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Managing Water Shortages in the Western Electricity Grids

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Managing Water Shortages in the Western Electricity Grids

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Abstract

British Columbia's electricity grid is comprised primarily of hydroelectric generating assets. The ability to store water in reservoirs is a significant advantage for the province allowing it to import from Alberta when prices are favourable. Alberta, has a heavily fossil-fuel based electricity portfolio, but has seen substantial growth in its wind energy capacity. However this variable energy technology impacts the province's grid operations. Wind energy is both variable and uncertainty. However, wind energy in Alberta can be stored via BC's reservoir systems. In this paper, we examine the extent that drought impacts the both overall operating costs as well as the cost of reducing CO_2 emissions. We model the Alberta and BC interconnected grids varying both the impact of the drought and the transmission capacity between the provinces. We determine that storing wind energy leads to an overall cost reduction and that emission costs are between \$20 and \$60 per tonne of CO_2.

Keywords: Wind power, carbon costs, electrical grids, mathematical programming

JEL Classification: Q54, Q41, C61

1. INTRODUCTION

Climate change will impact natural resources in Alberta and British Columbia, particularly water and energy resources. Climate change is projected to increase droughts, affecting how water will be allocated among competing uses. In the past, there have been conflicts over hydroelectric development on the Peace River (Canada et al. 1996), and concern about potential water shortages in southern Alberta caused by high demands due to urban growth and secondary oil recovery (Alberta Environment 2002). Climate mitigation places greater emphasis on renewable sources of energy, especially hydropower and wind. Impending climate change will greatly complicate the water-energy interface because carbon dioxide (CO_2) emission mitigation strategies increase demand for hydropower that is thwarted by reduced water availability. The storage provided by hydro reservoirs is ideal for integrating the vast intermittent wind power resources east of the Rockies, but climate-induced droughts are projected to lead to reduced hydropower that exacerbates the need for wind to replace the lost hydro energy and to offset increased CO_2 emissions from greater use of ubiquitous and cheap fossil fuels that inevitably replace some of the lost renewable hydropower.

The objectives in the current study are: (1) to investigate the potential of BC’s vast hydro storage capacity to facilitate the optimal use of wind energy east of the Rockies (BC hydro facilities are important for storage of wind power generated in Alberta, but the extant transmission intertie between the two grids has low capacity); (2) to model the potential effect that drought could have on hydroelectric generating capability in these provinces and the implications for future energy stability and supply; and (3) to investigate the impact that drought could have on the ‘performance’ of wind generation in terms of wind penetrability into the grid and on overall CO_2 emissions from production of electricity. Might drought reduce the effectiveness of renewable wind energy because drought reduces the capacity to store intermittent wind power as potential energy behind hydro dams? And what are the likely economic costs of reducing CO_2 emissions using wind-generated power with hydro storage under current versus more frequent drought conditions?

To address these objectives, we develop a mathematical programming model of the BC and Alberta electricity grids and the intertie between them. The model builds on earlier work by van Kooten (2009); van Kooten and Wong (2009); Prescott and van Kooten (2009); Maddaloni et al. (2008a, 2008b); Benitez et al (2008); Prescott et al. (2007); Weber (2005); Lund (2005); and Louck et al. (1981). The numerical model is solved in an Excel-Matlab-GAMS software environment (Wong 2009).

2. LITERATURE REVIEW

One of the earliest assessments of the costs of integrating renewable energy within a hydroelectric power system was developed by Bélanger and Gagnon (2002). The authors modeled Quebec as an isolated power system with no transmission interties to grids outside the province. The wind output was calculated using a power curve, with hydrometric data used to determine Quebec’s hydropower output. The authors showed that wind penetrations of more than 10% would require additions to Quebec’s hydro capacity to handle the increases in variability from wind output.

A later storage paper by DeCarolis and Keith (2006) included a cost-benefit analysis of Compressed Air Energy Storage (CAES) in combination with increases in the integration of intermittent renewables. The model included conventional fossil fuel generation, wind and compressed air storage, and was used to determine the optimal generation mixture to minimize costs given a carbon tax. The authors allowed the generation mix to change over time to adapt to increased wind power, while assuming that fossil fuel generation consisted only of single and combined-cycle natural gas plants with no coal generating capacity. Coal was excluded because even with low carbon taxes coal became prohibitively expensive. The gas generators were assumed to have a constant efficiency over the output range and the costs of using gas plants for regulation were not included as data were only available on an hourly time step. Fixed transmission constraints between regions were used, and wind-generated power output data were simulated using wind speed data and a power curve. Results indicated that wind penetrations of up to 50% of generating capacity were cost competitive with coal that included carbon capture and storage, as well as with other technologies designed to reduce carbon emissions in electricity generation.

