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Cost Competitiveness as a Moderator of Non-Economic Determinants of Renewable Energy Deployment: Comparing Solar and Wind Across Canadian Provinces

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ABSTRACT

Countries are pushing towards expanding renewable generation. Prior studies have considered policy, cost, and neighbouring examples as independent factors influencing the construction of renewable energy infrastructure. However, this view discounts the possibility that these factors are interrelated. Therefore, this paper seeks to analyze whether the effect of carbon pricing, and construction in neighbouring provinces work differently depending on how cheap the technology has already become, using 10 Canadian provinces between 2010 and 2023. This paper tests if the three are independent, using the 10 Canadian provinces between 2010 and 2023. During this period, technology costs fell steeply and provinces charged very different carbon prices. The influence of neighboring construction does not change as a technology grows cheaper. Carbon pricing however, acts differently as it is associated with new wind capacity mainly once wind is already cheap, though 10 provinces are too few to establish the result. If carbon pricing really does work mainly on cheap technology, a carbon price is worth different amounts at different stages of a technology's life, and models assuming a constant will misjudge both what climate policy achieves and when. Carbon pricing now applies to roughly a quarter of global emissions, increased from 7% a decade ago, and raised over USD 100 billion (World Bank, 2024). Knowing whether its effect changes in relative to cost would give the government a basis for timing the policy.

INTRODUCTION

Electricity and heat generation is the largest single source of carbon dioxide emissions in the world, releasing 14.8 gigatonnes in 2022 (International Energy Agency 2026). Reducing that figure requires replacing fossil-fuelled plants with renewable energy. However, governments do not build the capacity themselves. They operate through policy instruments such as regulations, carbon pricing and contracts for new generations. In Canada, the carbon price is fixed in advance based on the predictability for investors and the social cost of carbon (Environment and Climate Change Canada 2020). The price was therefore set from the estimated climate damage caused by emissions. The carbon price is also expected to cause

more wind and solar to be built. Whether it does this equally well when the technology is less competitive against local electricity prices and when it is more so has not been tested. This research offers the government a way to estimate how much new capacity a carbon price is associated with, and whether the amount depends on that comparison.

Global weighted-average levelized costs of electricity from renewable generation declined sharply between 2010 and 2023, falling by approximately 90% for utility-scale solar and 70% for onshore wind (International Renewable Energy Agency 2024). Such cost reduction is principally driven by global manufacturing scale, so every jurisdiction sees around the same prices in a given year. However, falling costs are only an incentive to build wind farms and solar panels. Capacity has to be procured, permitted, financed, and constructed; this leads to different amounts of renewable energy capacity due to very different decisions of government and utilities. Canada is a good example of how different governance results in differential capacity for renewable energy sources. Ontario accounts for 57% and Alberta accounts for 35% of the 5.33 GW of cumulative installed solar capacity recorded at the end of 2023 (Baldus-Jeursen et al. 2025). Wind capacity is also uneven, as Ontario, Alberta, and Quebec together account for 84% of the 12.1 GW added between 2010 and 2023 (Statistics Canada n.d.c). There is a systematic review of empirical work that finds little consensus on the economic, environmental, and energy factors that studies test most often, and writes that regulatory, political, and demographic factors matter as well (Bourcet 2020). No study appears to have asked whether these factors work the same way at every level of cost competitiveness. The paper therefore asks: To what extent does technology-specific cost competitiveness moderate the effect of non-economic determinants, specifically regional peer diffusion and carbon-pricing stringency, upon renewable energy deployment, and in what respect does this differ between utility-scale solar and onshore wind across Canadian provinces?

The knowledge of which factors decide the creation of renewable capacities matters beyond Canada because many governments now rely on carbon pricing to move toward clean generation. Sixty-one carbon pricing schemes now operate worldwide, covering around one fifth of global emissions (Green 2021). Each was adopted on the understanding that a price on carbon shifts investment toward clean energy generation. That expectation comes from studies estimating one effect for a carbon price, which was averaged over every year in their data. It is not possible to show whether the effect was stronger in some years than others with an average of the carbon price. If the effect depends on how cheap the technology is now, the same carbon price policy is worth different amounts of new capacities in different years, and the government needs to decide the timing to set the price.

