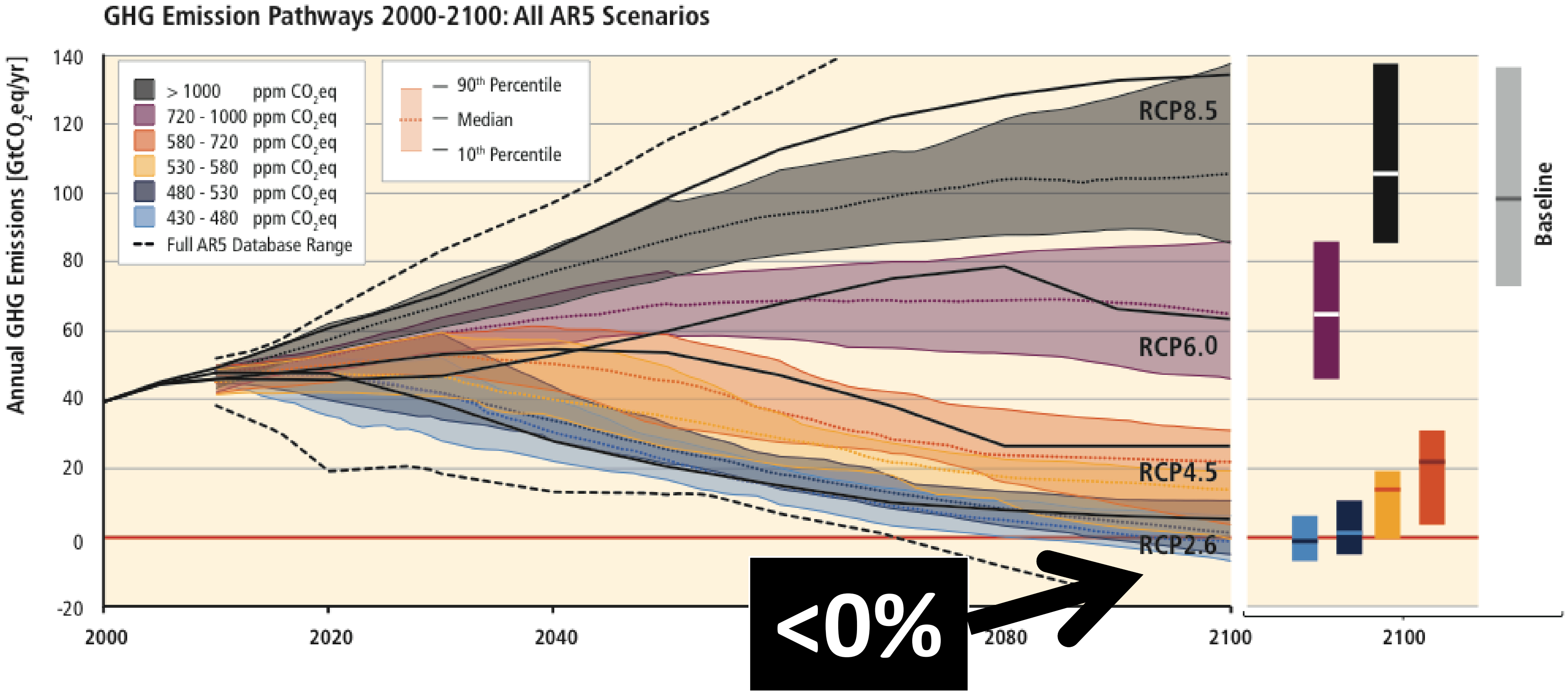
Decarbonizing the Canadian Electricity Sector

Brett Dolter and Nicholas Rivers

Agree “to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty, including **by holding the increase in the global average temperature to well below 2 °C** above pre-industrial levels **and to pursue efforts to limit the temperature increase to 1.5 °C** above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change” (Article 2)

The 2°C Challenge



GHG Emission Pathways 2000-2100: All AR5 Scenarios

<0%

IPCC, 2014: Summary for Policymakers. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Work- ing Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Canada’s Challenge

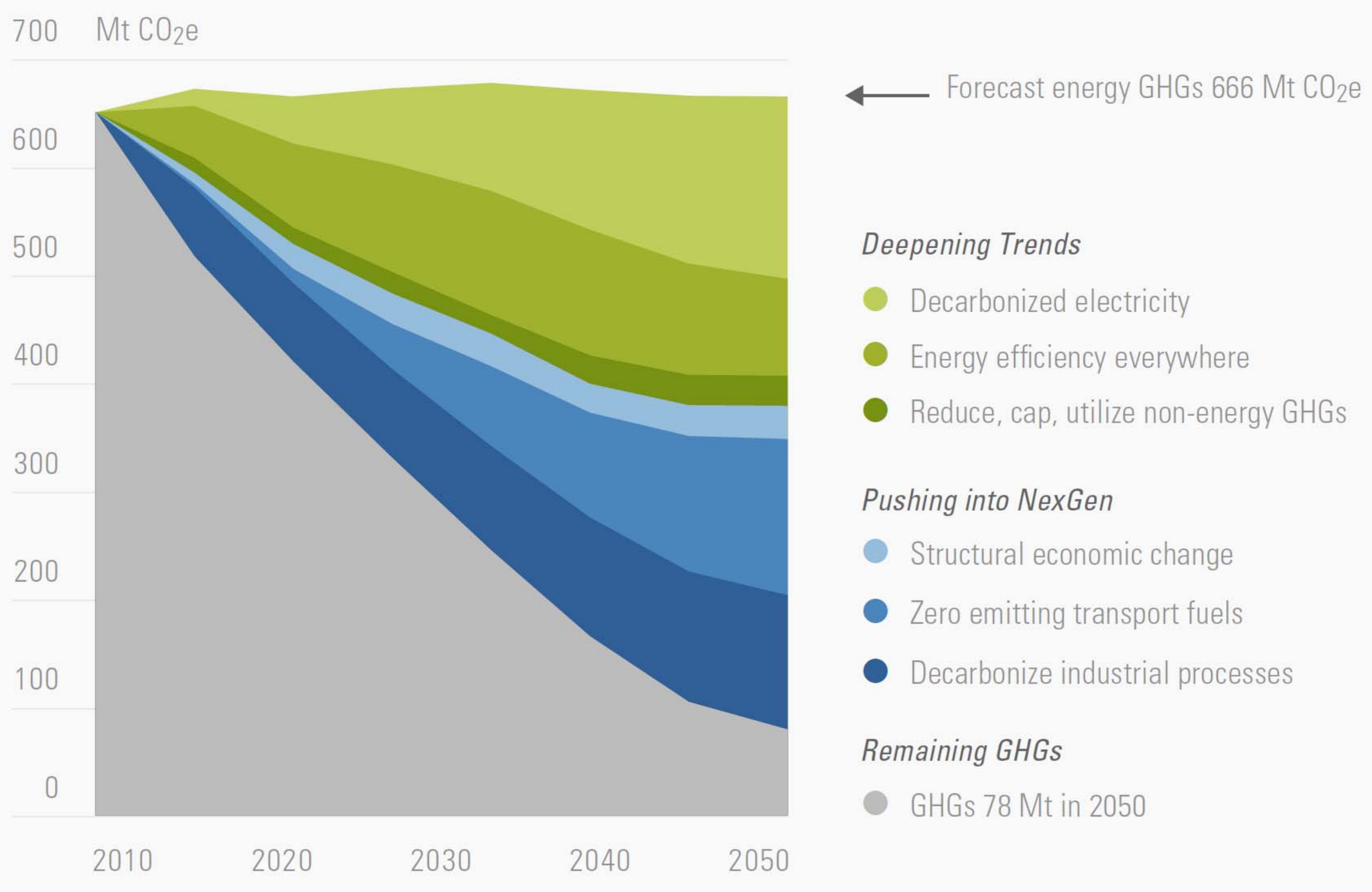
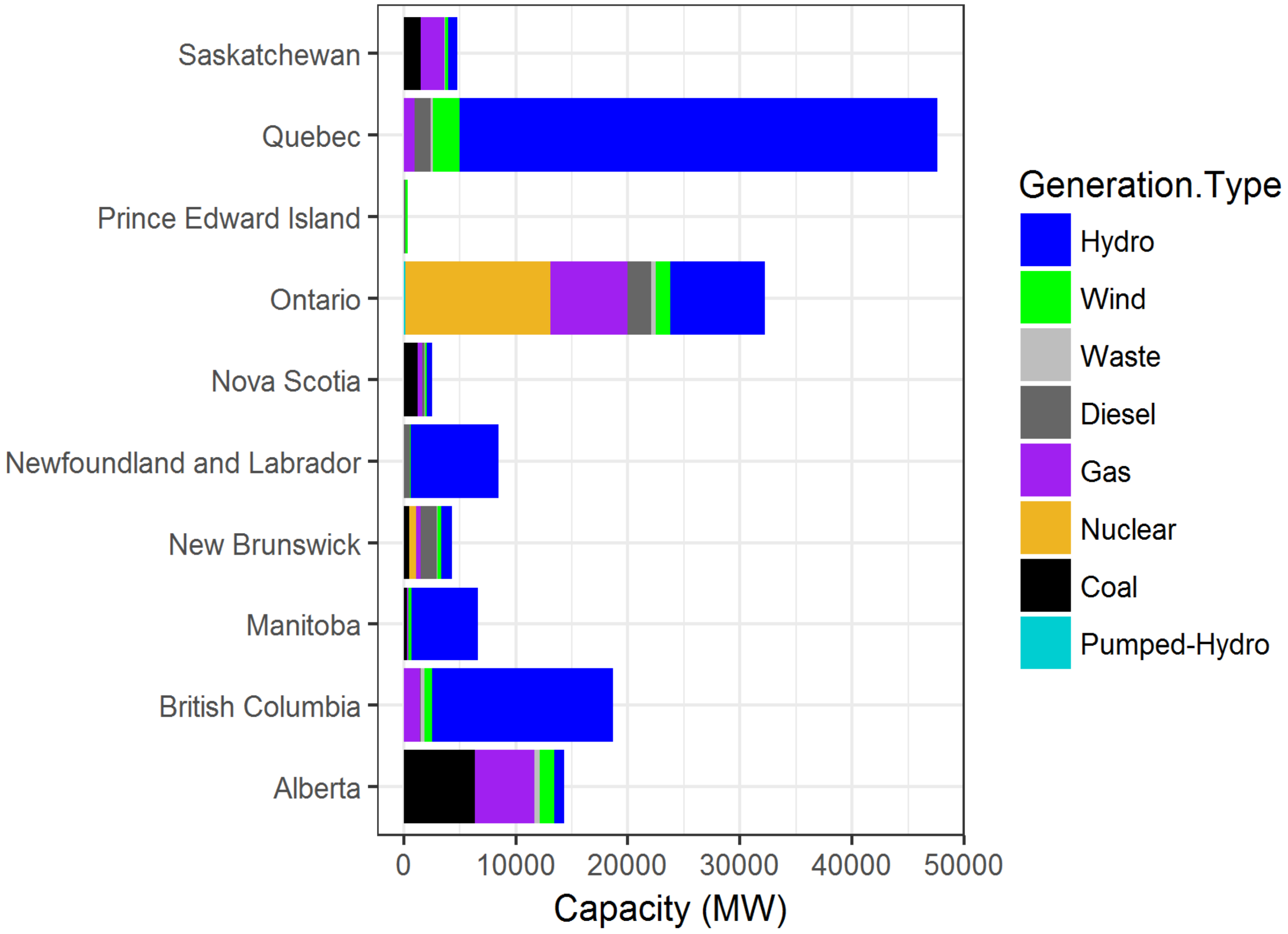
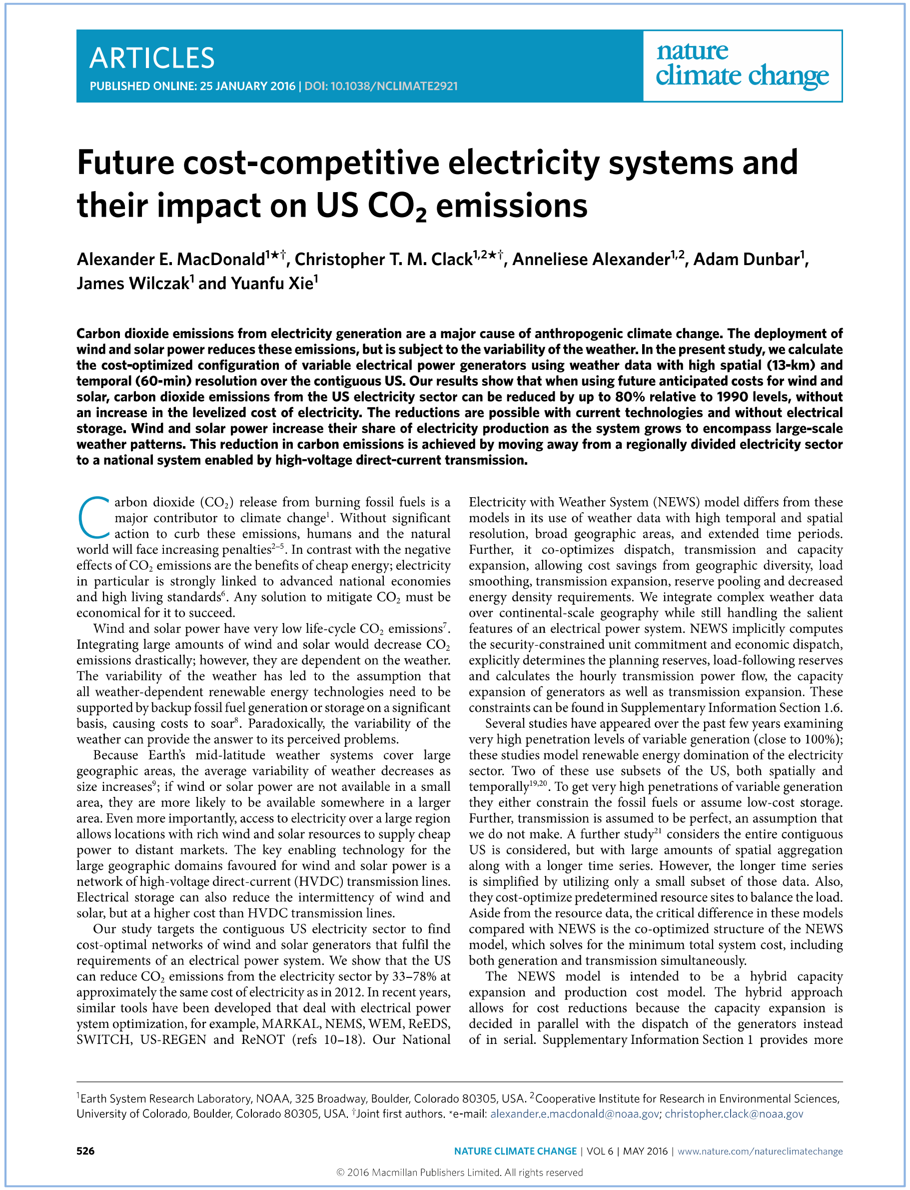


