Supplemental Information

Do electrical interties stimulate Canadian hydroelectric development? Using causal inference to identify second-order impacts in evolving sociotechnical systems

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Supporting tables

Supporting Figures

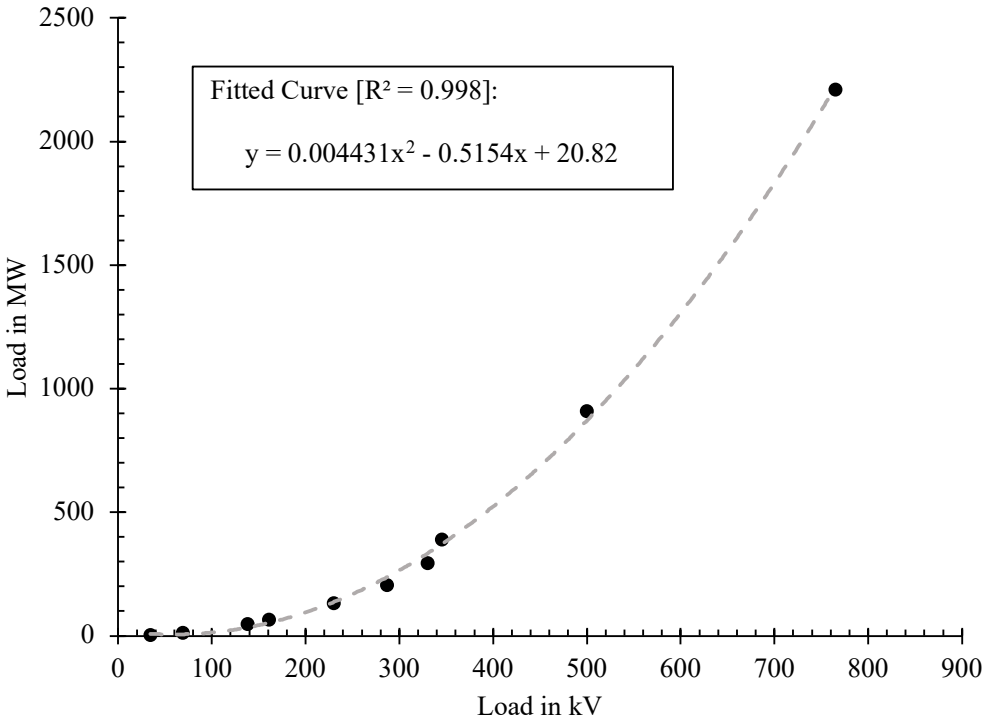


Figure S1: Calibrated curve for the New England/New York/Quebec intertie transmission network

Table S1: Capacity information for transborder transmission infrastructure. Bolded lines had capacity reported in kV and MW and were used to calibrate the St. Clair curve except for DC lines noted with * where St. Clair curve does not apply. Unbolded lines had capacity reported in kV, and MW was calculated using St. Clair curve.

Docket No.	Presidential permit labeled by company name	Date issued (YYYY-MM-DD)	Capacity (kV)	Total estimated capacity (MW) using St. Clair curve
PP-11-2	Fraser Papers	1999-02-28	6.6	0
PP-11-2	Fraser Papers	1999-02-28	**138**	**48**
PP-12	Maine	1963-12-05	**69**	**12**
PP-12	Maine	1948-01-03	**69**	**12**
PP-13	Niagara Mohawk Corporation	1948-01-31	38	7
PP-31	Niagara Mohawk Corporation	1958-02-28	**230**	**132**
PP-190	Niagara Mohawk Corporation	1958-02-28	115	19
PP-190	Niagara Mohawk Corporation	1958-02-28	**69**	**12**
PP-190	Niagara Mohawk Corporation	1958-02-28	**69**	**12**
PP-190	Niagara Mohawk Corporation	1958-02-28	38	7
PP-190	Niagara Mohawk Corporation	1958-02-28	12 (13 units)	47
PP-190	Niagara Mohawk Corporation	1998-12-22	115	19
PP-24	Long Sault	1980-06-06	115	19
PP-29	Maine Public Service	1968-03-22	**138**	**48**
PP-32	Eastern Maine	1959-02-05	**69**	**12**
PP-362	Champlain Hudson Power Express, Inc.	2014-10-06	**320 DC***	**1,000***
PP-43	Maine Electric	1969-07-25	**345**	**390**
PP-56	NYPA Ft Covington	1974-09-13	**765**	**2,210**
PP-66	Citizens Derby	1979-06-21	120	21
PP-74	NYPA	1980-11-24	**345 (2 units)**	**780**
PP-76	VETCO	1984-04-05	**450 DC***	**775***
PP-80	Citizens Vermont	1983-08-05	25 (2 units)	20
PP-82	Joint Owners of the Highgate	1985-05-14	120	21
PP-89	Bangor Hydro	1996-01-22	**345**	**390**
PP-438	NECEC Transmission LLC	2021-01-14	**1,250 DC***	**1,250***

Table S2: Summary of supplemental variables (1979-2021) aggregated to explore possible correlations, covariates, and confounders but not included in final causal analysis