If the effect instead depends on how cheap the technology already is, then the same cost is worth very different amounts at different moments, and a government spending scarce political capital on a carbon price has a timing problem. Conversely for the peer channel, if provinces imitate each other only under some cost conditions, then the case for demonstration projects rises and falls with the technology's maturity.

Two explanations can help explain the observed trends. Technology diffusion is the first explanation. Bass's defined way of technology diffusion is adoption as a function of both independent innovation and imitation of earlier adopters (Bass 1969). On some tendency, neighbouring provinces share contractors, grid interconnection, policy templates, or any accessibility that would create an easier transition of technology development; therefore the same mechanism can work between governments. This leads projects in a single province to lower the perceived risk and lower the cost of the neighboring. There is work on subnational energy policy that correlates with this theory: geographic neighbours are one of the major factors that affect administrative divisions policies (Carley et al. 2017). The second explanation for the uneven capacity in different provinces is policy stringency. Porter's hypothesis argues that properly designed systems with moderate stringency of an environmental regulation can induce investment and innovation; as innovation profits outweigh the compliance cost, companies will reduce the imposition of compliance costs (Porter and Linde 1995). There is cross-country panel evidence that carbon pricing policies guide renewable development more strongly (Xu and Yang 2024).

However, no research appears to have examined whether peer effects and carbon pricing operate with equal effects at different price levels. The models used to study these factors add each one in on its own, so each factor's effect is fixed and not dependent on the technology costs. Under such a model, the province observing neighbour build is assumed to react the same regardless of technology cost. Saskatchewan's response to an Alberta wind farm is thus held to have been the same in 2011 when the levelized cost of electricity (LCOE) onshore wind cost 0.109 USD/kWh, as in 2022, when the same technology cost 0.034 USD/kwh (International Renewable Energy Agency 2024). Therefore, this assumption seems unlikely to hold, though the direction in which it fails as a negative or positive interaction is not obvious, but two possible explanations for such a failure can be distinguished.

Under the first scenario (hereafter referred to as substitution), non-economic incentives play a major role where economic conditions are unfavorable. For example, a province having a weak investment rationale must rely on successful experience from neighbouring provinces or upon regulatory pressure. Once the technology demonstrates economic viability, the justification is not necessary anymore, and its impact should diminish consequently. Secondly, complementarity is the opposite. When a technology stays uneconomical, peer signals or carbon prices are too weak to be considered to influence other province decisions. Then, factors only become influential when costs fall low enough that marginal incentive becomes the decision factor. Because the two accounts predict opposite signs on the same coefficient, and are therefore separable by estimation.

Regression is required to answer this question for two reasons. First, moderation is not something that can be seen by looking because it is a coefficient on a product term, and a model without that term cannot report on it either way. Second, for comparison reasons, provinces that built a lot against provinces that built little confuses the question with province size, wind and solar resources available, so using fixed effects for province and year strip those out. Both peer diffusion and carbon pricing are treated identically in the regression, each as main effect and in interaction with cost competitiveness.

Canada's provincial setting is well suited to test this. Firstly, provinces have individual control over electricity generation and determine their own energy projects. They do not need to be approved by the federal government, so provinces differ considerably in electricity prices and in carbon pricing policies. Yet, they all share a single national cost trajectory. The two technologies examined, wind and solar, also are in different stages of development. Wind has attained maturity before the sample's data and utility-scale solar reaching material scale only close to the start of the used data. Therefore, onshore wind across the ten provinces will sustain more inference than solar, so wind is treated here as the principal test, and the solar results will be exploratory.

The experimental design is not specific to Canada, which allows for findings to extend to multiple countries. Canada has a combination of ten jurisdictions with authority over their own electricity systems, yet they face one national technology cost curve. Provinces are widely different in what they charge for carbon and what they charge for power. Any federation with subnational energy authority has the same structure, such as the American states, Australian states and the German Länder, so therefore the same estimation can be applied wherever a comparable panel exists.

In order to understand whether cost competitiveness changes the effect of carbon pricing or peer effect, three bodies of work are reviewed. Work on cost decline supplies the condition tested, as it discusses costs falls nationally rather than province by province. Work on diffusion supplies the peer effect factor. Work on environmental regulations supplies the carbon pricing effect. None of the three, however, examines how they interact with each other.