Figure. Deep Decarbonization Pathways to 2°C (excludes land-use emissions)

Bataille, Chris, David Sawyer, and Noel Melton (2015) *Pathways to Deep Decarbonization in Canada*. Deep Decarbonization Project. Available on-line at: http://deepdecarbonization.org/wp-content/uploads/2015/09/DDPP_CAN.pdf. Last accessed December 20, 2016.

Canada’s Advantage





ARTICLES
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nature climate change

Future cost-competitive electricity systems and their impact on US CO_2 emissions

Alexander E. MacDonald[1*†], Christopher T. M. Clack[1,2*†], Anneliese Alexander[1,2], Adam Dunbar[1], James Wilczak[1] and Yuanfu Xie[1]

Carbon dioxide emissions from electricity generation are a major cause of anthropogenic climate change. The deployment of wind and solar power reduces these emissions, but is subject to the variability of the weather. In the present study, we calculate the cost-optimized configuration of variable electrical power generators using weather data with high spatial (13-km) and temporal (60-min) resolution over the contiguous US. Our results show that when using future anticipated costs for wind and solar, carbon dioxide emissions from the US electricity sector can be reduced by up to 80% relative to 1990 levels, without an increase in the levelized cost of electricity. The reductions are possible with current technologies and without electrical storage. Wind and solar power increase their share of electricity production as the system grows to encompass large-scale weather patterns. This reduction in carbon emissions is achieved by moving away from a regionally divided electricity sector to a national system enabled by high-voltage direct-current transmission.

Carbon dioxide (CO_2) release from burning fossil fuels is a major contributor to climate change[1]. Without significant action to curb these emissions, humans and the natural world will face increasing penalties[2–5]. In contrast with the negative effects of CO_2 emissions are the benefits of cheap energy; electricity in particular is strongly linked to advanced national economies and high living standards[6]. Any solution to mitigate CO_2 must be economical for it to succeed.

Wind and solar power have very low life-cycle CO_2 emissions[7]. Integrating large amounts of wind and solar would decrease CO_2 emissions drastically; however, they are dependent on the weather. The variability of the weather has led to the assumption that all weather-dependent renewable energy technologies need to be supported by backup fossil fuel generation or storage on a significant basis, causing costs to soar[8]. Paradoxically, the variability of the weather can provide the answer to its perceived problems.

Because Earth's mid-latitude weather systems cover large geographic areas, the average variability of weather decreases as size increases[9]; if wind or solar power are not available in a small area, they are more likely to be available somewhere in a larger area. Even more importantly, access to electricity over a large region allows locations with rich wind and solar resources to supply cheap power to distant markets. The key enabling technology for the large geographic domains favoured for wind and solar power is a network of high-voltage direct-current (HVDC) transmission lines. Electrical storage can also reduce the intermittency of wind and solar, but at a higher cost than HVDC transmission lines.

Our study targets the contiguous US electricity sector to find cost-optimal networks of wind and solar generators that fulfil the requirements of an electrical power system. We show that the US can reduce CO_2 emissions from the electricity sector by 33–78% at approximately the same cost of electricity as in 2012. In recent years, similar tools have been developed that deal with electrical power ystem optimization, for example, MARKAL, NEMS, WEM, ReEDS, SWITCH, US-REGEN and ReNOT (refs 10–18). Our National Electricity with Weather System (NEWS) model differs from these models in its use of weather data with high temporal and spatial resolution, broad geographic areas, and extended time periods. Further, it co-optimizes dispatch, transmission and capacity expansion, allowing cost savings from geographic diversity, load smoothing, transmission expansion, reserve pooling and decreased energy density requirements. We integrate complex weather data over continental-scale geography while still handling the salient features of an electrical power system. NEWS implicitly computes the security-constrained unit commitment and economic dispatch, explicitly determines the planning reserves, load-following reserves and calculates the hourly transmission power flow, the capacity expansion of generators as well as transmission expansion. These constraints can be found in Supplementary Information Section 1.6.

Several studies have appeared over the past few years examining very high penetration levels of variable generation (close to 100%); these studies model renewable energy domination of the electricity sector. Two of these use subsets of the US, both spatially and temporally[19,20]. To get very high penetrations of variable generation they either constrain the fossil fuels or assume low-cost storage. Further, transmission is assumed to be perfect, an assumption that we do not make. A further study[21] considers the entire contiguous US is considered, but with large amounts of spatial aggregation along with a longer time series. However, the longer time series is simplified by utilizing only a small subset of those data. Also, they cost-optimize predetermined resource sites to balance the load. Aside from the resource data, the critical difference in these models compared with NEWS is the co-optimized structure of the NEWS model, which solves for the minimum total system cost, including both generation and transmission simultaneously.

The NEWS model is intended to be a hybrid capacity expansion and production cost model. The hybrid approach allows for cost reductions because the capacity expansion is decided in parallel with the dispatch of the generators instead of in serial. Supplementary Information Section 1 provides more

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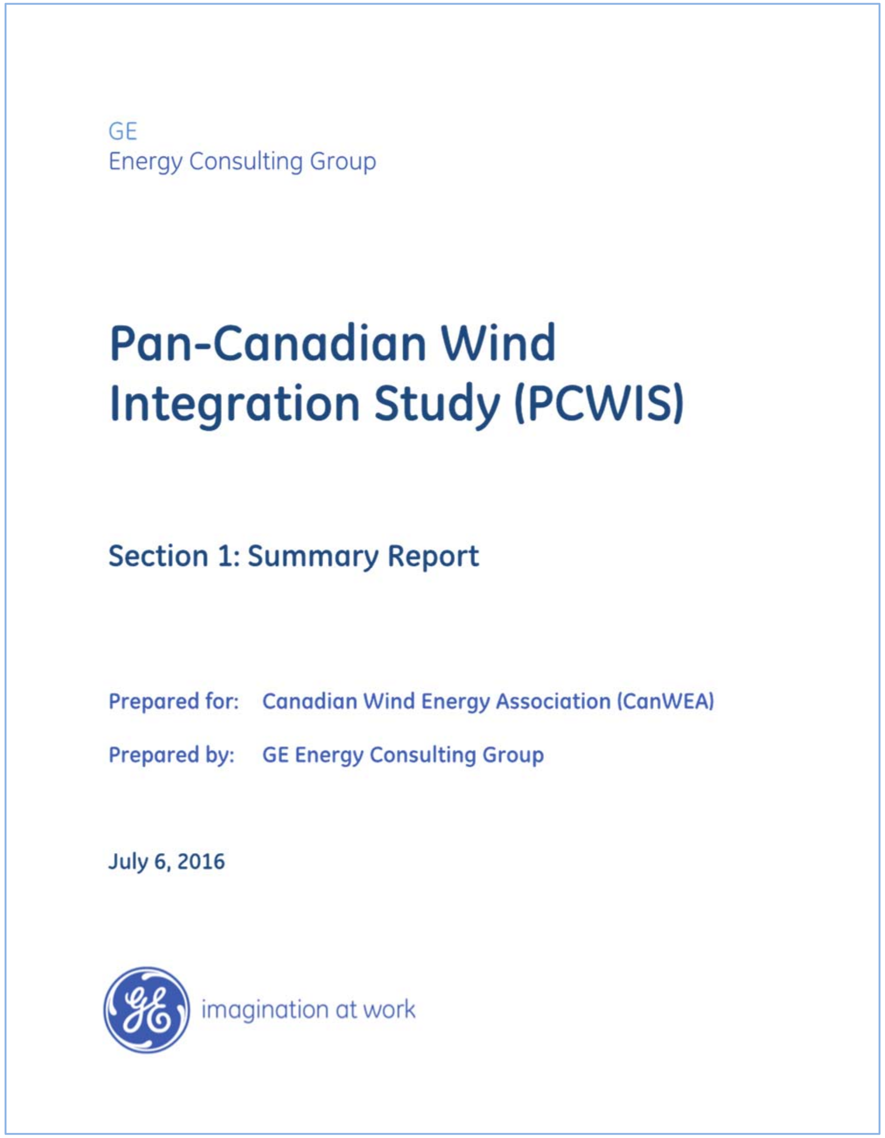


GE
Energy Consulting Group

Pan-Canadian Wind Integration Study (PCWIS)

Section 1: Summary Report

Prepared for: Canadian Wind Energy Association (CanWEA)

Prepared by: GE Energy Consulting Group

July 6, 2016

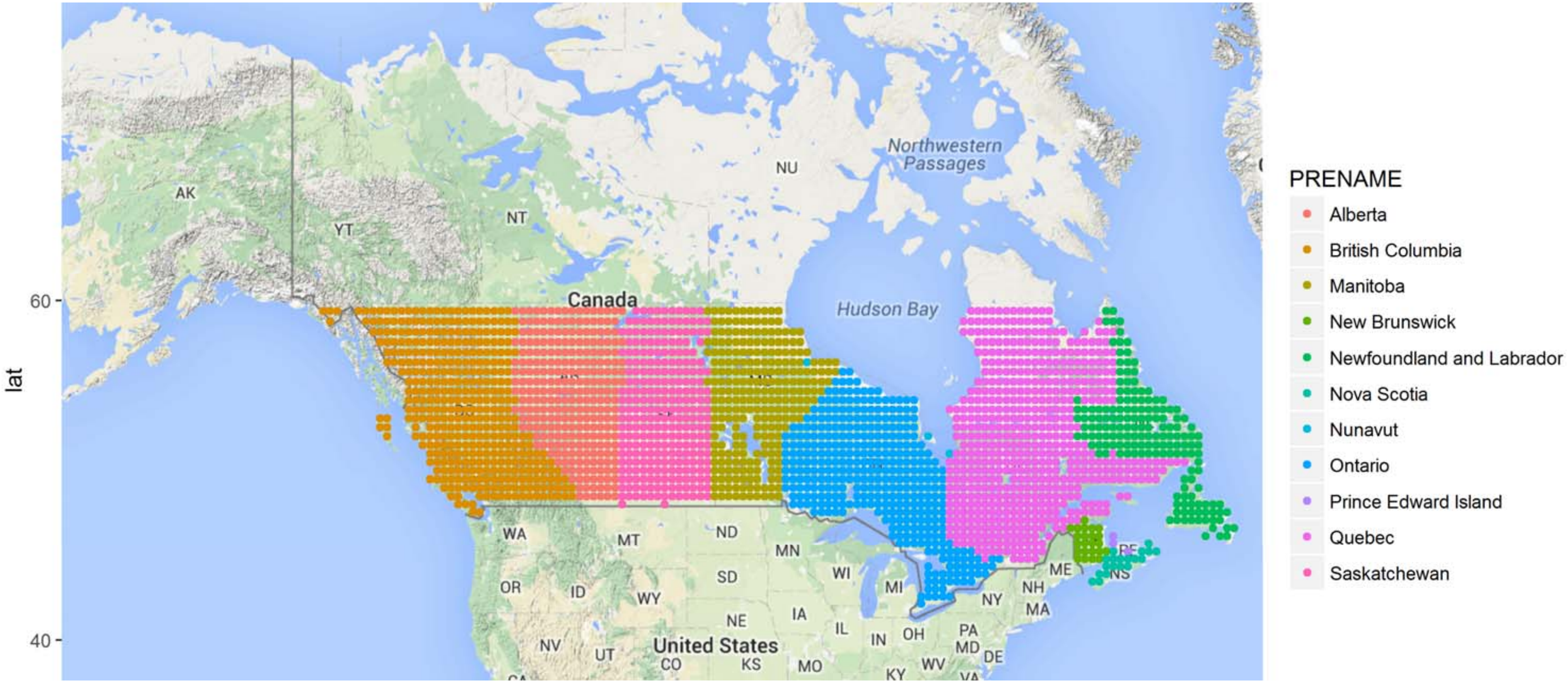
imagination at work

Wind and solar power increase their share of electricity production as the system grows to encompass large-scale weather patterns. This reduction in carbon emissions is achieved by moving away from a regionally divided electricity sector to a national system enabled by high-voltage direct-current transmission.