Variable name	Units	Description	References
REVENUE	CAD $year^{-1}$	Annual revenues to Hydro-Québec	Hydro-Québec (1979–2021)
PRICE_QC	\$CAD kWh^{-1}	Annual average retail electricity prices for electricity in Quebec	Hydro-Québec (2022)
PRICE_US	\$USD kWh^{-1}	Annual estimate of average electricity price in northeastern U.S.	U.S. Energy Information Administration (2022)
POP_US, POP_QC	millions	Population of New England - New York (POP_US) and Quebec (POP_QC)	Institut de la statistique du Québec (2022); U.S. Census Bureau (2023)
DSNW_US, DSNW_QC	days	Number of days in calendar year with snowfall ≥ 25 mm at any weather station in the northeastern U.S.[1] or Quebec[2].	Lawrimore et al. (2016)
DP10_US, DP10_QC	days	Number of days with rainfall more than 2.5 mm at any weather station in the northeastern U.S.[1] or Quebec[2].	Idem
TMIN_US, TMIN_QC	ºC	Average minimum temperature in calendar year. Average of the mean monthly minimum temperatures at any weather station in the northeastern U.S.[1] or Quebec[2].	Idem
TMAX_US, TMAX_QC	ºC	Average maximum temperature in calendar year. Average of the mean monthly maximum temperatures at any weather station in the northeastern U.S.[1] or Quebec[2]	Idem
TAVG_US, TAVG_QC	ºC	Average temperature in calendar year. Average of at any weather station in the northeastern U.S.[1] or Quebec[2]	Idem
CLDD_US, CLDD_QC	ºC	Cooling Degree Days. Computed when daily average temperature is more than 18.3 degrees Celsius [CDD = mean daily temperature – 18.3 degrees Celsius]. Daily CDDs are summed to produce an annual total. Annual totals are computed based on a calendar year in Northern Hemisphere at any weather station in the northeastern U.S.[1] or Quebec[2] and averaged.	Idem

[1] Weather station IDs for "_US" variables: USC00308600; USW00014605; USW00014606; USW00014607; USW00014732; USW00014733; USW00014739; USW00014742; USW00014750; USW00014755; USW00014764; USW00014771; USW00094705; USW00094725; USW00094746; USW00094765; USW00094789; USW00094790 (Lawrimore et al., 2016b).

[2] Weather station IDs for "_QC" variables: CA006085700; CA007014160; CA007014629; CA007015730; CA007020828; CA007020860; CA007024280; CA007060400; CA007066820; CA007080468; CA007091299; CA007091305; CA007091401; CA007091404; CA007093716; CA007093GJ3; CA007103536; CA00710S005 (Lawrimore et al., 2016b).

Table S2 (cont'd): Summary of data (1979-2021) for variables aggregated to explore correlations and possibly overlooked covariates and confounders but not included in final causal analysis

Variable name	Units	Description	References
PRCP_US, PRCP_QC	mm	Total annual precipitation averaged across weather stations in the northeastern U.S.[1] or Quebec[2]	Idem
SNOW_US, SNOW_QC	mm	Total annual snowfall averaged across weather stations in the northeastern U.S.[1] or Quebec[2]	Idem

[1] Weather station IDs for "_US" variables: USC00308600; USW00014605; USW00014606; USW00014607; USW00014732; USW00014733; USW00014739; USW00014742; USW00014750; USW00014755; USW00014764; USW00014771; USW00094705; USW00094725; USW00094746; USW00094765; USW00094789; USW00094790 (Lawrimore et al., 2016b).

[2] Weather station IDs for "_QC" variables: CA006085700; CA007014160; CA007014629; CA007015730; CA007020828; CA007020860; CA007024280; CA007060400; CA007066820; CA007080468; CA007091299; CA007091305; CA007091401; CA007091404; CA007093716; CA007093GJ3; CA007103536; CA00710S005 (Lawrimore et al., 2016b).