2.1 Cost Decline and Learning Curves

The empirical regularity underlying the cost side of this paper is antiquated, as it originates from aircraft manufacturing and not in energy. Studying airframe manufacturing, Wright observed that unit cost fell by a constant proportion with each doubling of cumulative output (Wright 1936). This explains why renewable costs fall predictably. The field's difficulty, then, is not whether costs fall but which curve describes the fall. Wright's formulation is debated if it is the best description of cost decline since several models fit historical data equally well. Nagy et al. (2013) addressed this debate by using hindcasting. They took a database of 62 technologies and used six laws to early data of each technology and compared predictions against observations. Wright's law performed best out of the six, with solar photovoltaics being one of the best fit with the real data. For the paper here, the implication is that the cost series can be used as an exogenous global trend.

2.2 Diffusion Between Adopters and Jurisdictions

This section establishes that jurisdictions respond to one another, and sets out what a peer correlation can and cannot do. Bass (1969) proposed that adoption of a new product is driven by two forces: innovation and imitation. Innovation is independent of how many others have adopted the product; the latter is proportional to the number who already have. Bass fitted the model to 11 different consumer durables where the model predicted the sale peak and its timing. The S-shaped adoption curve follows from the interaction of innovation and imitation. The model was about consumers buying items, but the imitation

mechanism can still be used in examples such as organizations where it is possible for observation of one another. The transfer from households to governments is where the literature became contested. Early work established that policies spread, but it is unclear whether jurisdictions actually behave this way. Carley et al. (2017) provided the evidence by looking at renewable portfolio standard adoption across the US states between 1996 and 2009. It was found that geographic peers contribute the strongest influence on adoption. However, it does not discuss the construction of capacity and only concerns about the adoption of policies, different from this paper, so applying it to physical deployment is an inference. Manski (1993) presented another difficulty, which he called it as the reflection problem. Manski stated that jurisdictions that behave alike may be influencing one another, but it can also be just responding to common conditions. Shipan and Volden (2008) go further and argue that a neighbour effect is not one mechanism. At least four learned from what worked elsewhere, economic competition, imitation of larger jurisdictions, and coercion from a higher level of government. All four predict the same thing, which is that a jurisdiction is more likely to act once its neighbours have. This work matters here because it establishes that jurisdictions respond to what their neighbours have done, which is what makes the peer variable worth including. It has also set the limits on what a correlation between a neighbor can show.

2.3 Environmental Regulation and Investment

Whether environmental regulation makes firms invest has been debated. It matters here because this paper puts carbon price effect as something that would cause more new capacity. If regulation does not change investment decisions, a carbon price has nothing to do. This review also shows the answer to why the question is worth asking. Porter and Linde (1995) argued against the view that environmental regulation necessarily imposes net costs on firms. If there was properly designed regulation, which signals resources inefficiency and prompts innovation, this can offset compliance cost partially or wholly. This argument was theoretical. It supports the mechanism that a carbon price might increase renewable deployment. Porter and van der Linde's article appeared alongside a rebuttal in the same issue arguing that firms already have every incentive to find profitable efficiencies without being regulated into them. Jaffe and Palmer (1997) made the debate tractable by splitting the claim into three: a weak version that induces innovation, a narrow version that flexible instruments such as taxes induce more innovation than standards, and a strong version that regulation improves firm performance overall. Ambec et al. (2013) find the weak version well established and the strong version still contested based on twenty years of evidence. This paper engages the narrow version, carbon pricing being the market-based instrument it distinguishes from a standard. Recent cross-country evidence is consistent. Xu and Yang (2024) assemble panel data on 196 countries and regions from 1985 to 2021. The data is then designed by using a staggered difference-in-differences to estimate the effect of introducing carbon pricing. They find carbon pricing is associated with faster renewable energy deployment by discouraging fossil generation. Yet, this assessment is contested. Green (2021) located only 37 ex-post evaluations meeting a causal-inference standard. Within the evaluations, reductions were between 0 and 2 percent a year. Green argues that carbon pricing prices the emissions flow. This works matters here because it establishes that carbon price can change investment behaviour.