Using pumped storage in the Alberta power system, Benitez et al. (2008) evaluated the cost-effectiveness of using wind energy to curtail GHG emissions. This model included constraints that limit the speed at which fossil fuel generators can ramp up and down, as well as variable head at the hydroelectric dams. Three scenarios were evaluated: one with no wind and two with increasing quantities of wind replacing coal generation. The wind output was generated using power curves and wind speed data. The model showed that variability increased with the penetration of wind and that new gas peaking units were required to meet the challenges posed by wind variability even with the inclusion of hydroelectric storage dams (although the scope for hydroelectric facilities is severely constrained in Alberta). The cost of including the new wind power to the system was estimated to be \$41-\$56 per tCO_2. Similarly, Prescott and van Kooten (2009) used a model that selected an optimal generating mix for integrating wind into the Alberta electricity grid to estimate the costs of reducing emissions at \$66/tCO_2.

A number of authors have employed mathematical programming models to investigate the integration of wind power into the small Vancouver Island electricity grid. The earliest of these found that there is not always sufficient wind when power is required and the development of large wind resources alone would be insufficient to meet the electricity needs of Vancouver Island (Prescott et al. 2007). The cost of reducing CO_2 emissions was estimated to be around \$100/tCO_2, primarily because Vancouver Island relies mainly on hydropower from the mainland. In a related paper, Maddaloni et al. (2008) considered the effect of transmission constraints on the integration of renewable wind technologies. They show that increasing wind penetration increases the costs attributable to other generation and necessitated an increase in transmission capacity. Specifically, they found that penetrations greater than 20% result in negative net benefits for the Vancouver Island system.

Finally, using Vancouver Island load data as a proxy for a small power system, Maddaloni et al. (2009) examined the effects of integrating wind power into electricity grids with three different extant generating mixes – a predominantly hydroelectric system similar to BC, a mix of fossil fuel and hydroelectric generation similar to the Northwest Power Pool, and a mix of generation heavily weighted toward nuclear and fossil-fuel generation similar to that characterizing U.S. power production. As wind power penetration increased (defined as wind generating capacity relative to peak load), the increased capital costs of installing wind turbines in a fossil-fuel based system overwhelmed the reductions in fuel costs and CO_2 emissions that are the primary benefits of wind. Costs of CO_2 uptake were also high in hydroelectric and the nuclear-coal grids because wind often displaced power production from hydro and/or nuclear facilities that produced little greenhouse gases.

With calibrated hydro and wind data derived from actual observations, Denault et al. (2009) use a simulation-based risk analysis to investigate annual energy inflows to the predominately hydroelectric Quebec electricity grid, focusing on the geographic dispersion of wind farms. The simulation model uses combinations of wind-generated power and hydropower to meet the load. The authors then examined water inflow deficits over the long term, with wind power as the primary means of diversifying the energy inflow portfolio, and concluded that wind power could provide substantial diversification in power supply for wind penetrations up to 30%.

In this study, we consider the economic and CO_2 emission-reduction benefits of integrating the Alberta and British Columbia electricity grids to take advantage of Alberta's capacity to generate wind power and BC's capacity to store energy behind hydro dams. We also examine the costs imposed on such an integrated system when climate change results in more frequent droughts.

3. METHODS

The Alberta electricity grid is predominantly fossil fuel based. In addition to 5946 MW of coal and 5116 MW of natural gas-fired capacity, Alberta has upwards of 871 MW of hydroelectric assets and 563 MW of recently integrated wind-generating capacity.

Hydro assets are primarily of run-of-river and there is little storage available in the Alberta system. The BC grid, on the other hand, is predominantly hydro based with a total installed generating capacity of over 11,000 megawatts (MW); it comprises 30 primarily large-scale hydroelectric generating facilities, two gas-fired thermal power plants and one combustion turbine station. A transmission intertie exists between the two provinces, but, as discussed below, its capacity is currently limited by operating constraints on the Alberta side of the border.