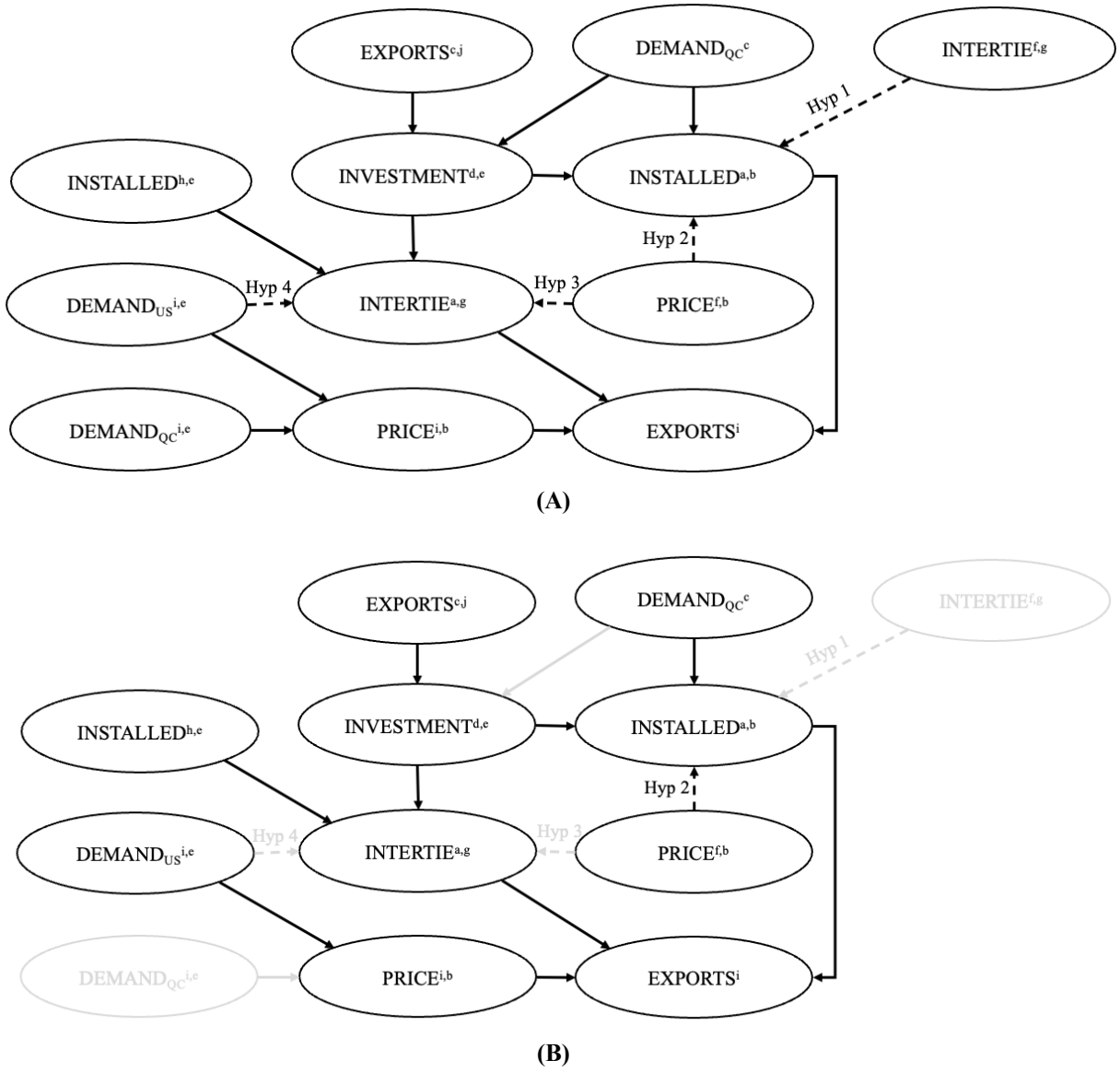
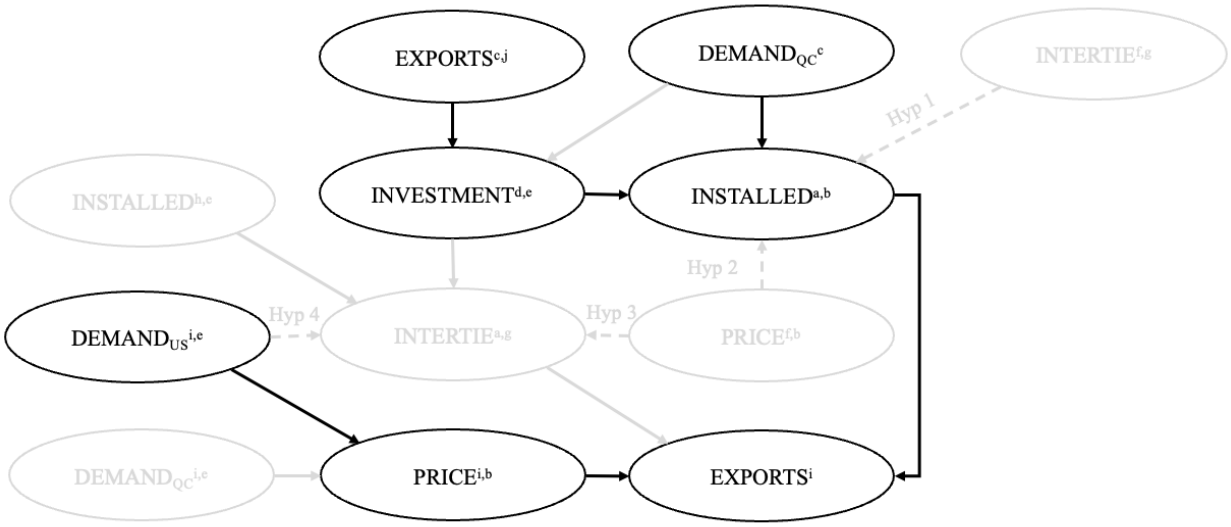
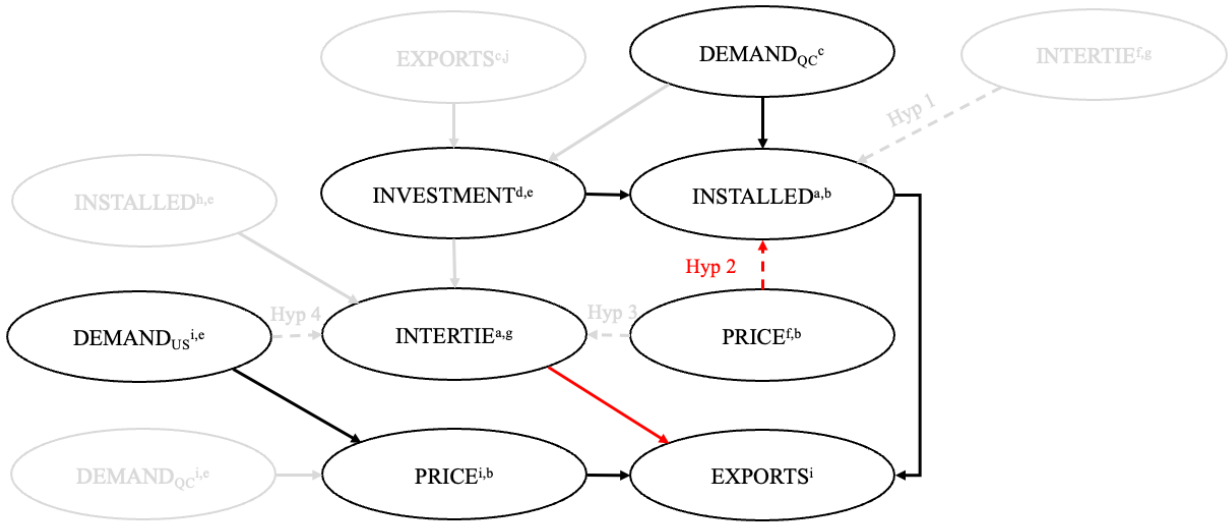