2.4 Determinants of Deployments, and the Gap

Bourcet (2020) reviewed the empirical literature on renewable deployment determinants. Economic, environmental, and energy-related variables are tested most frequently. It was found there was conflict between the studies on their direction and significance. The review did not identify a dominant determinant. This suggests that the effect of any factor may depend on conditions that additive specifications were held fixed, so therefore could not detect any dependence. This work matters because it shows that decades of studies have not agreed on which factors drive deployment, which is the evidence that treating non-economic determinants separately failed to settle the question.

3. METHODS

The research question is to what extent does the cost competitiveness of a specific technology moderate the relationship between non-economic determinants (peer diffusion and the stringency of carbon pricing) and renewable energy deployment, and how does this relationship differ by comparing utility-scale solar PV and wind power across Canadian provinces? To address the research question, we create a province-year-technology panel with a span of the ten total Canadian provinces and estimate the two way fixed-effects regression separately for onshore wind and solar. To align, the methodology includes creation and verification of the panel, construction of the variables, specification of the model, and lastly to do estimation strategy and robustness checks.

4.1 Panel Construction and Verification

The unit of observation is the province-year-technology. Solar and wind are estimated in separate regression because the two technologies differ in their cost trajectory. They are different in market maturity: wind has already been used widely before the solar sample was available. They are also distinct in their relation to provincial electricity prices. Pooling them together would create a common coefficient, which would disregard these major differences. The data are shown in Table 1.

Table 1: Data sources

Variable	Source	Note
Installed capacity, wind and solar	Statistics Canada (n.d.c), Table 25-10-0022-01	Annual, by province and type of generation. Filtered to the total across all classes of electricity producer.
Levelized cost of electricity	International Renewable Energy Agency (2024), accessed through Our World in Data (n.d.)	National series with no provincial variation. Wind available from 2010, Canadian solar from 2018 only. OWID is the proximate source and IRENA the underlying one.
Electricity price index	Statistics Canada (n.d.b), Table 18-10-0204-01	Published monthly on a 2014 = 100 base and aggregated to annual as the unweighted mean of the 12 monthly values. The series for customers above 5,000 kW is used where available.
Carbon price	Environment and Climate Change Canada (n.d.), together with provincial legislation and Western Climate Initiative auction results	Compiled by hand, since no single published file covers all ten provinces across the period.
Median total income	Statistics Canada (n.d.a), Table 11-10-0239-01	Median total income, all persons aged 16 and over.
Tertiary attainment	Statistics Canada (n.d.d), Table 37-10-0130-01	Share aged 25 to 64 holding a tertiary qualification, category "Tertiary education," both genders.

Two corrections have been made of the carbon price series since there was a difference between the federal

schedule and the provincial rate. British Columbia's 2020 rate stayed at $40 per tonne instead of the scheduled $45. (Government of British Columbia, 2020). Alberta had no carbon price for approximately seven months of 2019 between repealing its provincial levy in May and the federal charges taking effect in January 2020 (Department of Finance Canada, 2020).

In the data sources, the capacity figures count only stations above a minimum size, covering utility-scale installations rather than rooftop panels. They total 3.27 GW of solar at the end of 2023, within 280 MW of the comparable published figure of 3.55 GW (Baldus-Jeursen, Poissant, & Côté, 2025).

The data is between 2010 to 2023, but neither technology is studied over all of it. For wind, Statistics Canada did not publish a figure for 2012 capacity. Since new capacity is a year's total minus the previous year's total, that leads to the removal of the new capacity to the year 2013. The peer variable measures the previous new capacity from a province's neighbours. Therefore, wind is studied from 2015 to 2023. Solar, on the other hand, starts its data from 2018 where IRENA reports the first year of solar's levelized cost.

Two choices were made about gaps in the data. When Statistics Canada's capacity table has no entry at all, the cell is treated as zero which the paper inferred that there are no utility-scale stations existed to report. Yet, whether that inference is correct cannot be checked against the table, since it could mean no stations were built or it did not publish, so all results were produced both with and without those cells and both are reported. The Results report the alternative treatment of both as sensitivity checks.

3.2 Variable Construction

Working from the dataset above, the analysis estimates a two-way fixed-effects regression separately for wind and solar. This section is about how each variable is constructed.