Model

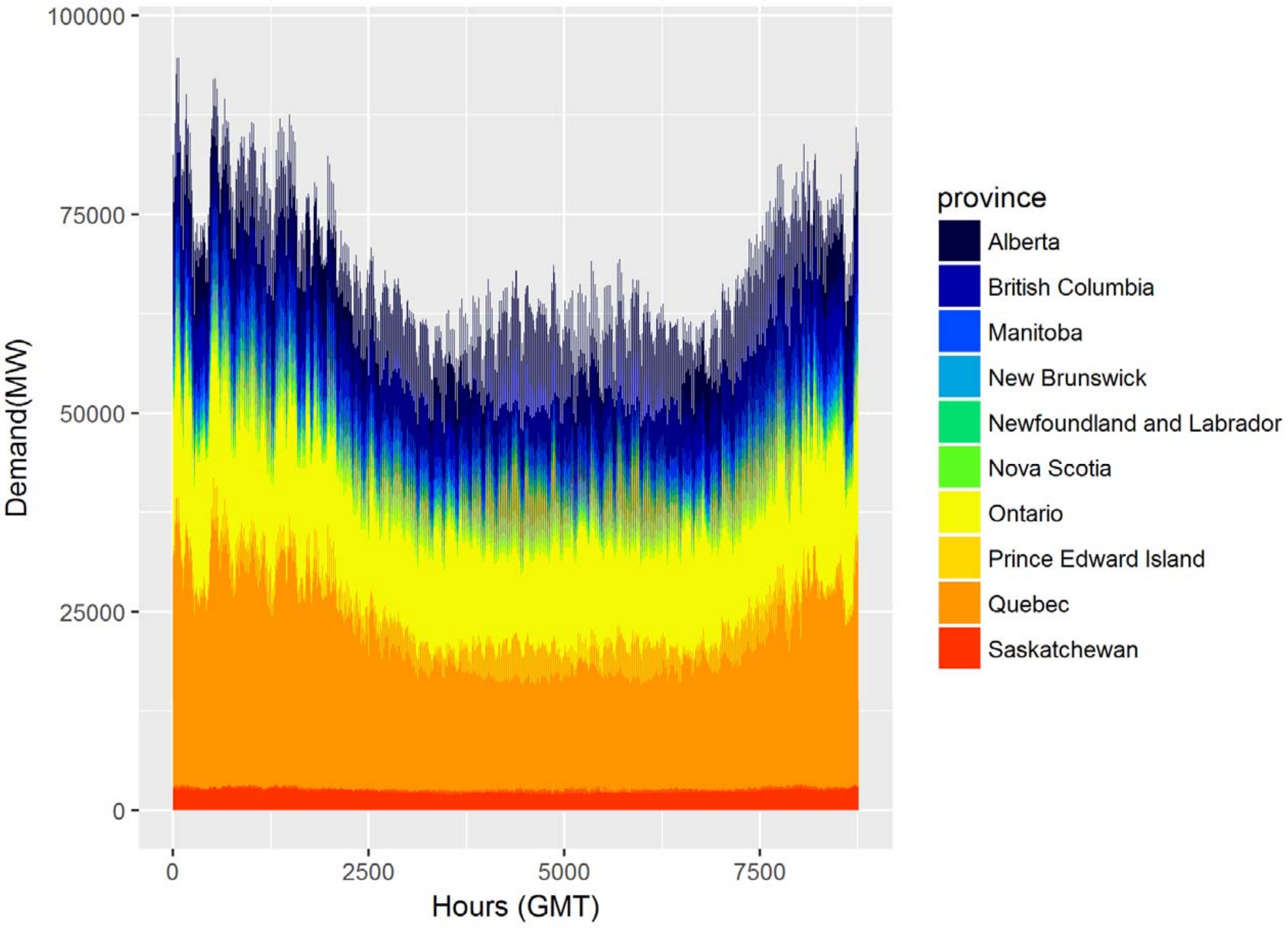
- Linear programming model with rich spatial and temporal detail

Spatial Data

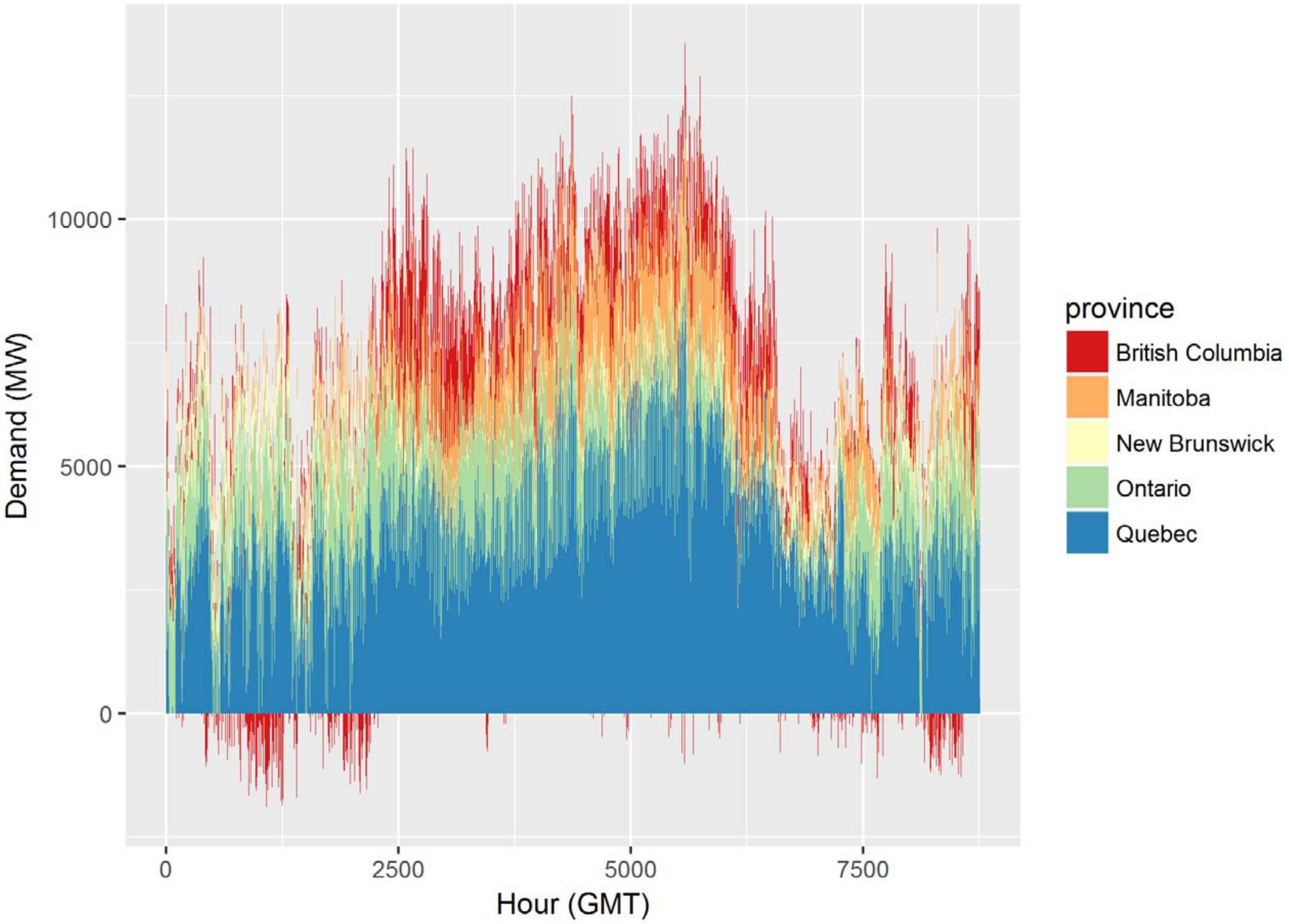


- MERRA wind database with 2281 grid cells
- Grid cells: ½ degree latitude & 2/3 degree longitude
- Keep cells south of 60 latitude

Hourly Demand Data



Hourly Export Data



Model

- Linear programming model with rich spatial (2281 grid cells) and temporal (8760 hours) detail
- Objective: Minimize annual cost
  - Annualized capital costs for new generation, transmission and storage
  - Fuel costs
  - Operations and maintenance costs
  - Carbon costs

Cost Assumptions

Technology	Capital Cost ($CAD/kw)	Amortization (yrs)	Annualized Capital Cost ($CAD/MW)	Efficiency (%)	Variable O&M ($/MWh)	Fixed O&M ($/MW/yr)	Capacity Factor (%)	
							Min.	Max.
Coal	$3,836	25	$440,647	39.0%	$4.48	$76,723	40%	93%
Diesel	$831	25	$95,474	39.0%	$19.18	$19,181	10%	95%
Natural Gas Combined Cycle	$1,471	20	$178,355	50.9%	$3.52	$7,480	40%	70%
Natural Gas Simple Cycle	$1,151	20	$139,582	28.0%	$7.80	$19,181	5%	20%
Nuclear	$8,695	25	$998,801	32.7%	$0.80	$172,626	40%	90%
Pumped Hydro	$2,500	25	$287,169	75.0%	-	$18,000	-	-
Solar	$1,790	20	$205,635	-	-	$14,705	-	-
Waste	NA	NA	NA	39.0%	$100.00	$100,000	40%	80%
Wind	$1,598	20	$193,864	-	-	$47,952	-	-

Lazard v 9.0 (2015) and Trottier Energy Futures Project (2016)

Fuel	$ per GJ	tonnes CO_2e per GJ
Coal	1.80	0.090
Diesel	25.80	0.072
Natural Gas	4.91	0.051
Uranium	1.00	0.000

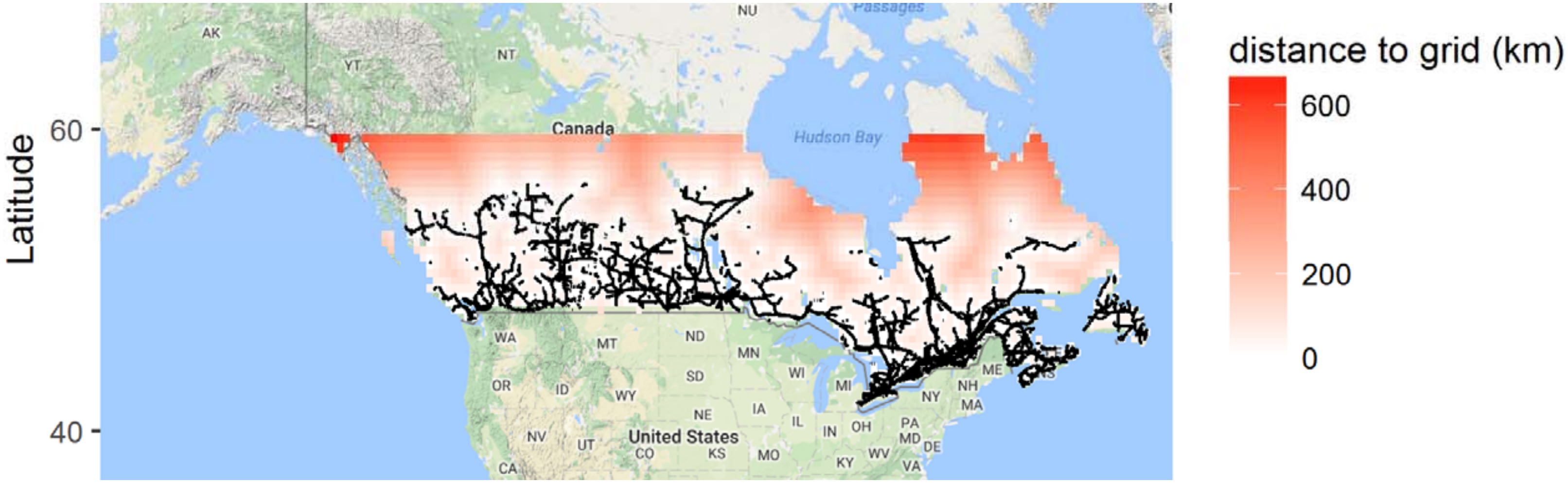
NEB (2016) and Westmoreland Coal (2016) and Lazard v 9.0 (2015)

Cost Assumptions

Transmission Technology	Capital Cost ($Million CAD/km)	Annualized Capital Cost ($CAD/MW/km/yr)	Fixed O&M ($/MW/yr)
Double-circuit 345 kv HVDC	$2.4	$184	$10,860
Single-circuit 230 kv HVDC	$1.6	$557	-

CANWEA and General Electric (2016)

Distance to the Existing Grid



Model

- Linear programming model with rich spatial (2281 grid cells) and temporal (8760 hours) detail
- Objective: Minimize annual cost
  - Annualized capital costs for new generation, transmission and storage
  - Fuel costs
  - Operations and maintenance costs
  - Carbon costs
- Decision variables:
  - Investment in new generation, transmission, storage
  - Hourly dispatch