Figure S2: Hypothesized DAG (Panel A) and 5- and 8-year BN model DAG from loglik scoring (Panel B). Identical model structures returned under 5- and 8-year model versions. Models are expanded versions of structures presented in Figures 2 (Panel A) and 3 (Panel B) representing lag-transformed variables separately. Grayed our links are not supported. [a] Total expansion in 5 or 8-year period up to year *t*; [b] Box-Cox transformed variable; [c] 5-year lag of the 5 or 8-year moving average for the incremental expansion, i.e., value in year *t* minus value in year *t-1*; [d] Average total investment in 5 or 8-year period up to year *t;* [e] Discretized variable ("low", "medium", "high"); [f] 5 or 8-year lag of the total intertie capacity expansion/price difference in 5 or 8-year period up to year t; [g] Discretized variable ("non-significant", "significant"); [h] 5 or 8-year lag of the total expansion in 5 or 8-year period up to year *t;* [i] Average expansion in 5 or 8-year period up to year *t*; [j] Discretized variable ("negative", "positive").

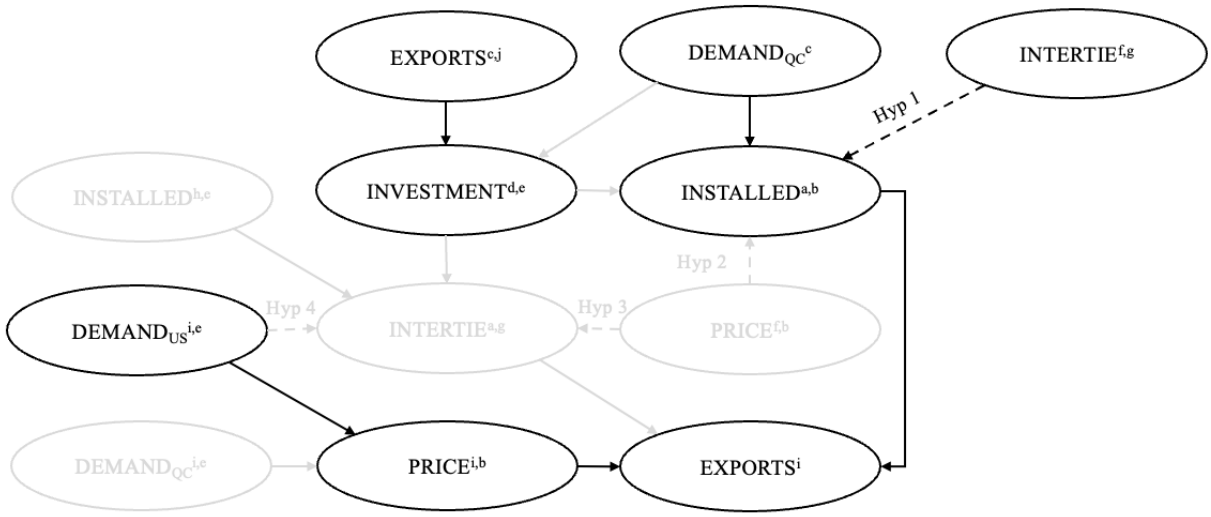


(A)