3.2.1 Dependent Variable

Let $K_{i,\tau,t}$ denote the total installed capacity (in kW) of technology τ in province i at the end of year t. New capacity is taken as the first difference as written in Equation (1):

$$\Delta K_{i,\tau,t} = K_{i,\tau,t} - K_{i,\tau,t-1}$$

Equation (1) defines the quantity the paper sets out to explain. It is the new capacity a province built in a year, obtained by subtracting last year's total from this year's. A large positive value is a year with a l, and a zero is a year in which nothing was added.

The dependent variable is $ln(1 + \Delta K)$. This transformation is used because preliminary estimation in raw kilowatts produced badly non-normal residuals with a skewness of approximately 3.2 and excess kurtosis of approximately 20.8 for wind. This indicates that a handful of very large observations dominated the fit; but under logarithm these figures fall to approximately -0.45 and 0.14. The natural logarithm of ΔK itself cannot be used because many province-years record zero additions, meaning that

the logarithm is undefined and $ln(1 + \Delta K)$ accommodates them. It is undefined for $\Delta K <- 1$, which is handled by the negative-change rule described above.

3.2.2 Cost Competitiveness

The theoretical quantity of interest is the log ratio of the electricity price a technology would displace to the cost of generating from that specific technology, and it is shown in Equation (2):

$$COMP = ln\left(\frac{Price}{LCOE}\right)$$

A positive value here means a technology already cheaper than the electricity it displaces, and a negative value one that is not. No Canadian series reports provincial electricity prices in dollars per kilowatt-hour on a consistent basis across the whole period examined, so the ratio is approximated. It is approximated by two indices and it is shown in Equation (3):

$$COMP_{i,\tau,t} = ln\left(PriceIndex_{i,\tau,t}\right) - ln\left(LCOEIndex_{\tau,t}\right)$$

The $PriceIndex_{i,\tau,t}$ is the Electric Power Selling Price Index of province i, and its re-based to 100 in the first year technology τ is observed. As for the $LCOEIndex_{\tau,t}$, it is the national IRENA levelized cost of technology τ, rebased to 100 in the same year. So constructed, COMP measures whether provincial electricity prices have risen faster or slower than the national cost of the technology since the shared base year, and it rises as the technology becomes more competitive. Here, both of the components must have the same base year.

COMP measures whether a technology's cost has moved closer or further from the price of electricity in a province. A high value means the technology's cost has fallen faster than that province's electricity price has risen, meaning building it becomes relatively more attractive there; a low value means it has not. COMP is the moderator the research questions asks about. It answers how competitive a technology was in a given province and year; without that figure, it cannot be determined whether a carbon price works differently at different cost levels.

Equation (3) has an identification property on how β_2 should be interpreted. Given that national LCOE takes a single value yearly, $ln(LCOEIndex)$ is collinear with the year dummies within each technology's regression, which gets absorbed. The estimated main effect of COMP is going to be identical to the coefficient on $ln(PriceIndex)$. We can then prove this by doing direct substitution COMP for $ln(PriceIndex)$, to get the same results. Therefore β_2 is read as a price effect. The cost index can be only identified with its interactions: the peer deployment and the carbon price, but both of them vary across provinces within a year due to its nature.

4.2.3 Peer Diffusion

The peer variable is the mean new capacity installed by a province's neighbors in the preceding year. This is shown as in Equation (4):

$$Peer_{i,t-1} = \frac{1}{|N_i|} \sum_{j \in N_i} \Delta K_{j,\tau,t-1}$$

N_i here is the set of neighbours of province i. $|N_i|$ is the number of provinces in that set. j denotes a neighboring province. Neighbors in this paper are defined as provinces sharing a land border. The exception of Prince Edward Island with New Brunswick and Nova Scotia treated as adjacent due to the water connection by ferry.

Equation (4) averages what a province's neighbours built in the previous year. A high value means the neighbours added substantial capacity; a value near zero means they added almost none. The variable therefore tests whether construction in neighbouring provinces in one year is followed by construction in the province itself the next year.