Model

In this section, a model of the combined Alberta and British Columbia power systems is developed. The model is an extension of models developed by Prescott et al. (2007), Benitez et al. (2008), and Prescott and van Kooten (2009), but captures the Alberta power system in greater detail and takes a different approach to scaling the wind output. The linear mathematical programming model minimizes total variable costs subject to the operating constraints in the two power systems and the intertie constraint. The objective is to minimize fuel costs (b_i) plus the variable operating and maintenance costs (OM_i) for each generator i multiplied by the generator output ($Q_{i,t}$) in each period t and then summed over the entire planning horizon:

$$\underset{Q_{i,t}}{Minimize}\; TC = \sum_{t=1}^{24\times d} \left[\sum_{i} \left(OM_i + b_i \right) Q_{i,t} \right], \tag{1}$$

where d is the number of days (taken to be 365 so that there are 8760 hours in the model).

The costs of the two power systems are jointly optimized, and the loads in each province must be met separately. For each province (P), the sum of the generator outputs in each period must equal the customer load ($L_{t,P}$), net exports ($X_{t,P}$) and wasted power ($W_{t,P}$). This constraint can be written as:

$$\sum_{i}^{N_P} Q_{i,t,P} - L_{t,P} - X_{t,P} - W_{t,P} = 0, \quad P = AB, BC;\ t = 1,\ldots,T\,, \tag{2}$$

where there are N_P generators in province P. Net exports refer to power delivered along the BC-Alberta intertie, whether from Alberta to BC or in the other direction.

If loads and generation are not equal, there will be a deviation from the scheduled interchange of electricity in an interconnected power system, or a deviation from the target system frequency in a closed power system. Instead of including these power system characteristics, we employ the notion of wasted power, which captures events where unusable excess power is produced because generators cannot be ramped down quickly enough or have already reached their minimum generation (and cannot reduce output further). In practice, the system operator would curtail unwanted generation by not accepting power from the source most capable of regulating production, which is usually a hydro or wind source. In our model, the waste variable constitutes a measure of the wasted wind energy that cannot be used by the Alberta or British Columbia electricity grids (or elsewhere if there are opportunities for export to other regions).

Hydroelectric power generation is simplified to keep the model linear. We assume that the output of hydroelectric generator h ($\subset i$) at time t is a function of η_h the generator efficiency, g the gravitational constant (m/s^2), d the density of water (kg/m^3), $F_{t,h}$ the flow of water through the penstock (m^3/s), H_h the fixed head height (m), and the factor 10^{-6} used to convert the output in watts to MW:

$$Q_{t,h} = \eta_h \times g \times d \times F_{t,h} \times H_h \times 10^{-6}. \tag{3}$$

The simplification here is to keep the head constant. A more detailed model would allow for a head height that is a function of the reservoir volume. Including this detail, however, would result in a non-linear model requiring significantly longer solution times while providing little insight on the question of how effectively wind power can be integrated into the two power systems.

The volume of water stored behind hydro dam h at time t, $V_{h,t}$, is equal to the water behind the dam in the previous period plus inflows during the period ($I_{h,t}$), minus the flows into the penstocks ($F_{h,t}$) and the amount of water that is spilled ($\mathrm{S}_{\mathrm{h,t}}$):

$$V_{h,t} = V_{h,t-1} + I_{h,t} - F_{h,t} - S_{h,t}. \tag{4}$$

Rivers in British Columbia and Alberta often have a legislated minimum river flow. Therefore, we require that the sum of the flows into the penstocks and the spilled water must be greater than the minimum river flow:

$$F_{h,t} + S_{h,t} \geq F_h,\ \forall h. \tag{5}$$

Further, the hydro reservoirs have storage limits:

$$V_{h,t} \leq \max V_h,\ \forall h, \tag{6}$$

where for each reservoir the volume of water in the reservoir at any given time may not exceed the maximum volume of the reservoir.

Generators cannot exceed their capacity and their output must be above a minimum level or they will shut down:

$$Q_{i,t} \leq \max Q_{i,t},\ \forall i, t \tag{7}$$

$$Q_{i,t} \geq \min Q_{i,t}, \ \forall\, i, t. \tag{8}$$

We do not model the shutdown and startup of individual generators per se, because several power plants or generating sources are combined into single units for computational ease. Thus, the lower bound on generation reflects the necessity to keep certain generating sources at an adequate level of output for load balancing and reserve purposes. Given the nature of thermal generating assets in Alberta and British Columbia, it is also necessary to ensure that generator output between any two periods (between one hour and the next) does not exceed the ability of output from a generating source to ramp up or down. This is a critical constraint that frequently binds for Alberta's coal assets and particularly when highly variable wind enters the grid. The constraints are specified as follows:

$$Q_{i,t} - Q_{i,t-1} \leq R_i, \ \forall\, i \text{ and} \tag{9}$$

$$Q_{i,t-1} - Q_{i,t} \leq D_i, \ \forall\, i, \tag{10}$$

where R_i refers to the amount by which generator i can ramp up between two periods and D_i the amount by which it can ramp down.