Model Constraints

- Supply ≥ demand in each hour and balancing area

$$\sum_{p} supply_{h,aba,ap,p} + \ (1 - trans_{loss}{}_{abba,app,aba,ap})\times transmission_{h,abba,app,aba,ap})$$

$$\geq \ demand_{h,aba,ap} + transmission_{h,aba,ap,abba,apa}$$

- Supply ≤ capacity in each balancing area

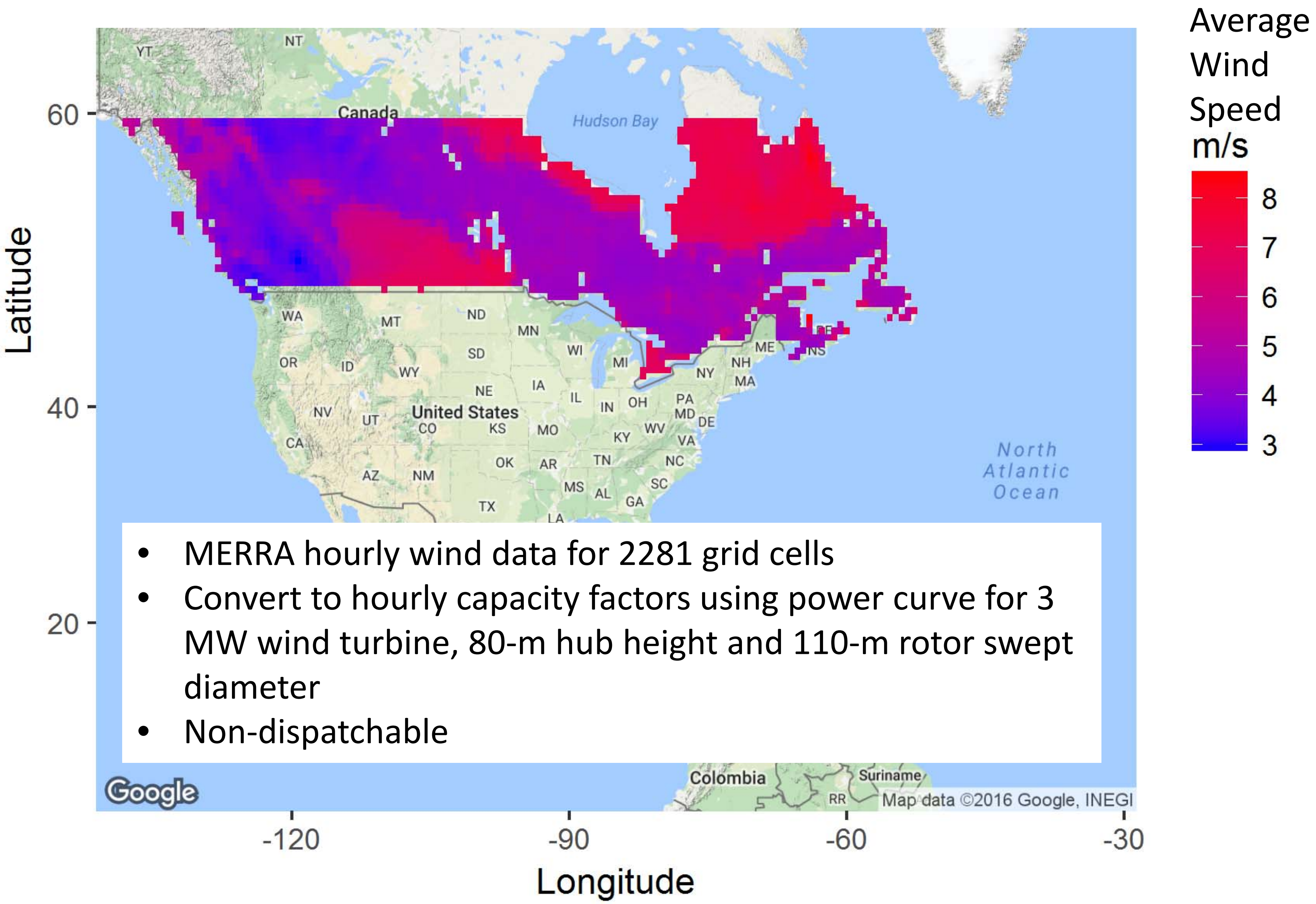
$$supply_{h,aba,ap,tp} \ \leq \ new\ capacity_{aba,ap,tp} \ + \ \ extant\ capacity_{aba,ap,tp}$$

- Ramp rate constraints

$$supply_{h+1,ap,aba,tp} \ \leq \ supply_{h,ap,aba,tp} + \left(capacity_{ap,aba,tp}\right) \times ramp\ rate_{tp}$$

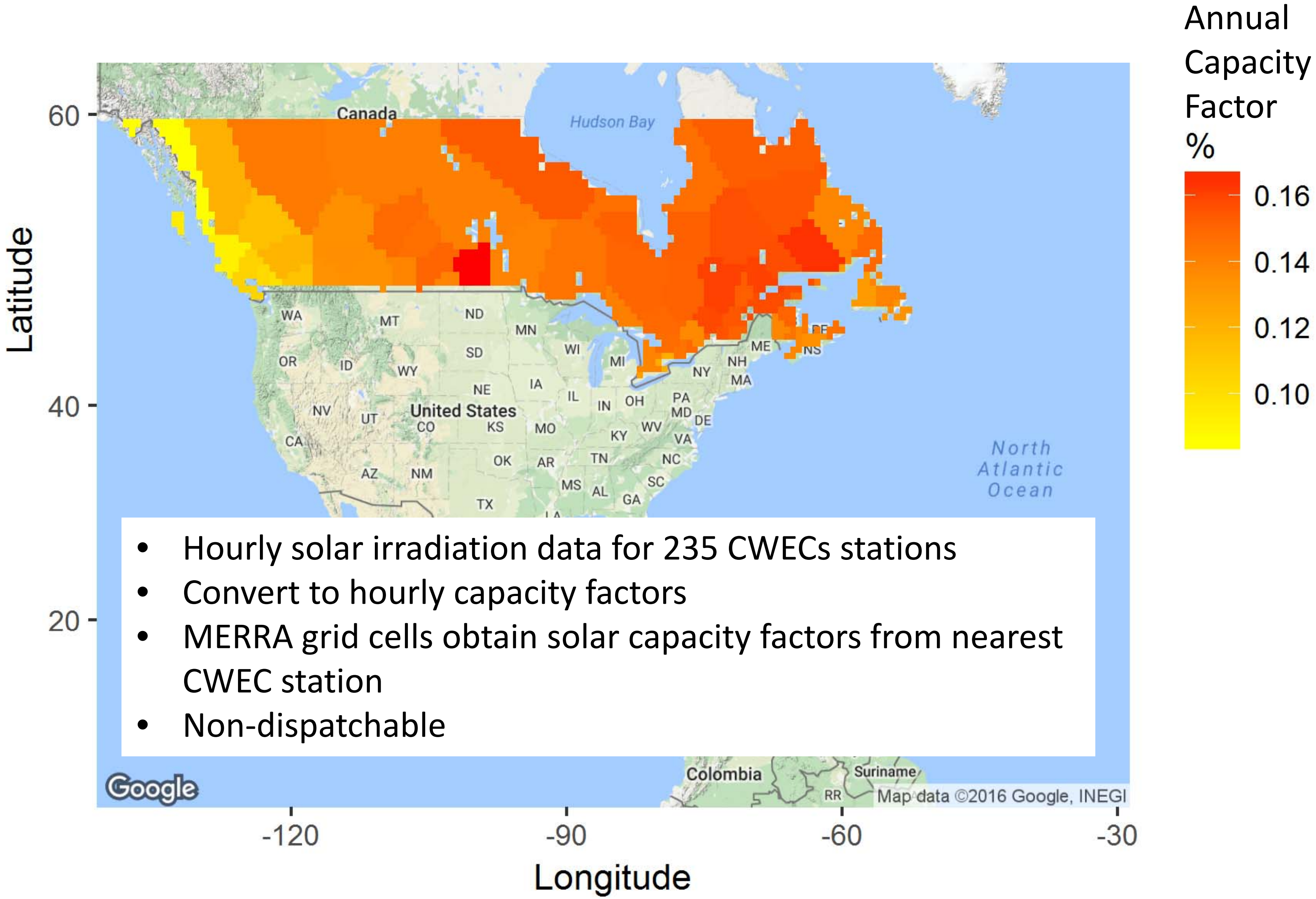
$$supply_{h+1,ap,aba,tp} \ \geq \ supply_{h,ap,aba,tp} - \left(capacity_{ap,aba,tp}\right) \times ramp\ rate_{tp}$$

Wind Modelling



- MERRA hourly wind data for 2281 grid cells
- Convert to hourly capacity factors using power curve for 3 MW wind turbine, 80-m hub height and 110-m rotor swept diameter
- Non-dispatchable

Solar Modelling

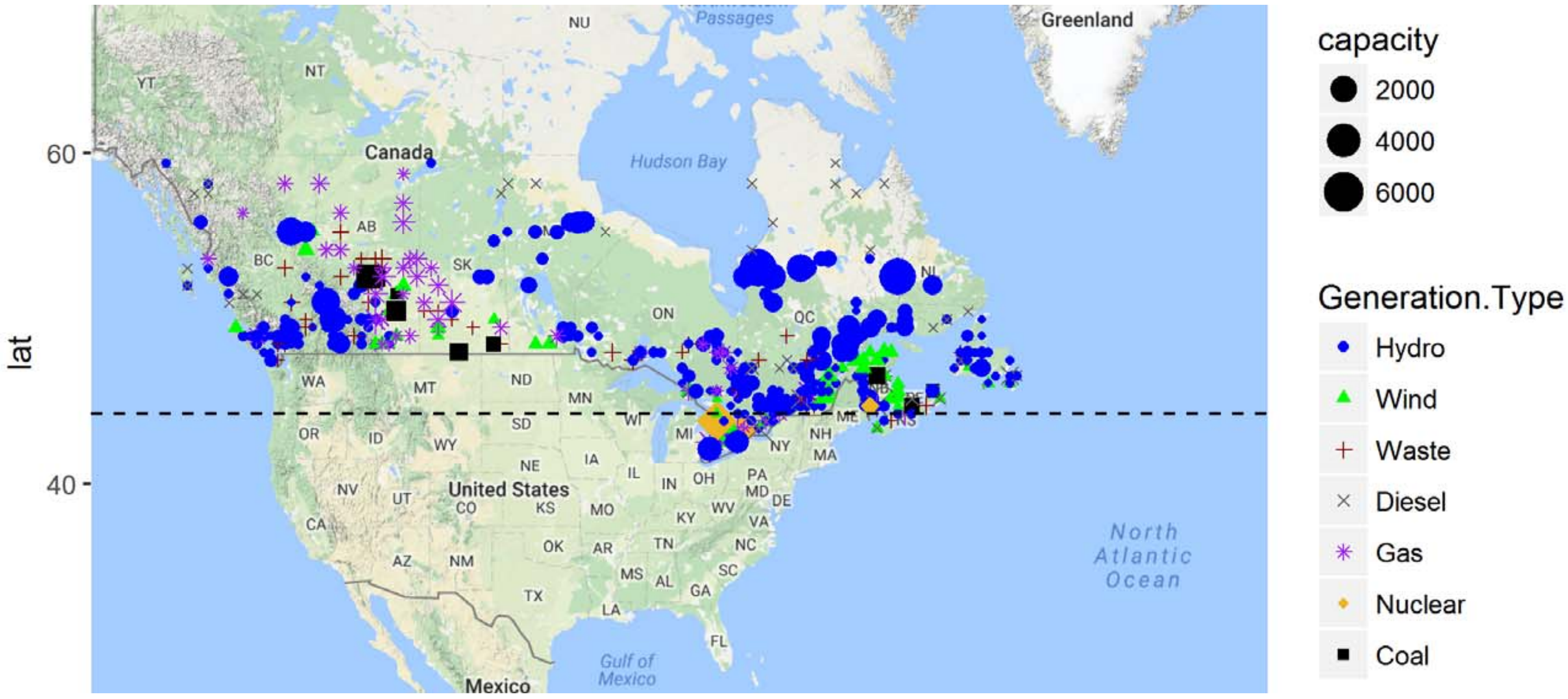


- Hourly solar irradiation data for 235 CWECs stations
- Convert to hourly capacity factors
- MERRA grid cells obtain solar capacity factors from nearest CWEC station
- Non-dispatchable

Hydro Modelling

- Distinguish between run-of-river and reservoir
- Differentiate intra-day versus intra-month storage