Table 2: Provincial neighbour definitions

Province	Neighbours	N_i
Newfoundland and Labrador	Quebec	1
Prince Edward Island	New Brunswick, Nova Scotia	2
Nova Scotia	New Brunswick, Prince Edward Island	2
New Brunswick	Quebec, Nova Scotia, Prince Edward Island	3
Quebec	Ontario, New Brunswick, Newfoundland and Labrador	3
Ontario	Quebec, Manitoba	2
Manitoba	Ontario, Saskatchewan	2

Electrical systems and geographic definition do not always coincide; for example, Quebec and Ontario are strongly interconnected with its electrical grid and geographically, while Alberta and British Columbia are less connected with its electrical grid even though their province is neighbouring each other. Since this definition of peer is geographic and not by electrical systems, an alternative peer measure will be tested. It is tested by the average across all nine other provinces, and observes the difference with the results tested by the geographic definition. The peer variable is lagged by one year to address the reflection problem (Manski 1993). When two provinces are built in the same year, based on the reflection problem, one may be imitating the other, or both may be responding to something in common that affects them equally. So a peer term measured in the current year cannot separate these. Lagging imposes an ordering in time as the neighbor builds first, so the later build cannot affect the earlier one. The year fixed effects absorb any shock common to all ten provinces. Both measures are partial as the year effects do not affect regional shocks, and factors that affect several provinces but not others would be indistinguishable from diffusion under the design. The peer estimates should therefore be seen as associations.

3.2.4 Policy Stringency

The policy variable is the provincial carbon price in Canadian dollars per tonne of CO_2 equivalent, and is under provincial carbon tax, cap-and-trade system, and federal backstop. Quebec needs separate treatment for this policy variable. It had a carbon duty until 2012 and joined the Western Climate Initiative cap-and-trade market in 2013, after which it has no posted rate. To convert this into Canadian dollars per tonne, we used the auction settlement price. The carbon price enters at year t and it is not lagged as the peer variable is. Projects require years to build, so therefore a price seen in the commissioning year cannot have affected the decision.

3.2.5 Controls and Fixed Effects

Median total income and the share of the population aged 25 to 64 who has a tertiary qualification are used as controls. Provincial population was tested as a control and removed because when the province and year fixed effects absorbing both its between-province differences and its almost linear within-province trend, the variance inflation factor exceeded 11,900. But, removing it moved no coefficient of interest across a conventional significance threshold. The province fixed effects absorb all

time-invariant provincial characteristics and the year fixed effects absorb everything common to all provinces in a year.

Table 3: Summary statistics for the estimation sample

	Wind ($N = 85$)				Solar ($N = 45$)			
	Mean	SD	Min	Max	Mean	SD	Min	Max
$ln(1 + \Delta K)$	5.358	5.602	0.000	14.379	4.413	4.740	0.000	13.236
ΔK (kW)	89,404	238,379	0	1,756,593	48,638	130,962	0	560,264
COMP	1.128	0.512	0.257	2.688	0.668	0.357	0.000	1.568
Peer, lagged (kW)	122,010	191,894	−15,000	948,400	43,481	120,230	−278,632	560,264
Carbon price (CAD/t)	25.600	21.411	0.000	65.000	34.089	17.081	0.000	65.000
LCOE (USD/kWh)	0.058	0.022	0.032	0.089	0.105	0.034	0.071	0.182
Median income (CAD)	43,941	3,357	38,300	51,800	45,189	2,803	40,500	50,700
Tertiary attainment (%)	55.224	5.915	41.000	70.000	56.489	5.173	44.000	69.000

3.3 Model Specification

We distinguish between a determinant and a moderator with the standard terminology of interaction analysis. The determinant of this model is to shift the expected levels of deployment and the moderator changes the effect that another determinant has. A model that includes cost only as a determinant cannot detect it operating as a moderator. A model like such does not test for moderation and assumes there is none before estimation. Thus, the model has both non-economic channels with the same treatment to be entered on its own and again multiplied by cost competitiveness, as shown in Equation (5):

$$ln(1 + \Delta K_{i,\tau,t}) = \alpha_i + \lambda_t + \beta_1 Peer_{i,t-1} + \beta_2 COMP_{i,\tau,t} + \beta_3\left(Peer_{i,t-1} \times COMP_{i,\tau,t}\right) + \beta_4 Policy_{i,t} + \beta_5\left(Policy_{i,t} \times COMP_{i,\tau,t}\right) + \gamma' X_{i,t} + \varepsilon_{i,t}$$