The Alberta and BC grids are connected via two 138 kV lines and one 500 kV line. Thus, we model a single transmission line between the provinces. The Western Electricity Coordinating Council (WECC) has rated the intertie between Alberta and BC at 1000MW capacity for export from Alberta and 1200MW for import into Alberta; however, operating limits within Alberta often restrict the export value to 600MW and the import value to 760MW(IPA Energy and Water Consulting, COWI A/S, SGA Energy, 2008). In this study, we model zero transmission, the normal operating limits, and the limits as if Alberta had invested in improving internal infrastructure so that the transmission line can operate at capacity.

We require that exports from one province be equal to imports into the other province (and ignore line losses). In addition, more cannot be imported by one province than the export maximum of the other province, and a province cannot export more than its maximum. For convenience, it is assumed that there is no connection to other grids in North America. The forgoing requirements can be represented by three constraints:

$$X_{BC} + X_{AB} = 0 \tag{11}$$

$$X_{BC} \leq \max X_{BC} \tag{12a}$$

$$X_{AB} \leq \max X_{AB} \tag{12b}$$

Wind Output Data

Electricity generated using the wind is treated as self-scheduled generation that the system operator must integrate into the system. The modeling of wind data inputs differs from some of the approaches employed by others (e.g., see Soder and Holttinen 2008). Instead of physically modeling the wind (see Dua et al. 2008), or scaling or shifting an observed wind profile (Maddaloni et al. 2009), we construct wind output profiles for different time periods during the year based on time-series observations and then synthesize the new wind outputs in a manner similar to MacCormack et al. (2008). This approach is more satisfactory when the available wind speed data are insufficient for proper modeling of the mechanics of wind generators and scaling of wind output is desired.

To construct the wind output profiles, we use the five-minute observations of wind generation output in Alberta over the latest available year. We begin by subtracting the annual mean from the whole series, thereby giving a mean-zero residual series for the whole year. Then the monthly averages are subtracted from each month's data giving mean-zero residuals for each month. This is then done for days and hours until there is a mean-zero residual for each five-minute period. From this mean-zero series a distribution was fitted and new values were drawn from the distribution to give a new wind series. Finally, the averages are added back into this new series to give a new annual wind output profile that represents existing capacity in Alberta. To generate profiles with twice the wind power output, the output profile created using averages is doubled and a new random mean-zero series is overlaid on top. This is doubled again for the 4× wind scenario.

4. MODEL RESULTS

We investigate normal precipitation and drought, high and low wind energy outputs, and differing intertie transmission capacities. Drought conditions were estimated from historical hydrometric data. The last severe drought in Alberta and British Columbia was in 2001-2002 when river flows were reduced to 37.5% of their peak flows. This corresponded to the 'electricity crisis' (characterized by rolling black outs) in California, which relies heavily on hydropower from the Pacific Northwest (which was also affected by drought). In this application, we modeled drought by reducing water inflows to 37.5% of normal.

Under drought conditions and with no transmission between Alberta and British

Columbia, there is no solution to the mathematical programming model. When water levels in British Columbia are low, the province must import electricity. In the model, energy must be imported from Alberta, but there was insufficient transmission capacity to import the required power. Of course, in practice BC imports power from the United States, but this is not modeled here. Despite the U.S. link, reduced precipitation will negatively impact British Columbia's energy security. Without significant increases in generating capacity, the goal of energy self-sufficiency as expressed in the BC Energy Plan (2009) may well be unattainable.

Once transmission is added to the model, British Columbia simply imports power from Alberta (just as it imported power from the U.S. during 2001-2002). The source of the imported energy depends on whether and how much wind power is produced in Alberta. Some of the key observations from the model are found in Figure 1. By increasing both installed wind generating capacity in Alberta and the capacity of the transmission intertie, changes occur in: (1) Alberta's production of power from coal and natural gas; (2) BC's thermal generation (primarily from the Burrard gas plant); (3) BC's hydropower output; and (4) power flows along the transmission intertie.