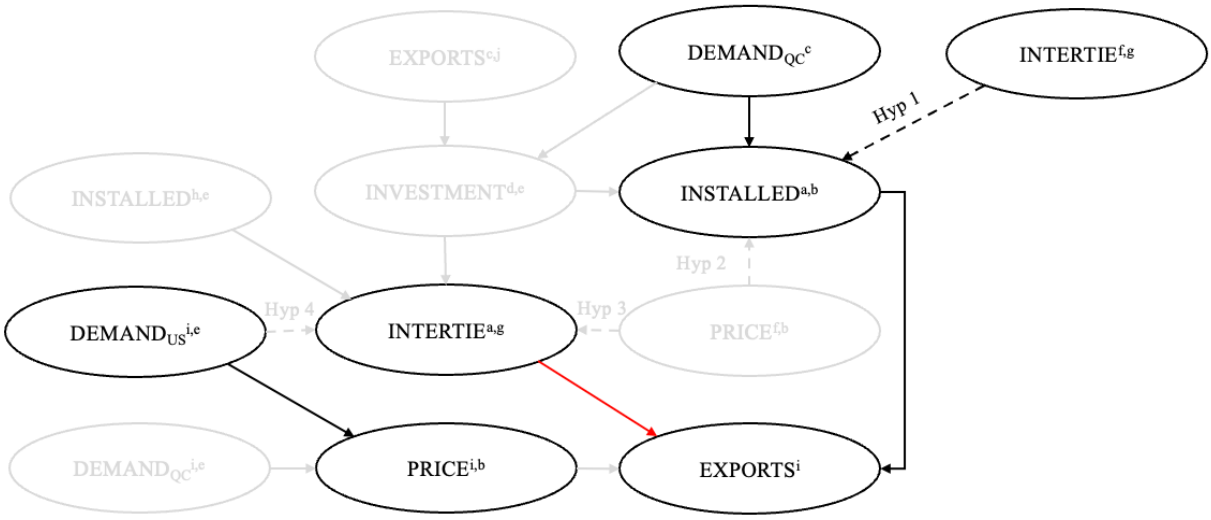


(B)

Figure S3: 5-year (Panel A) and 8-year (Panel B) BN model DAG (AIC scoring). Grayed our links are not supported. [a] Total expansion in 5 or 8-year period up to year *t*; [b] Box-Cox transformed variable; [c] 5-year lag of the 5 or 8-year moving average for the incremental expansion, i.e., value in year *t* minus value in year *t-1*; [d] Average total investment in 5 or 8-year period up to year *t;* [e] Discretized variable ("low", "medium", "high"); [f] 5 or 8-year lag of the total intertie capacity expansion/price difference in 5 or 8-year period up to year t; [g] Discretized variable ("non-significant", "significant"); [h] 5 or 8-year lag of the total expansion in 5 or 8-year period up to year *t;* [i] Average expansion in 5 or 8-year period up to year *t*; [j] Discretized variable ("negative", "positive").



(A)



(B)

Figure S4: 5-year (Panel A) and 8-year (Panel B) BN model DAG (BIC scoring). Grayed our links are not supported. [a] Total expansion in 5 or 8-year period up to year *t*; [b] Box-Cox transformed variable; [c] 5-year lag of the 5 or 8-year moving average for the incremental expansion, i.e., value in year *t* minus value in year *t-1*; [d] Average total investment in 5 or 8-year period up to year *t;* [e] Discretized variable ("low", "medium", "high"); [f] 5 or 8-year lag of the total intertie capacity expansion/price difference in 5 or 8-year period up to year t; [g] Discretized variable ("non-significant", "significant"); [h] 5 or 8-year lag of the total expansion in 5 or 8-year period up to year *t;* [i] Average expansion in 5 or 8-year period up to year *t*; [j] Discretized variable ("negative", "positive").

Table S3: Summary of BN model when using AIC scoring criterion (5-year average and lag)

Child	Parent(s)	r squared	Accuracy
INSTALLED[a,b]	$DEMAND_{QC}$[c], INVESTMENT[d,e]	0.77	n/a
EXPORTS[f]	PRICE[f,b], INSTALLED[a,b]	0.78	n/a
INVESTMENT[d,e]	EXPORTS[c,g]	n/a	0.60
PRICE[f,b]	$DEMAND_{US}$[h,e]	0.58	n/a

[a] Total expansion in 5-year period up to year *t*
[b] Box-Cox transformed variable
[c] 5-year lag of the 5-year moving average for the incremental expansion, i.e., value in year *t* minus value in year *t-1*
[d] Average total investment in 5-year period up to year *t*
[e] Discretized variable ("low", "medium", "high")
[f] Average expansion in 5-year period up to year *t*
[g] Discretized variable ("negative", "positive")
[h] 5-year lag of the average expansion in 5-year period up to year *t*

Table S4: Summary of BN model when using AIC scoring criterion (8-year average and lag)

Child	Parent(s)	r squared	Accuracy
INSTALLED[a,b]	$DEMAND_{QC}$[c], INVESTMENT[d,e], PRICE[f,b]	0.96	n/a
EXPORTS[g]	PRICE[g,b], INSTALLED[a,b], INTERTIE[a,h]	0.92	n/a
PRICE[g,b]	$DEMAND_{US}$[i,e]	0.76	n/a

[a] Total expansion in 5-year period up to year *t*
[b] Box-Cox transformed variable
[c] 5-year lag of the 5-year moving average for the incremental expansion, i.e., value in year *t* minus value in year *t-1*
[d] Average total investment in 5-year period up to year *t*
[e] Discretized variable ("low", "medium", "high")
[f] 5 or 8-year lag of the total intertie capacity expansion/price difference in 5 or 8-year period up to year *t*
[g] Average expansion in 5-year period up to year *t*
[h] Discretized variable ("non-significant", "significant")
[i] 5-year lag of the average expansion in 5-year period up to year *t*

Table S5: Summary of BN model when using BIC scoring criterion (5-year average and lag)

Child	Parent(s)	r squared	Accuracy
INSTALLED[a,b]	$DEMAND_{QC}$[c], INTERTIE[d,e]	0.72	n/a
EXPORTS[f]	PRICE[f,b], INSTALLED[a,b]	0.78	n/a
INVESTMENT[g,h]	EXPORTS[c,i]	n/a	0.45
PRICE[f,b]	$DEMAND_{US}$[g,h]	0.59	n/a