Extant Generation



- Account for scheduled retirements by 2025

Extant Transmission

Table 1 - Inter-Provincial Trade Parameters

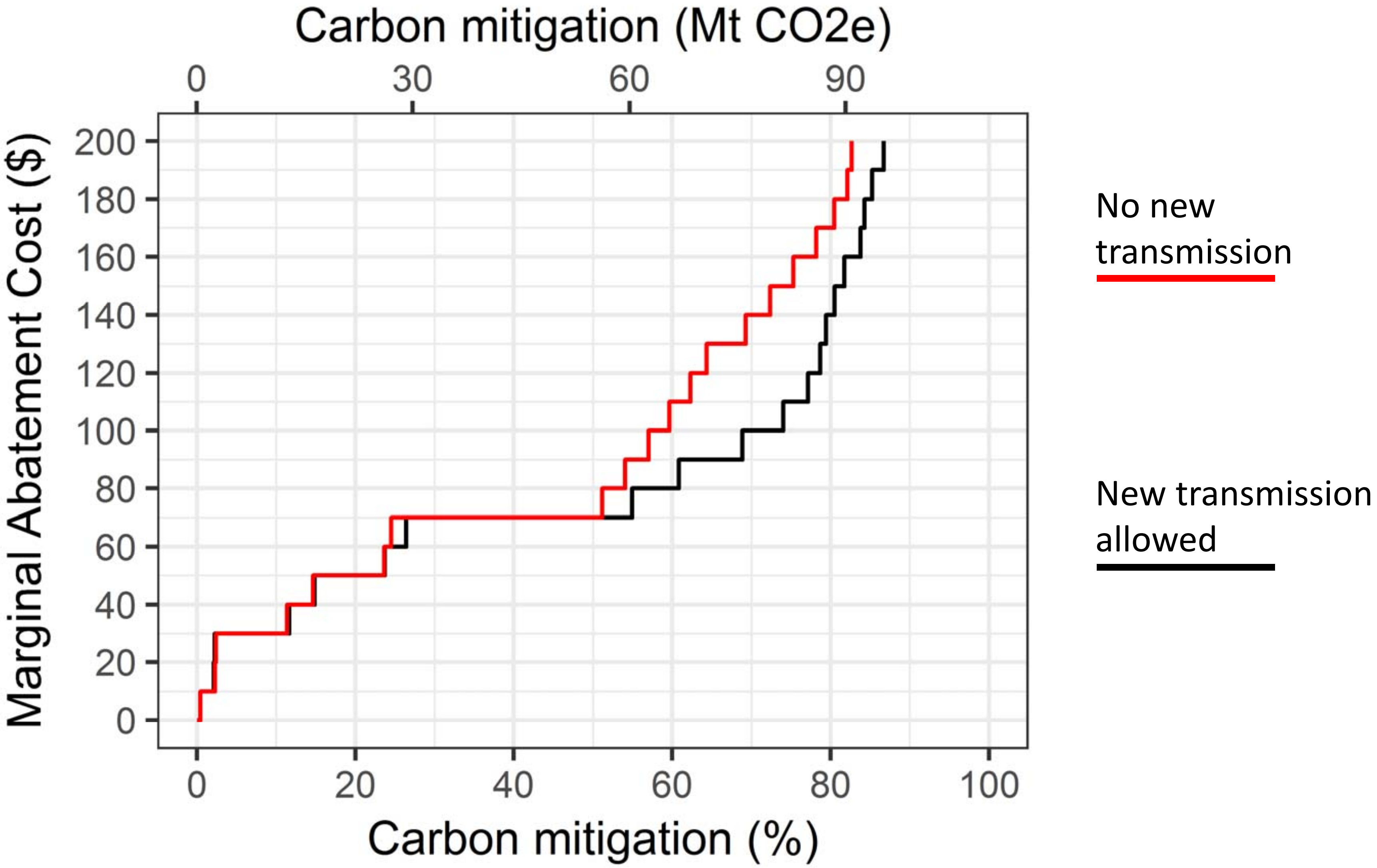
Exporting region to destination	Installed Capacity in 2011	Exporting region to destination	Installed Capacity in 2011
	MW		MW
AB to BC	1000	NS to NB	350
AB to SK	80	PE to NB	220
BC to AB	1200	ON to MB	280
MB to ON	343	ON to QC	1980
MB to SK	150	QC to NB	1030
NB to NS	300	QC to NL	0
NB to PE	220	QC to ON	2380
NB to QC	790	SK to AB	150
NL to QC	5150	SK to MB	50

Source: Trottier Energy Futures Project (2016: 103)

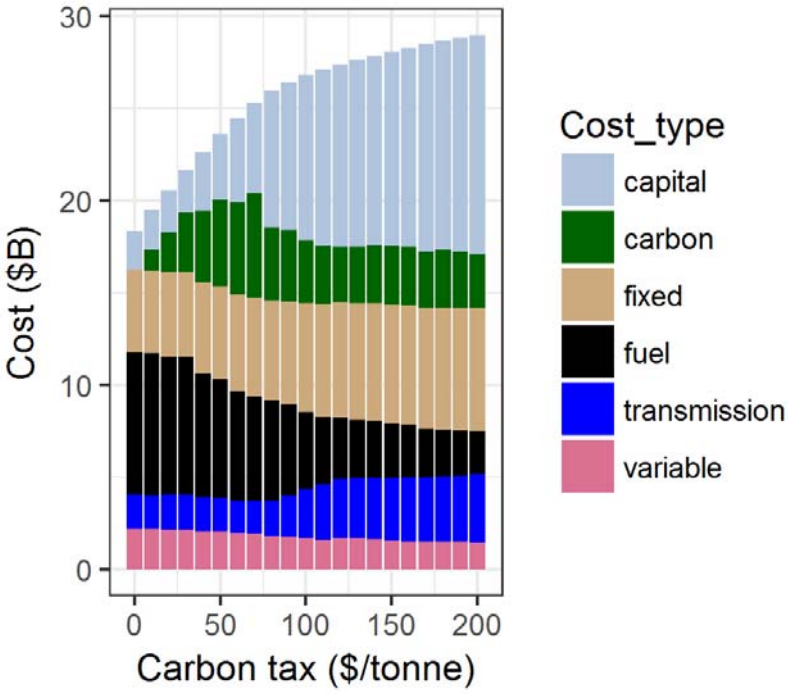
Scenarios

- **2025** electricity demand
- **Carbon pricing** \$0 - 200/tonne CO_2e
- New inter-provincial **transmission** vs.
  No new inter-provincial **transmission**