As wind output increases, Alberta's coal and natural gas generation fall. The transmission capacity between the two provinces is a key factor. As the capacity of the transmission intertie increases, more wind-generated power and inexpensive coal-generated power is exported from Alberta to BC. That is, BC will import wind-generated electricity from Alberta to meet domestic load, thereby storing water in hydro reservoirs that is used to generate electricity in the future. Higher water levels in British Columbia lead to greater energy output from the province's hydroelectric generator and thereby also reduce coal imports from Alberta.

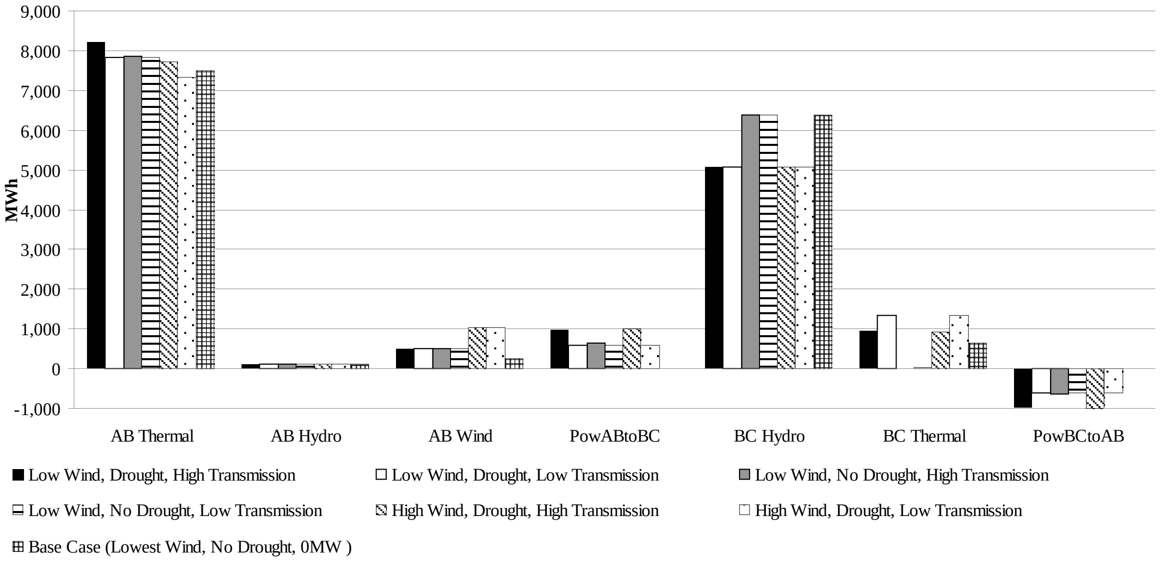

Figure 1: Electricity Output by Energy Source, Alberta and British Columbia, Various Model Scenarios

Six scenarios are provided in Figure 1. Not surprisingly, Alberta thermal output is highest under low wind and low water conditions and greatest transmission capacity, thereby providing greater energy to British Columbia when the BC hydroelectric generators are least able to do so. Under drought conditions, transmission capacity is fully utilized with BC importing energy from Alberta. Drought increases thermal generation while transmission capacity determines its location – Alberta or BC.

Drought conditions may also exacerbate CO_2 emissions as increased transmission allows BC to import inexpensive coal-generated electricity from Alberta (Figure 2). As wind energy is increased, the amount of coal-fired electricity needed by British Columbia falls. Thus, wind production in Alberta can decrease CO_2 emissions associated with meeting BC’s internal load.