[a] Total expansion in 5-year period up to year *t*
[b] Box-Cox transformed variable
[c] 5-year lag of the 5-year moving average for the incremental expansion, i.e., value in year *t* minus value in year *t-1*
[d] 5-year lag of the average expansion in 5-year period up to year *t*
[e] Discretized variable ("non-significant", "significant")
[f] Average expansion in 5-year period up to year *t*
[g] Average total investment in 5-year period up to year *t*
[h] Discretized variable ("low", "medium", "high")
[i] Discretized variable ("negative", "positive")

Table S6: Summary of BN model when using BIC scoring criterion (8-year average and lag)

Child	Parent(s)	r squared	Accuracy
INSTALLED[a,b]	$DEMAND_{QC}$[c], INTERTIE[d,e]	0.94	n/a
EXPORTS[f]	INSTALLED[a,b], INTERTIE[a,e]	0.91	n/a
PRICE[f,b]	$DEMAND_{US}$[g,h]	0.53	n/a

[a] Total expansion in 5-year period up to year *t*
[b] Box-Cox transformed variable
[c] 5-year lag of the 5-year moving average for the incremental expansion, i.e., value in year *t* minus value in year *t-1*
[d] 5 or 8-year lag of the total intertie capacity expansion/price difference in 5 or 8-year period up to year *t*
[e] Discretized variable ("non-significant", "significant")
[f] Average expansion in 5-year period up to year *t*
[g] 5-year lag of the average expansion in 5-year period up to year *t*
[h] Discretized variable ("low", "medium", "high")

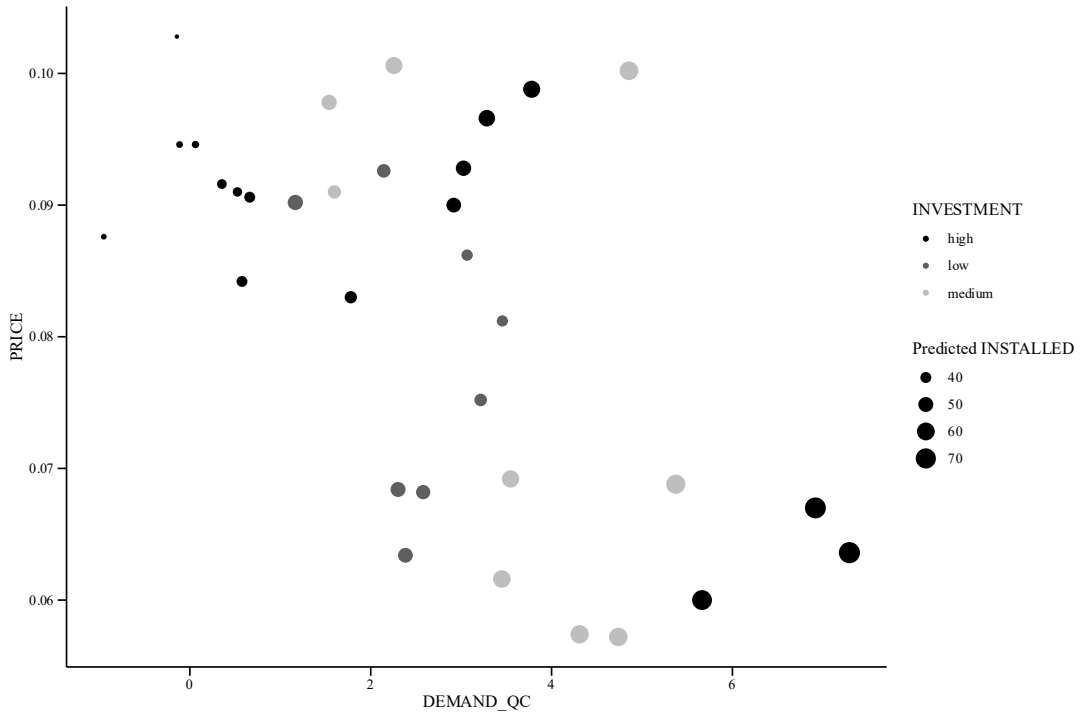


Figure S5: 5-year model results graph for installed generation capacity; child of total investments, lagged price difference and lagged new demand in Quebec.

