent class analysis, we recommend that additional market research may be required to optimize the uptake of the UCC program for the consumer segments within a particular jurisdiction.

The results of Chapter 4 also hold implications for climate policy more generally. Other studies have established the potential GHG reduction benefits of controlling the charging of PEVs (Sioshansi & Denholm, 2009). Chapter 4 further demonstrated the market potential for UCC programs. To realize widespread GHG reductions from PEVs and renewable electricity, policymakers will need to coordinate the strategies and policies implemented in both the transportation and electricity sectors. For example, standards enacted in each sector may be interdependent, such as a renewable energy production requirement for electricity and a vehicle emission standard. Actively developing UCC programs could create clear linkages between the feasibility of the two policies - having PEV buyers enroll in UCC programs could facilitate the uptake of
renewable electricity, and the planned deployment of renewable electricity could increase the desirability of PEVs among some consumer segments. The design and success of UCC programs would also impact policies that follow a “life-cycle” method of GHG accounting, such as California’s low-carbon fuel standard. For example, if a UCC program is successfully increasing the amount of renewable electricity being used to charge PEVs in a given jurisdiction, then electricity should be given credit (towards achieving the low-fuel standard) as a transportation fuel with relatively low carbon intensity. Such an accounting method may also provide incentives for other fuel providers regulated by the low carbon standard to help incentivize UCC programs, if that is a lower cost means of policy compliance.

6.1.4. Chapter 5 - Is awareness of public charging infrastructure associated with consumer interest in plug-in electric vehicles?

While the utility controlled charging (UCC) of PEVs is important for energy management, the ability for PEVs to play a role in UCC and concurrent grid management is limited without adequate adoption of PEV technology. Chapter 5 investigated the role of public charging infrastructure in generating interest for PEVs. If consumers do not adopt PEV technologies, then PEVs cannot be used in the transition to a reduced-GHG emission transportation industry or in UCC. Barriers to PEV adoption include, vehicle costs, technology unfamiliarity, refuelling capabilities and perhaps most importantly, policy. PEV adoption requires policy support, and countries and regions vary in their adoption of PEV-oriented policies. Some regions such as California adopt supply-focused policies, which may mandate that a certain portion of vehicles sold to consumers emit no emissions (a zero-emissions vehicle mandate) (Collantes & Sperling, 2008). Likewise, they may require that fuels used in a given region exhibit low-carbon emissions when burned (a low-carbon fuel standard). Alternately, other regions such as Norway adopt strong demand-focused policies, which include financial (e.g. vehicle rebates) and non-financial incentives (e.g. reserved parking for PEVs) and the development of charging infrastructure (Zhou, Wang, Hao, Johnson, & Wang, 2015). Chapter 5 concentrates on demand-focused policies and specifically the development of charging infrastructure. Policymakers often seek to increase the visibility of PEV
chargers in public locations in an effort to build familiarity and interest in PEVs. However, the actual effect of prevalent and visible public charging stations on PEV demand has been unclear. Chapter 5 assessed current levels of visibility for public PEV charging infrastructure within Canada and identified whether or not a statistically significant relationship exists between consumer awareness of public charging infrastructure and interest in purchasing a PEV.

Chapter 5 demonstrates that as of 2013, 18% of Canadian respondents reported being aware of at least one public charger. For comparison, a 2011 US survey found that 12% of respondents had seen public charging locations in their community (Carley, Krause, Lane, & Graham, 2013). Awareness of at least one charger was much higher in BC (31%), which is likely a consequence of the Clean Energy Vehicle Program initiated in 2011, which drastically increased the number of public chargers in the province. Chapter 5 also found evidence that across Canada, charger awareness was higher in urban areas relative to rural areas, and that public chargers were most likely to have been seen in shopping malls, retail stores, or grocery store parking lots.

We used a binary logistic regression and, after controlling for other explanatory factors, we found that consumer awareness of public charging infrastructure did not have a statistically significant relationship with consumer interest in PEVs. Results from the logistic regression also suggest that other factors besides perceived charger abundance were statistically related to PEV interest. Residents within the province of BC were more likely to express interest in PEV technology than those in the rest of Canada. Interest was also higher in respondents under the age of 35 and among those who possess a graduate degree. In terms of PEV readiness, respondents with Level 1 (110/120-volt) charger access at home and respondents who have previously researched PEV technology were more likely to be interested in PEVs. As with previous findings in Germany (Hackbarth & Madlener, 2013), our study suggests that, Level 1 charger access at home seems to be a key predictor of interest in PEVs, being a significant predictor at a high significance level (99%) in all regression models.

Given that public charger awareness does not seem to be the most significant determinant of PEV interest, this study highlights how direct resources aimed to support
PEV adoption, including trade-offs between public charging, home charging, vehicle subsidies, R&D funding and other PEV-related policies, might be considered to increase use of PEV technology. In particular, policies aimed at investment in home recharge accessibility - such as subsidies for home charger installation or building regulations that require or facilitate charger installation - could have a greater impact on PEV adoption than those that focus on public charging infrastructure. Development of home charging availability may be particularly effective among residents of apartment buildings and in housing situations where respondents are less likely to already have some form of home charger access.