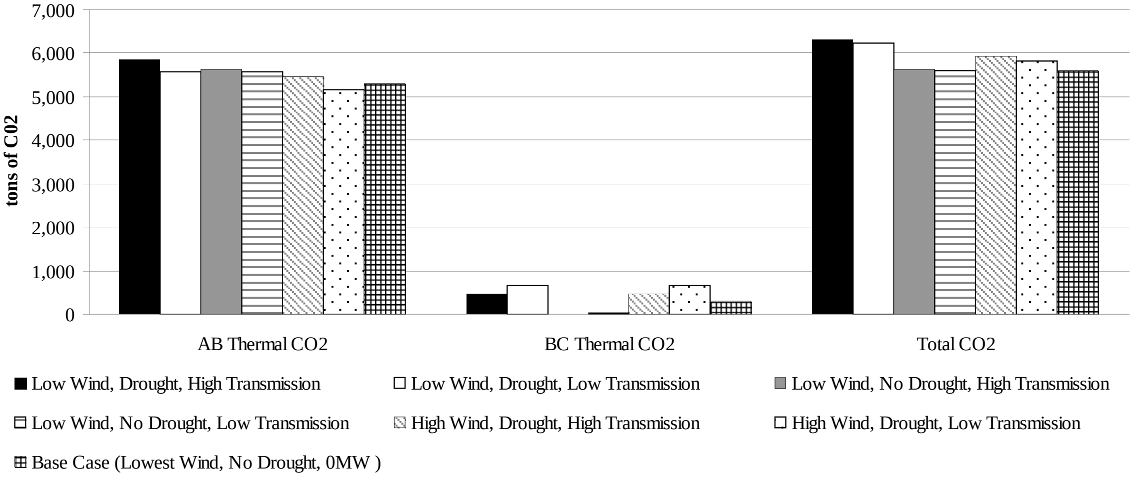

Figure 2: CO_2 Emissions for Alberta and British Columbia

Carbon dioxide emissions by province are shown in Figure 2. The lowest CO_2 emissions occur when there is no drought and low transmission capacity between the two provinces. This restricts British Columbia's ability to import inexpensive but highly CO_2-intensive electricity from Alberta. BC uses its hydroelectric assets to create electricity and meet domestic demand, thereby keeping CO_2 emissions low. Increasing the capacity of the transmission intertie, but keeping water levels high and the wind level low, increases CO_2 emissions as BC will import thermally-generated electricity from Alberta. The highest emission scenario occurs with low wind, drought and high transmission between the provinces. With low wind, Alberta produces electricity with its thermal units and BC imports a large amount of this energy through the transmission intertie.

Finally, we consider the climate benefits of integrating the BC and Alberta electricity grids to take advantage of BC's ability to store Alberta's wind-generated energy in an optimal fashion. This is done by examining the costs of reducing CO_2 emissions, which are provided in Table 1. There are four things to notice. First, if the cost of addressing climate change is in the neighborhood of \$40-\$50 per t CO_{2e}, then wind energy is competitive with other means of reducing greenhouse gas emissions, even in a region where fossil fuels (coal and gas) and other sources of nonrenewable energy (particularly hydro) are ubiquitous and therefore inexpensive.

Table 1: Incremental Cost of Reducing CO_2 Emissions (\$ per t CO_{2e}), Various Scenarios

	1×Wind	2×Wind	4×Wind
600MW Transmission Scenario			
Drought	\$44.94	\$49.63	\$52.97
Normal river inflow	\$53.35	\$53.49	\$54.75
1200MW Transmission Scenario			
Drought	\$19.55	\$30.69	\$42.97
Normal river inflow	\$56.24	\$36.72	\$55.96

Second, the ability to store wind energy in hydro reservoirs lowers the costs of reducing CO_2 emissions. This is indicated by the result that costs are reduced when the capacity of the intertie between the two provinces is increased. This is true even when the costs of increasing transmission capacity are taken into account.

Third, under drought conditions, wind energy and storage are even more important, as evidenced by the lower costs compared to ‘normal’ river inflows. This occurs because, with drought, wind tends to replace fossil-fuel generated electricity to a greater degree than under normal circumstances, simply because there is less water available to generate electricity and that electricity would otherwise have been generated using fossil fuels.

Finally, as wind penetrates the grid, the costs of reducing CO_2 emissions further increases. Under drought conditions and with ample ability to import wind energy from

Alberta, the costs associated with CO_2 abatement are low. Initially, wind output effectively displaces thermally generated units of energy and therefore it is relatively inexpensive to reduce CO_2 emissions. However, with high wind output and normal water flows, the ability to further displace thermal generation (and reduce CO_2 emissions) becomes increasingly constrained, raising the cost of additional emissions abatement.

5. CONCLUSIONS

One focus of climate change policy is the reduction of CO_2 emissions from the generation of electricity. Government policies in many jurisdictions encourage the development of wind capacity with the aim of lowering carbon dioxide emissions from thermal power generation. However, unless wind energy can somehow be stored, the variability inherent to wind-generated power can have a negative impact on the existing generation mix, causing thermal power plants to operate below their optimal levels and/or in standby mode for longer than necessary, thereby increasing the costs of reducing CO_2 emissions above prices at which CO_2 offsets trade in markets. As demonstrated in this study, storage and increased transmission capacities can reduce such indirect costs.

Climate change may itself dramatically alter another zero-emission energy source, namely hydroelectric generation. In examining the impacts of drought on energy output, we find that, even with increases in wind energy output, thermal generation rises along with CO_2 emissions. Transmission capacity is vital in providing system security, because, in drought conditions without inter-provincial power flows, it is possible that demand in some region cannot be met.

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