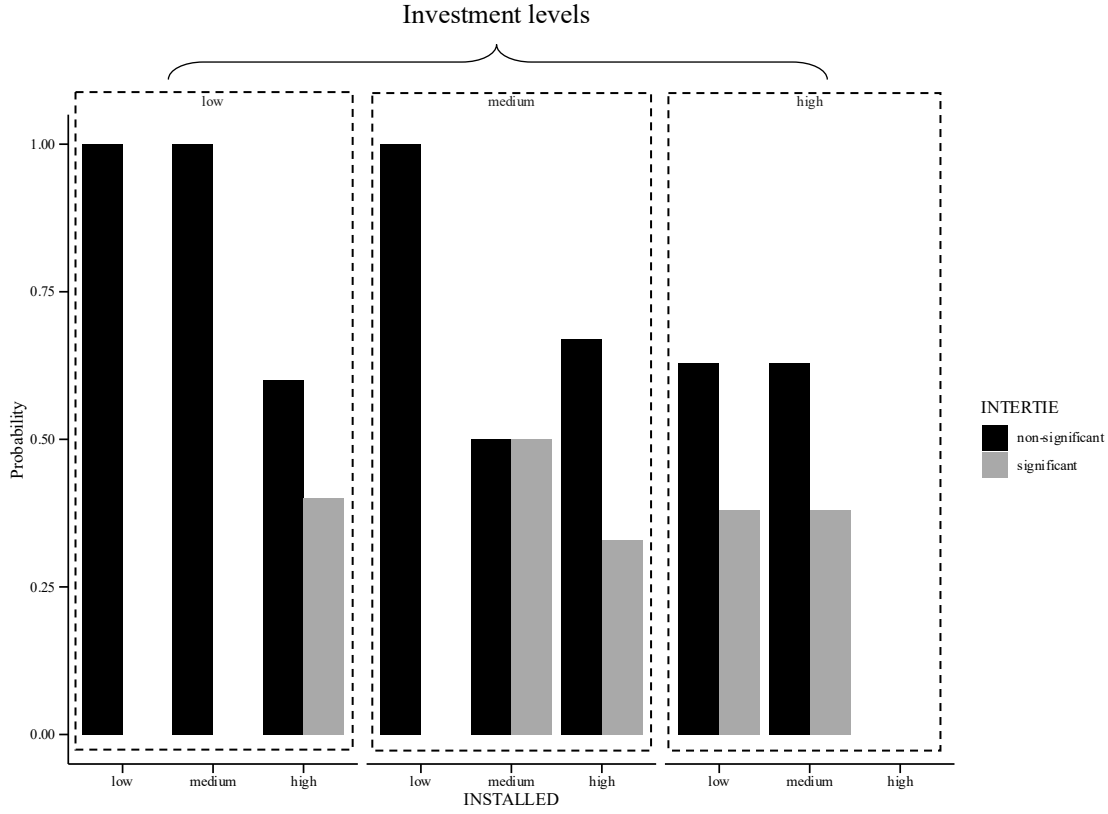


Figure S6: 5-year model results graph for intertie capacity; child of lagged installed generation capacity and total investments.

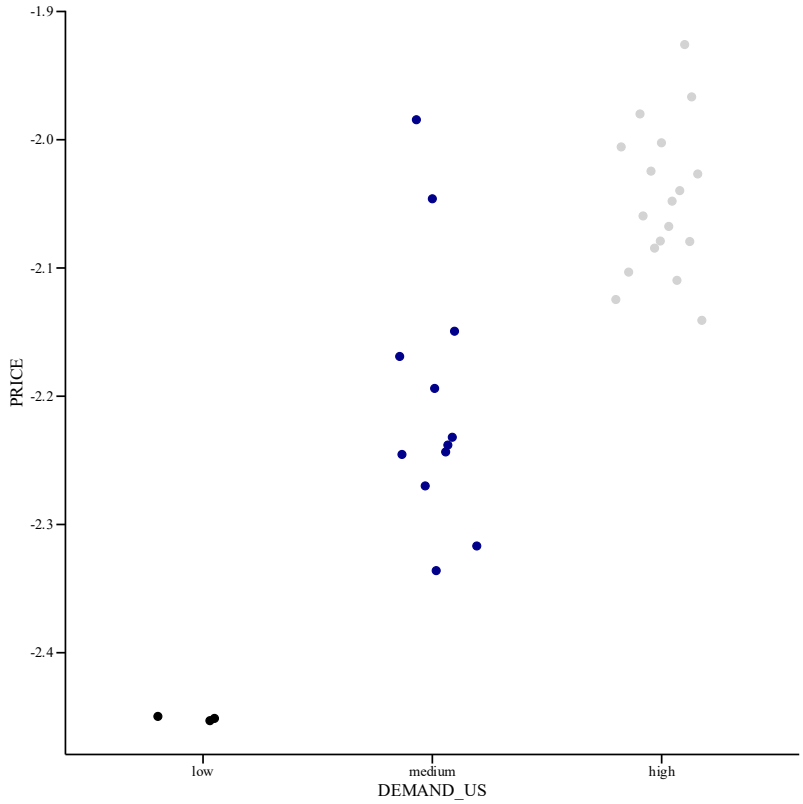
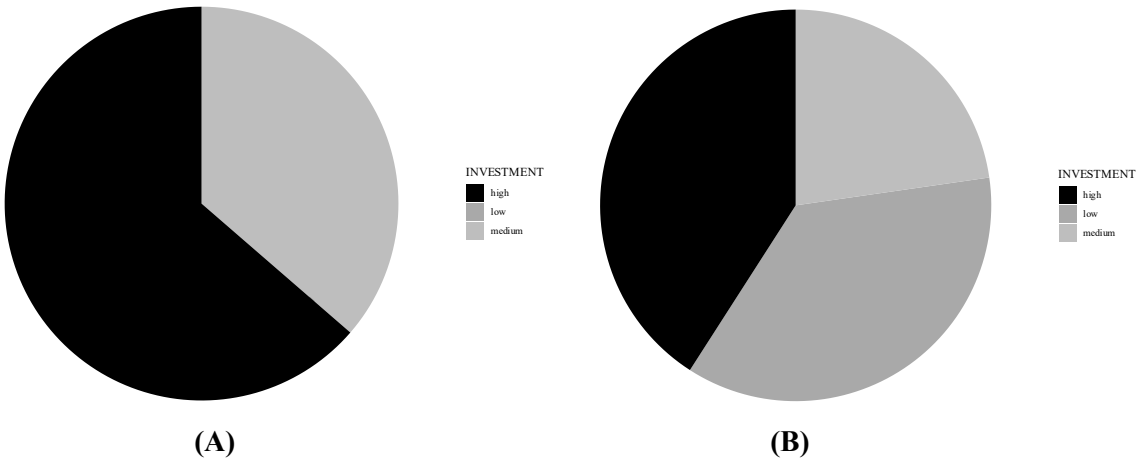