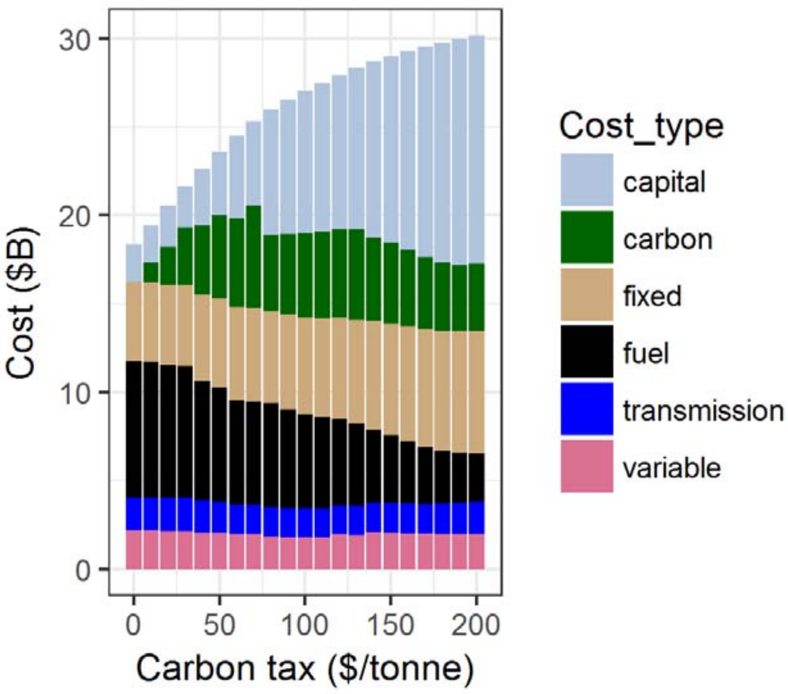
Marginal Abatement Costs



Incremental Electricity System Cost

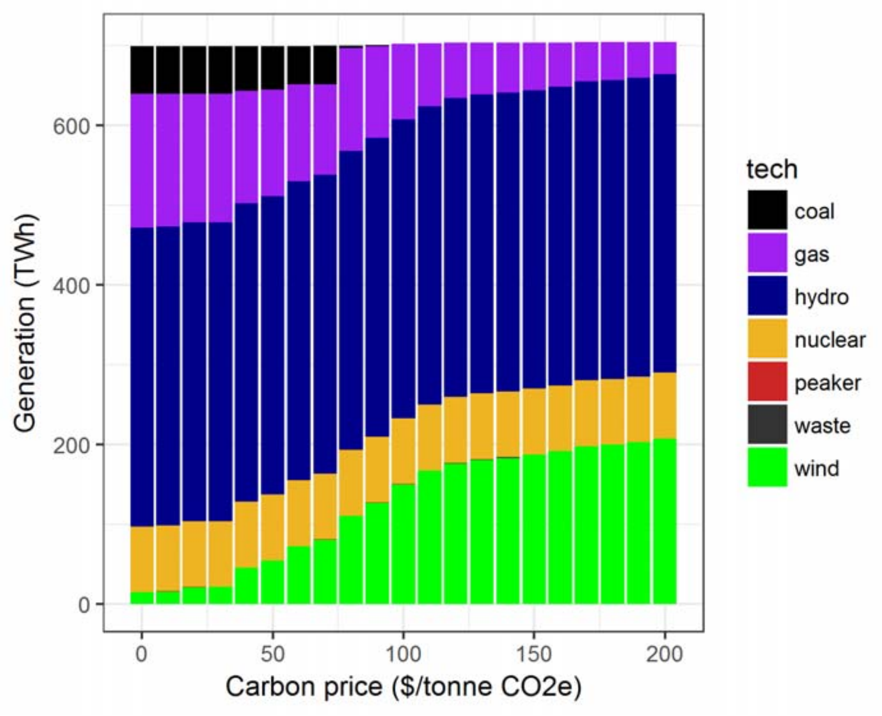


New transmission allowed

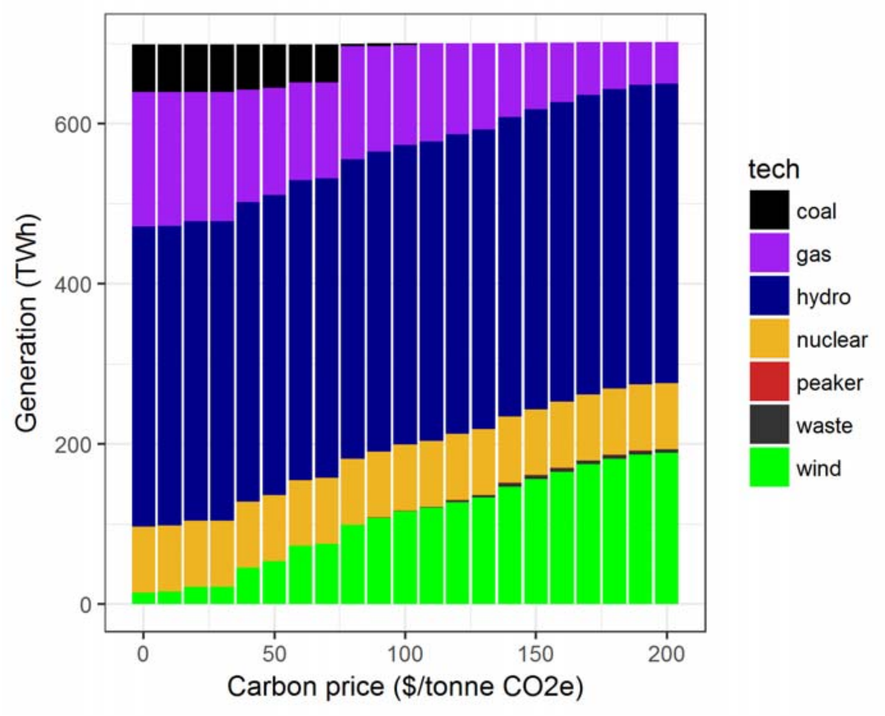


No new transmission

Generation Mix



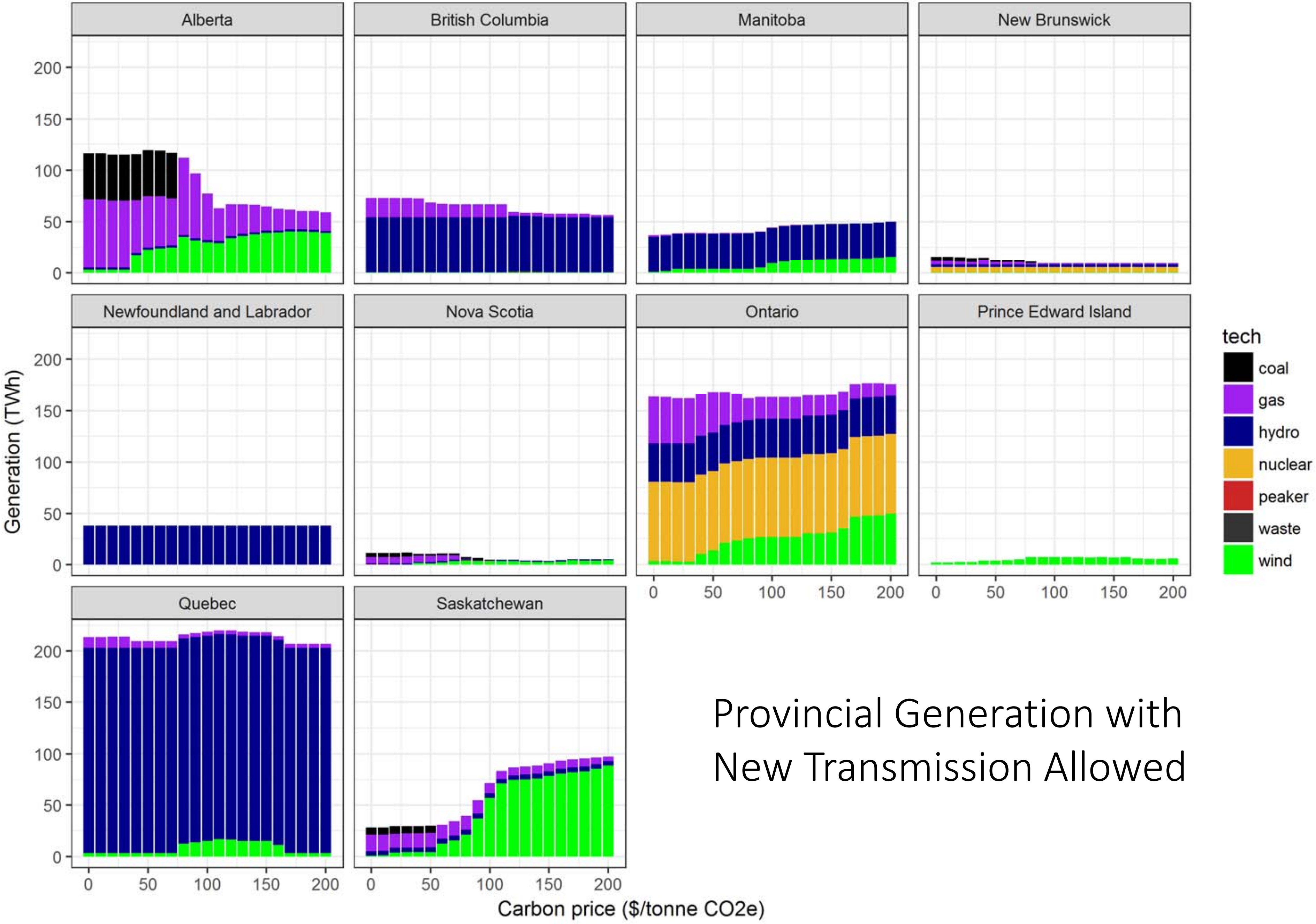
New transmission allowed



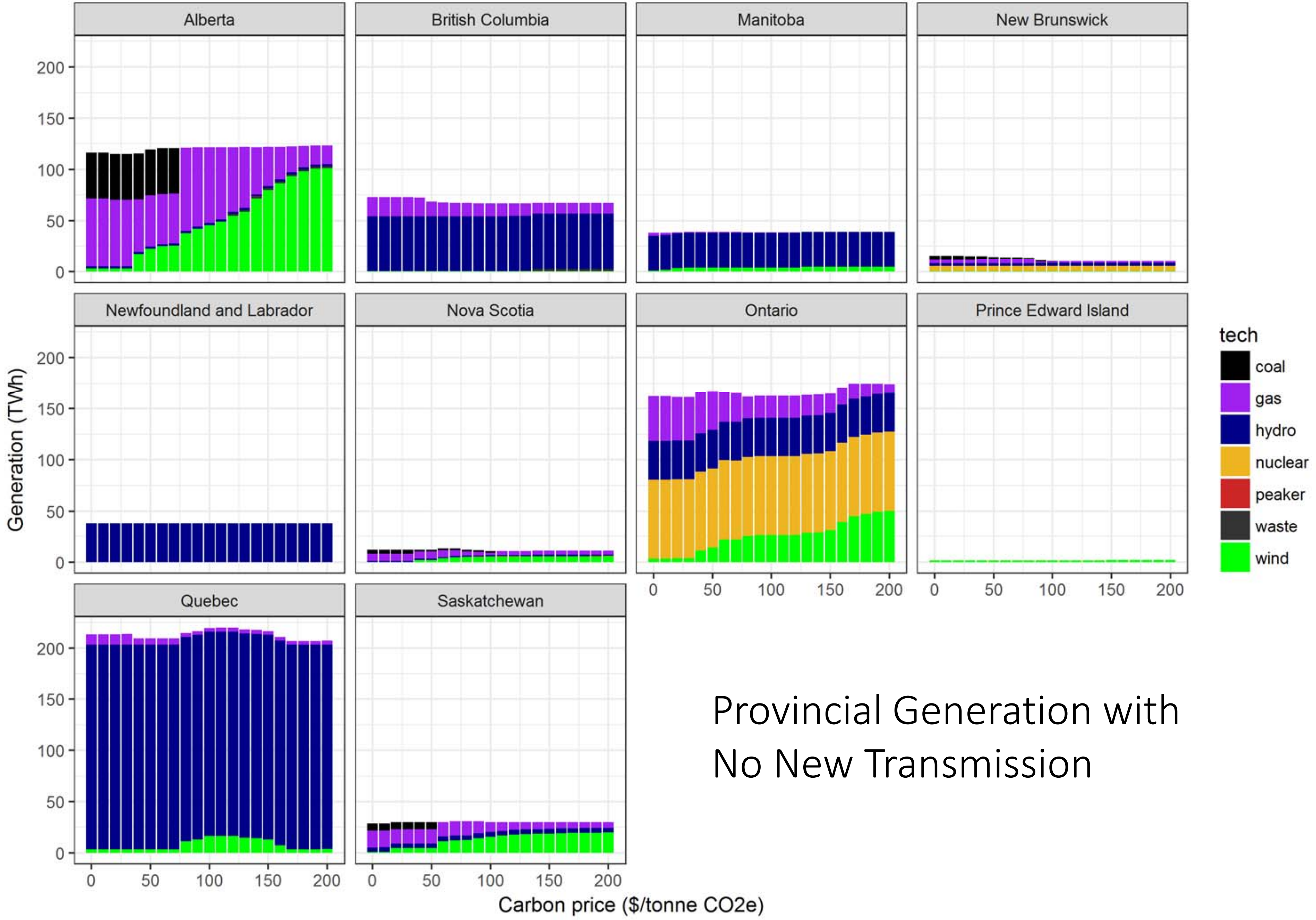
No new transmission

New Transmission (\$200/tonne CO_2e)

Exporting Province	Importing Province	MW
Alberta	British Columbia	1700
Saskatchewan	Alberta	9552
Manitoba	Saskatchewan	1858
Ontario (north)	Quebec (south)	459
Quebec (north)	Quebec (south)	7167
Quebec (north)	New Brunswick	356
Newfoundland and Labrador (south)	Nova Scotia	48
Newfoundland and Labrador (north)	New Brunswick	340
Newfoundland and Labrador (north)	Newfoundland and Labrador (south)	759
Newfoundland and Labrador (north)	Nova Scotia	954
Newfoundland and Labrador (north)	Prince Edward Island	440
Prince Edward Island	New Brunswick	437
Prince Edward Island	Nova Scotia	549