α_i and λ_t here are province and year fixed effects. $Policy_{i,t}$ is the carbon price. Let $X_{i,t}$ be the control variable with the use of median income and tertiary attainment dataset. The error term clustered by province is $\varepsilon_{i,t}$. β_3 and β_5 show the implementation of the moderation hypothesis. Non-economic effects weakens when cost competitiveness increases, so substitution requires β_3 and β_5 to be negative. Complementarity on the other hand requires them to be positive. A second specification (referred to throughout as the LCOE specification) replaces COMP with the national LCOE level, and interactions with the two channels. Its own main effect is not estimable, being collinear with the year fixed effects. The sign convention reverses in this specification because LCOE falls as technology becomes more competitive while COMP rises.

Equation (5) is the econometric model the paper estimates. β_1 measures the association between a province's new capacity and what its neighbours built the previous year, and β_4 the association with the carbon price the province charges. β_2 is the association with cost competitiveness itself. β_3 and β_5 measure whether peer effect, or the effect of the carbon price, varies with the technology's cost competitiveness. Under the COMP specification a positive means it is associated with more building once a technology is cheap than while it is expensive, and a negative value means that it is stronger while the technology is still expensive.

3.4 Estimation Strategy

Both specifications are estimated by ordinary least squares, the standard method of choosing coefficients so that the model's prediction comes as close as possible to what was observed. The province and year effects are included as dummy variables. One category of each is dropped to avoid the collinearity with the intercept. Using QR decomposition of the design matrix, the covariance matrix is computed. This is a precaution because the columns are close to redundant, and arithmetic on nearly redundant columns loses precision.

Standard errors are cluster-robust at the province level. It is computed using a Sandwich estimator with the finite-sample correction: $[G/(G-1)] \cdot [(n-1)/(n-k)]$ for $G = 10$ clusters (Cameron and Miller 2015). Clustering places no restrictions on how errors are correlated within a province on this level; nor how the error variance differs between them. Placing no restrictions matters as within province autocorrelation in annual additions is inconsistent: it ranges from $+\ 0.60$ in Alberta to $-\ 0.70$ in New Brunswick. The dispersion of additions also is different by the orders of magnitude as the standard deviation ranges from 510,000 kW in Ontario to under 200 kW in Newfoundland and Labrador.

Every coefficient is reported with two p-values. To get to a p-value from a t-statistic, it required a reference distribution, there are two options: the normal and the t-distribution with $G - 1$ degrees of

freedom, where G is the number of clusters. With the large number of clusters, the two distributions agree closely, but they do not in ten clusters. The same estimate receives a larger p-value. Cameron and Miller (2015) recommend the t distribution in this case, so we treat those figures as the operative. Two coefficients are significant at the 5% level under the normal approximation and not under $t(9)$.

The number of parameters takes an important role at these sample sizes. The COMP specification has seven regressors and the LCOE specification has six, with the LCOE has no cost main effect. Yet, the fixed effects add nine province dummies, eight year dummy for wind and five year dummy for solar, and an intercept. Wind on 85 observations estimated 25 parameters under the COMP specification and 24 under the LCOE specification. Solar estimates 22 and 21 from 45 observations. This is close to one parameter for every two data points.

3.5 Robustness Checks

Robustness checks are conducted by doing six different tests.

1. Variance inflation factors are computed for every regressor to measure how much independent variation remains after the fixed effects.
2. Leverage values are examined to identify observations that fit themselves rather than contributing to a cross-sectional test.
3. The model is re-estimated ten times, dropping one province each time to see whether any results depend on a single province.
4. The neighbour-based peer variable is replaced by the average across all nine other provinces. This tests whether the diffusion based on the geographic definition produces the result.
5. The dependent variable is estimated in raw kilowatts as well as in logarithms.
6. The structural-zero fill is switched off. This reduces the solar sample to 24 observations in six provinces and both of those sets of estimates are reported.

4. RESULTS

Table 4 reports the four regressions made. It is each technology under each specification, with the estimation based on the primary rule for capacity decreases. Here, the peer coefficients are scaled $\times\ 10^{-5}$ for legibility, as well as the peer variable measured in kilowatts.