Figure S7: 5-year model results graph for price difference; child of average demand in the U.S.



(A) **(B)**

Figure S8: 5-year model results graph for total investment; child of lagged new total exports. **A:** Negative exports, **B:** Positive exports.

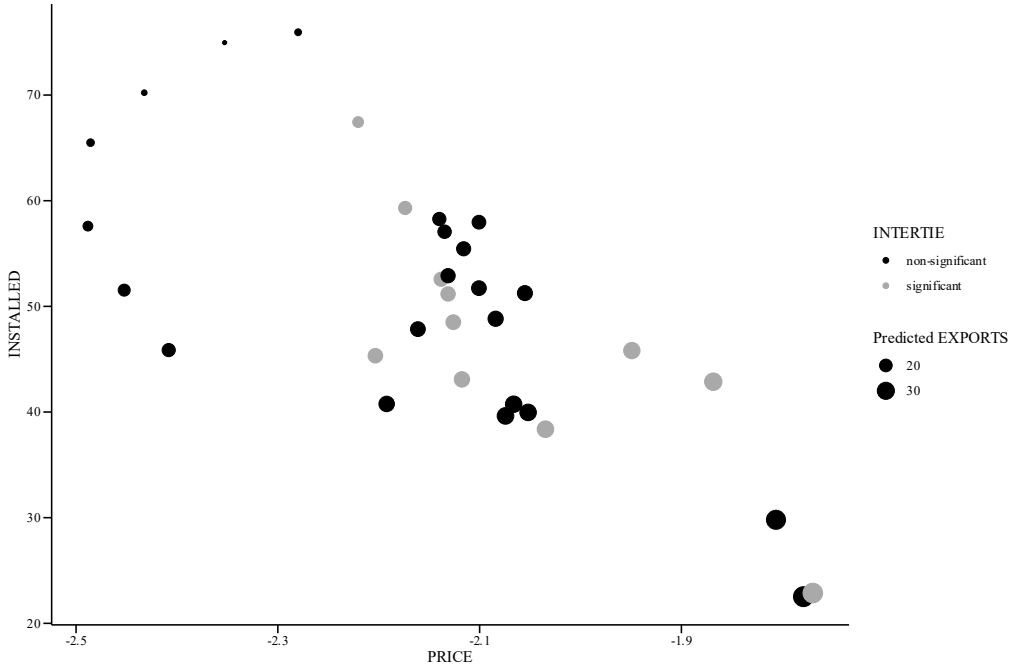


Figure S9: 5-year model results graph for exports; child of total expansion of intertie capacity, installed generation capacity and price difference.

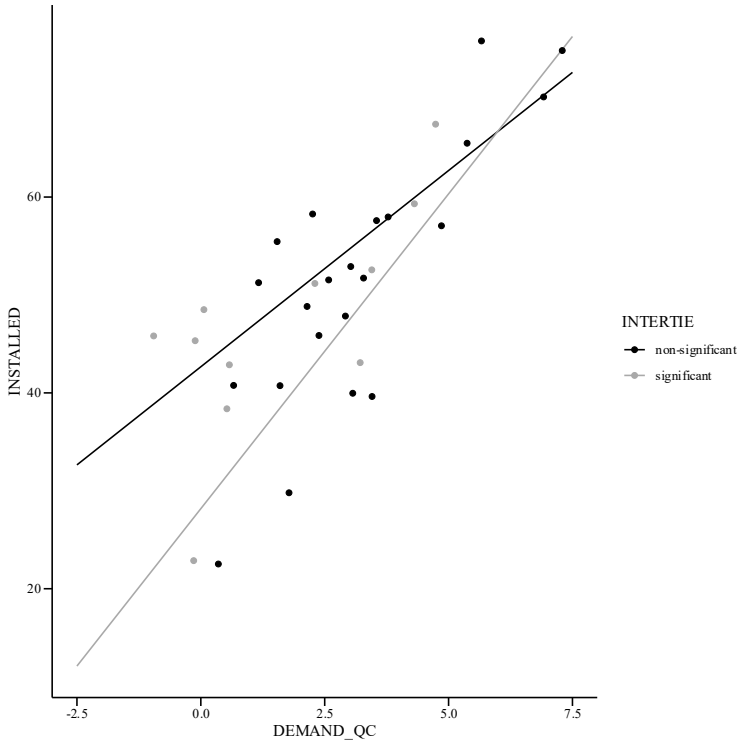


Figure S10: 5-year model results graph for installed generation capacity (BIC scoring); child of lagged intertie capacity expansion and lagged new average demand levels in Quebec.