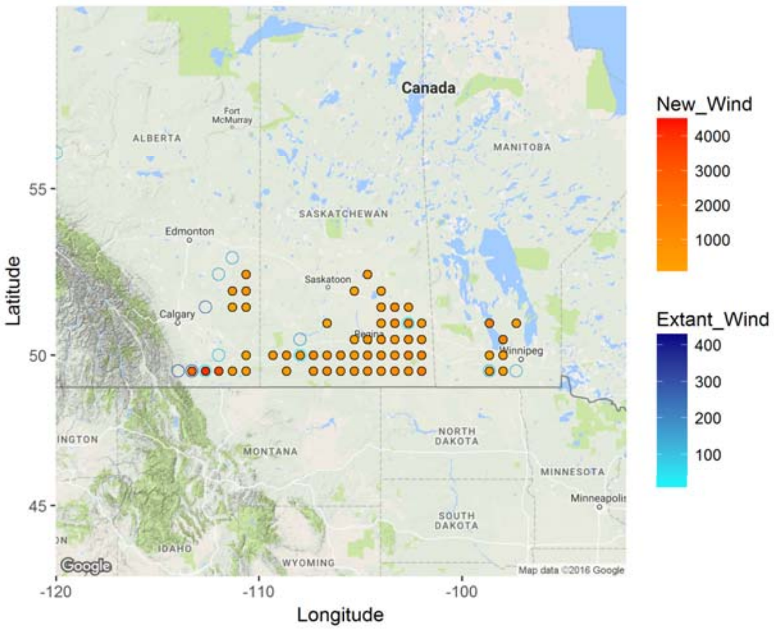


Provincial Generation with New Transmission Allowed

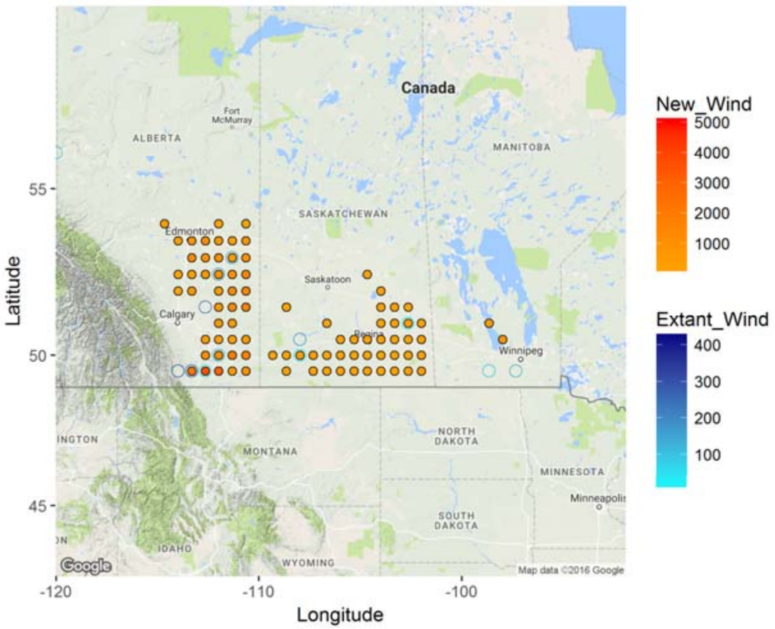


Provincial Generation with No New Transmission

Wind Locations
at $200/tonne CO2e



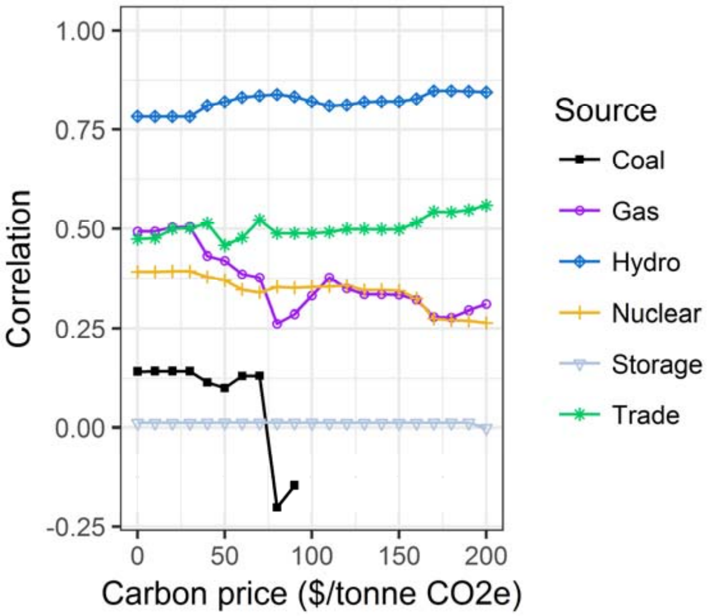
New transmission allowed



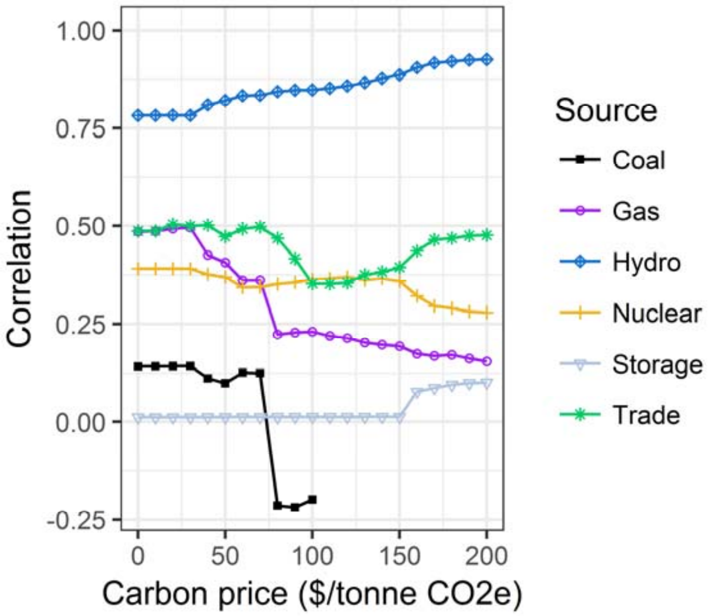
No new transmission

Balancing Variability

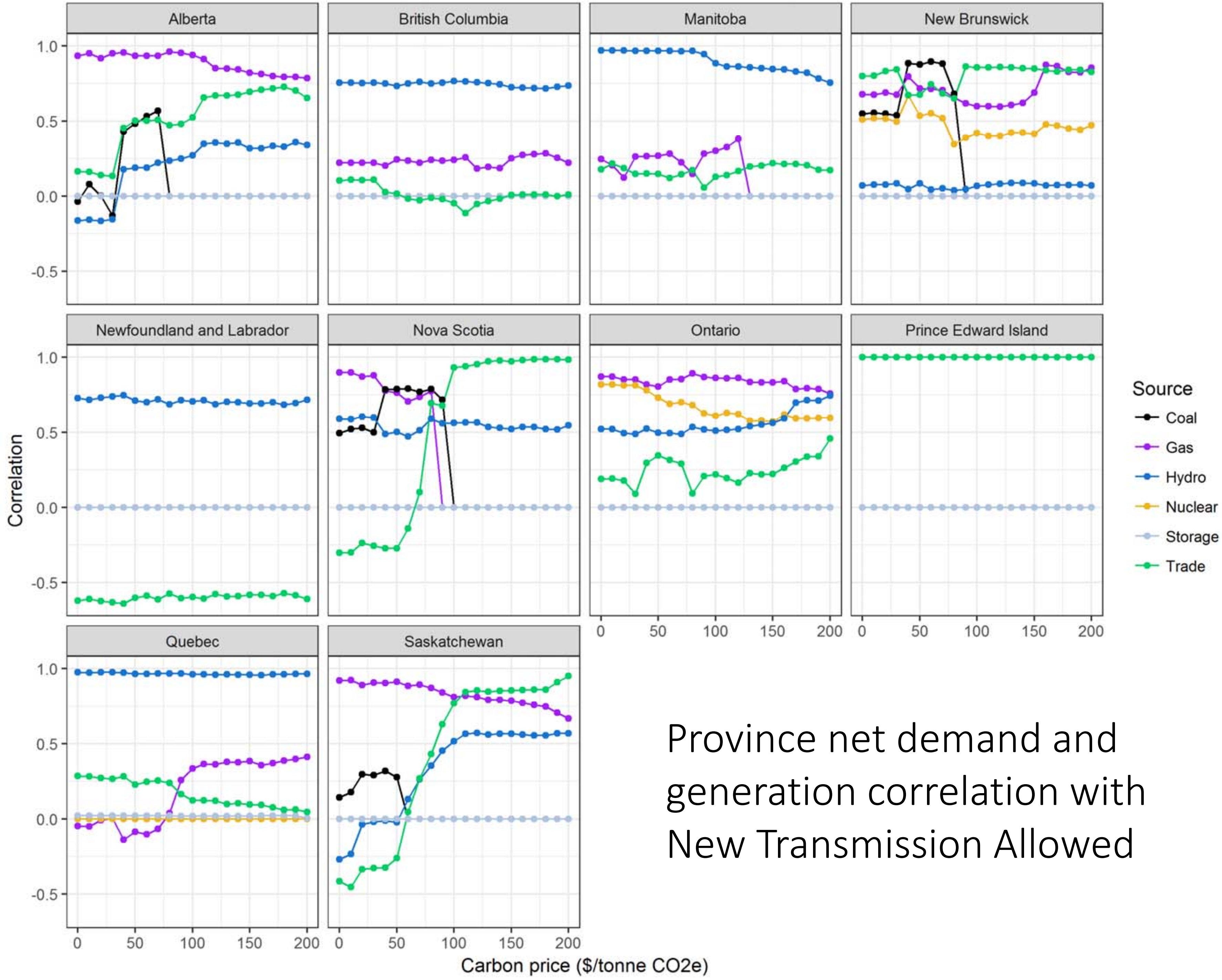
Correlation of Net Demand and Generation