6.2. Implications

Taken together, Chapters 2 to 5 in this thesis suggest that supply and demand approaches to mitigating intermittency could be used in optimising BC’s supply and use of renewable electricity. By considering the temporal availability of wind speed and runoff resources and using utility controlled charging as tools to manage the supply and use of renewable electricity, BC could potentially increase its use of renewable electricity, improve the cost-effectiveness of renewable electricity, or lower climate abatement costs and spur the uptake of other technologies such as PEVs.

The success of these approaches requires a co-ordinated effort between scientists, policymakers and utilities to optimise the consumption of renewably generated electricity. In this regard, BC may benefit from having a single electric utility (BC Hydro) rather than an open electricity market with multiple providers because coordinating renewable electricity supply with demand can be challenging. However, for both the supply and demand approaches to be implemented effectively, the increasing contribution of independent power producers (who generate wind power and run-of-river hydropower) to BC’s electricity supply will need to be closely integrated with BC Hydro’s planning and with entities responsible for PEV incentives and related vehicle policies.

BC’s Clean Energy Act (Government of British Columbia, 2010a) is a key component in BC’s steps towards decarbonisation and in comparison with energy regulation in other parts of the world, is stringent when considering the technologies that
it allows. The persistence or development of BC’s Clean Energy Act is key to fostering the uptake of intermittent renewable electricity. BC’s electricity demand will continue to grow and BC Hydro must source sufficient electricity to meet growing demand by using different renewable electricity sources (BC Hydro 2014). Because of the Clean Energy Act, the need to meet this growing demand is likely to stimulate the development of more intermittent electricity resources such as wind power and run-of-river hydropower. Regardless, with current population growth and economic development, BC’s electricity needs will continue to grow beyond 2050, and the approaches investigated here provide some alternatives for efficient planning and development of BC’s electricity supply.

To maximise the potential for UCC to facilitate the integration of renewable electricity into BC’s grid, BC must follow the lead of California where intensive PEV policies, such as a zero emission vehicle mandate (ZEV), have been adopted (Collantes, Sperling 2008). Mandates such as the ZEV have been implemented in California and require automobile manufacturers to sell a certain percentage of PEVs or hydrogen fuel-cell vehicles as part of their overall vehicle sales in a region. This type of policy, which affects the supply of vehicles to consumers, is very likely to be more effective than demand related incentives such as the rebates provided by the government of BC (Axsen, Goldberg et al. 2015, Axsen, Wolinetz 2014). Previous research has estimated that demand related policies, such as rebates, will be insufficient for BC to reach its transportation emission goals and that a ZEV must be adopted for success (Axsen, Goldberg et al. 2015, Axsen, Wolinetz 2014).

The results from this research have also spurred additional questions. Chapter 2 demonstrates the significant differences in wind speed and runoff resources over 30-year periods. Future research ought to investigate more specifically how climate change might affect the large-scale climate oscillations that modify BC’s wind speed and hydrological resources on decadal timescales. These specific 20-30 year periods are likely to have significant impacts on wind power resources, particularly when considering the ~20 year life of a wind turbine and ~50 year life of grid infrastructure (Martinez, Sanz et al. 2009). Unfortunately, even in the latest generation of ocean-atmosphere general circulation models, projecting large-scale climate oscillations remains extremely difficult (Kim, Webster et al. 2012). Another logical step would be to estimate the potential costs
and benefits of specifically developing renewable energy infrastructure in regions with complementary (anti-correlated) wind speed and streamflow resources. For example, over a project life cycle, how does financial consideration of complementary wind power and hydropower resources compare to a project that does not consider the value of complementarity between resources. Preliminary investigations have been conducted to optimize integration between wind power and solar power in southern Europe (Santos-Alamillos, Pozo-Vázquez et al. 2015), and similar types of analyses could benefit further integration of wind and hydrological resources, or perhaps even wind, hydrological, and solar resources in BC.

We believe that the approaches investigated in this thesis may also be used to inform energy and transportation policy elsewhere. For example, regions boasting strong hydroelectricity resources, such as China, Brazil, Scandinavia and the US, could also benefit from investigating the complementarity of wind speeds and hydropower. In most cases globally, countries are increasing their use of intermittent sources of renewable electricity and diversifying the electricity generation mix is rarely detrimental to grid system resilience. Likewise, the adoption of PEVs is increasing in other jurisdictions, and the US, Japan and China accounted for 54% of the global PEV stock in 2014 (International Energy Agency 2015). In the Netherlands and Norway, PEV’s represented 5% and 13% of new market share in 2014 respectively (International Energy Agency 2015). The increased adoption of intermittent renewable electricity and PEVs bodes well for the development of complementary resources and using utility controlled charging as a tool to manage the supply and use of renewable electricity.

When compared with other regions globally, BC’s electricity sector emits relatively low levels of GHGs. BC’s capacity for renewable electricity generation and the social acceptance of technologies such as PEVs mean that BC is an excellent staging ground to demonstrate how the energy and transportation industries may co-operate – particularly with respect to the approaches discussed in this thesis. As is often the case, however, the success of using complementary renewable resources, UCC, and the adoption of PEVs to reduce GHG emissions depends on federal and provincial governments and the overall priority that Canadian citizens place on the issues of climate change.
6.3. References