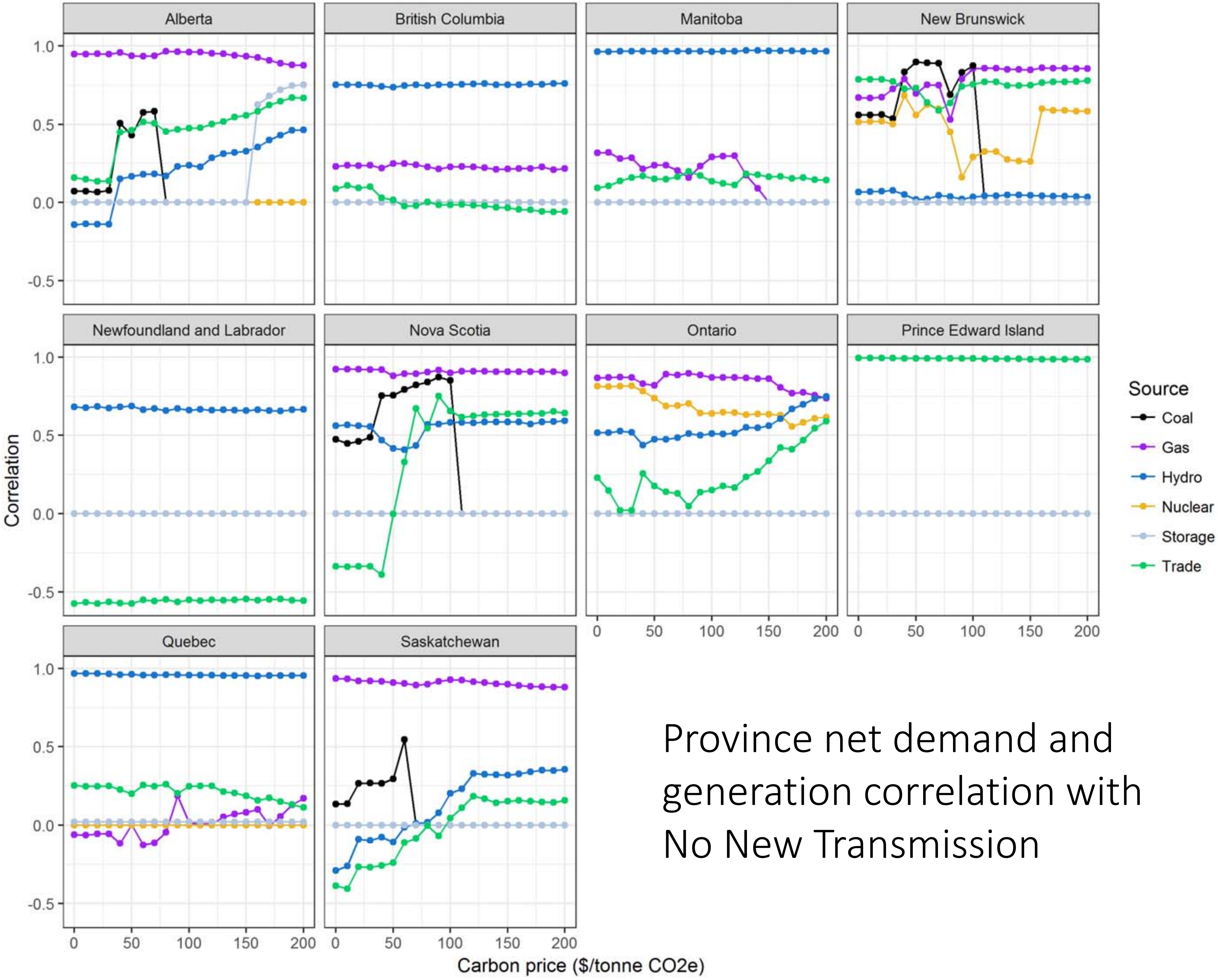
New transmission allowed



No new transmission

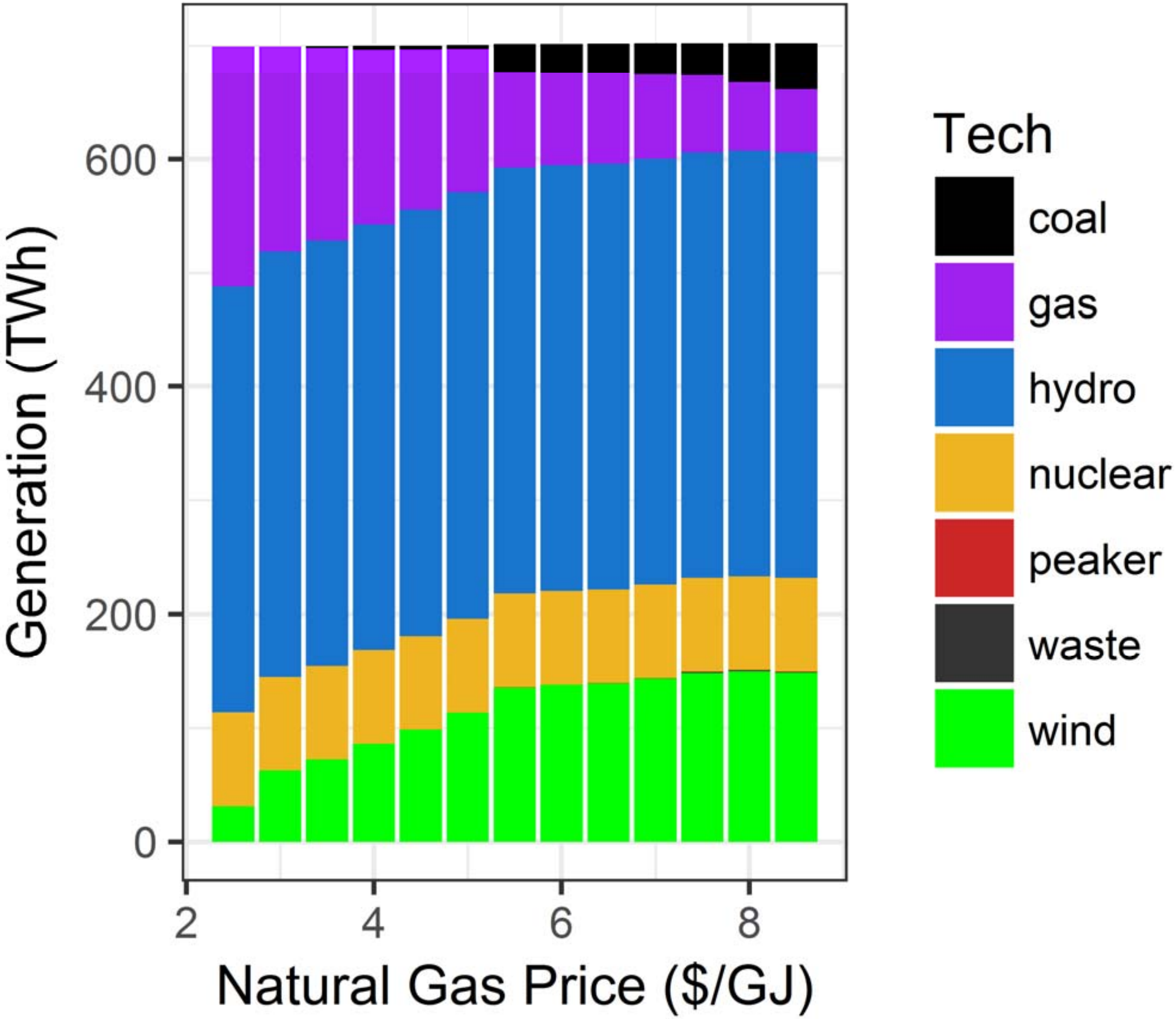


Province net demand and generation correlation with New Transmission Allowed

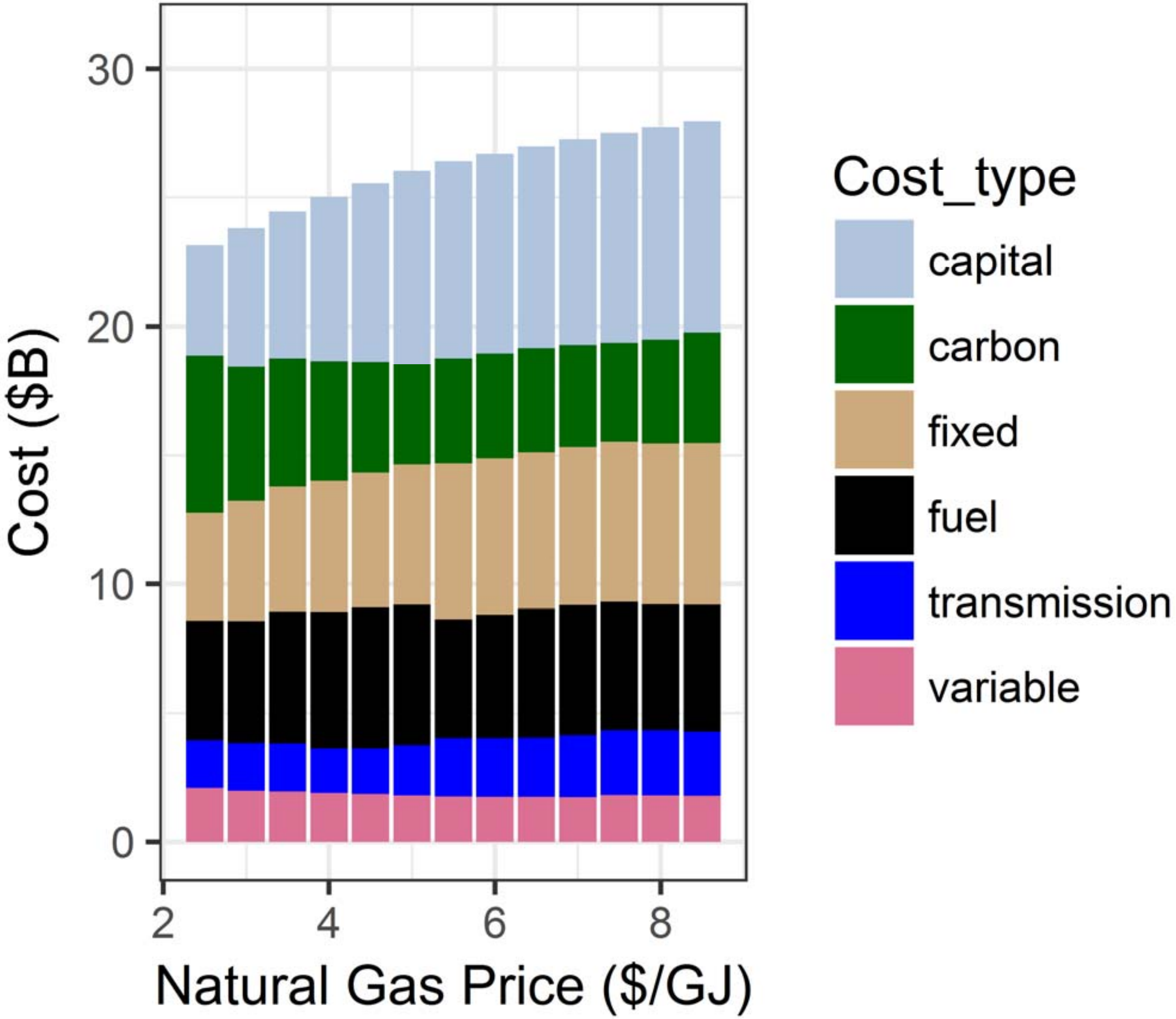


Province net demand and generation correlation with No New Transmission

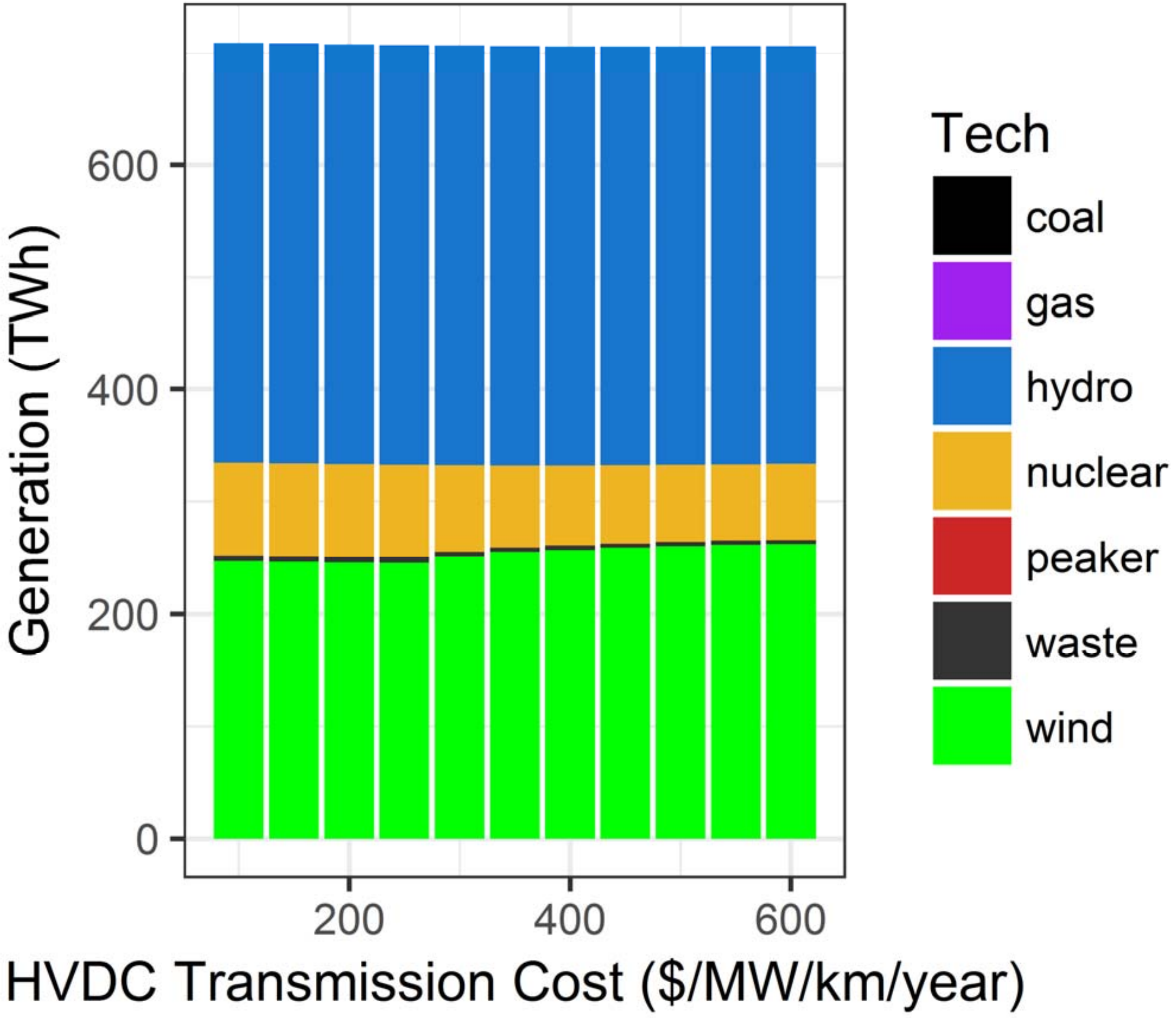
Sensitivity to Natural Gas Prices



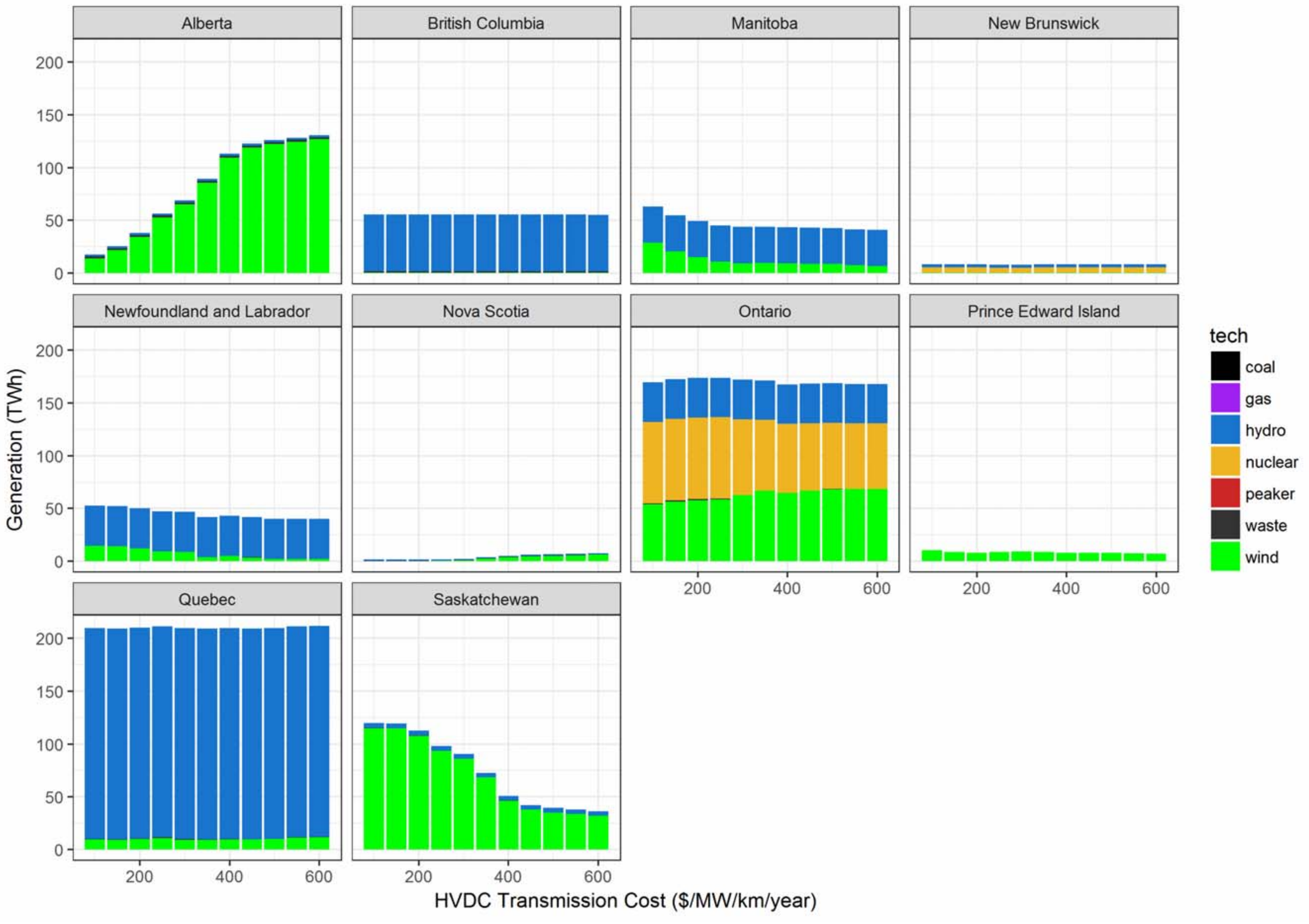
Sensitivity to Natural Gas Prices



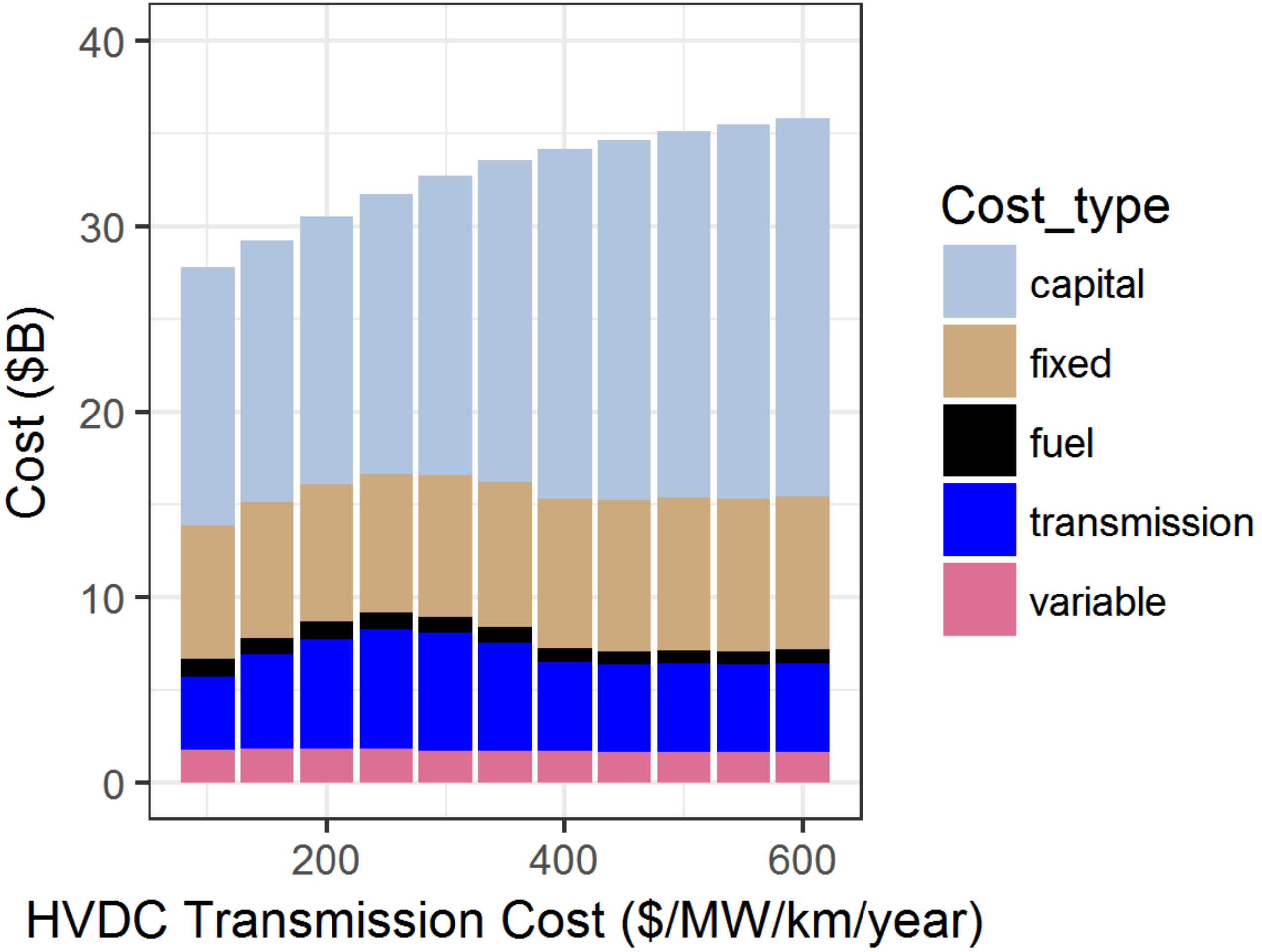
Sensitivity to HVDC Transmission Costs



Sensitivity to HVDC Transmission Costs



Sensitivity to HVDC Transmission Costs



Summary of Results

- New transmission allows greater emissions reductions at any given MAC
- Coal phase-out equivalent to a roughly $60-$100/tonne carbon price
- Wind the least-cost replacement for coal and natural gas as carbon prices increase
- Optimal location of wind depends on whether new transmission can be built
- Hydro and trade help to balance wind variability. Natural gas more important without new transmission
- The price of natural gas influences the optimal generation mix in 2025. The cost of HVDC lines influences the optimal location of wind turbines within Canada.

Thank-you!

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Twitter: @BrettDolter

Find the paper on-line at SSRN:

https://ssrn.com/abstract=2907924