Table 4: Main estimates. Dependent variable $ln(1\ +\ \Delta K)$

	Wind COMP	Wind LCOE	Solar COMP	Solar LCOE
Peer ($\times\ 10^{-5}$)	0.237 (.732 / .740)	-0.950 (.039 / .069)	-0.024 (.984 / .985)	4.075 (<.001 / .006)
COMP	7.943 (.507 / .523)	—	-16.368 (.269 / .298)	—

	Wind COMP	Wind LCOE	Solar COMP	Solar LCOE
Peer × COMP ($\times 10^{-5}$)	-0.319 (.546 / .561)	—	2.193 (.278 / .306)	—
Peer × LCOE ($\times 10^{-5}$)	—	10.42 (.214 /.245)	—	-24.82 (.013 / .034)
Carbon Price	0.105 (.584 / .597)	0.486 (.001 / .009)	-0.183 (.129 / .164)	1.297 (.002 / .011)
Policy × COMP	-0.002 (.990 / .990)	−6.398 (.030 / .059)	0.364 (.054 / .086)	−8.841 (.001 / .010)
Policy × LCOE	—		—	
Median Income	0.0002 (.775 / .782)	-0.0003 (.521 / .537)	-0.0012 (.080 / .114)	-0.0004 (.546 / .561)
Tertiary attainment	0.272 (.468 / .487)	0.136 (.659 / .670)	-0.181 (.695 / .704)	-0.539 (.075 / .108)
N	85	85	45	45
R^2	0.639	0.647	0.845	0.874

Note. Two p-values appear in the parentheses. It is ordered by the normal approximation first, followed by the t distribution with 9 degrees of freedom. Peer coefficients are scaled by 10^5. All the regressions do include province and year fixed effects, and the standard errors are clustered by province. R^2 is the share of variation.

4.1 The Peer Channel

No moderation of peer diffusion is detected in either technology. Peer interaction is insignificant for wind (p = 0.561) and for solar (p = 0.305), and under the alternative all-province definition of a neighbour for wind (p = 0.245). So Provinces do not appear to follow their neighbours' example.

The solar Peer × LCOE term showed significance under the primary rule with a p-value of 0.034. Yet, it is not found significant under the alternative treatment of capacity decreases, so therefore not treated as a finding. The same interaction was significant when the solar sample only had the six provinces with published capacity rows is something to note. Then extending the sample to all ten with the structural-zero fill removed the significance. The six-province sample excludes all of Atlantic Canada; they had almost no utility-scale solar built over the period. A result that depends on omitting those provinces is better attributed to their absence than to a relationship in the population. The peer main effects act in opposite directions with the LCOE specification: it is negative for wind where $p = 0.069$, and positive for solar at $p = 0.006$.

4.2 The Policy Channel

The policy interaction is different from the peer channel results. Under the LCOE specification the interaction is -6.398 for wind and -8.841 for solar. The negative sign in this data is set out in Methods by convention, the complementarity direction. The solar estimate is significant on either reference distribution ($p = 0.001$ normal, 0.010 under $t(9)$). The wind estimate is not significant as it is $p = 0.030$ under the normal approximation but 0.059 under $t(9)$. For the COMP specification, the wind term is null with $p = 0.990$, and the solar term is positive with $p = 0.086$. It is seen that it's still in the complementarity direction because COMP rises with competitiveness and LCOE falls. For wind the point estimates imply a marginal effect of carbon pricing of $0.486 - 6.398 \times LCOE$, which Table 5 evaluates at observed costs.

Wind LCOE (USD/kWh)	Years	Marginal effect	Implied change in $(1 + \Delta K)$
0.089	2015–2016	−0.084	−8.1%
0.076	n/a	0.000	Sign change
0.072	2017	0.025	2.6%
0.059	2018	0.110	11.6%
0.032	2021	0.280	32.3%

*Table 5: Implied marginal effect of a $1/tonne carbon price increase on wind deployment*Point estimates under the primary rule. The sign change at 0.076 USD/kWh falls between the 2016 and 2017 values of the Canadian series.

It is taken at face value. The table describes a carbon price whose association with wind deployment is negative while the technology still is expensive. Then, it turns to positive as cost falls through the threshold in 2017. Then, it grows substantially between 2018 and 2021. The solar estimates imply the same structure, it has the sign change near 0.147 USD/kWh between 2018 and 2019.

4.3 Sensitivity

Face value is not the appropriate valuation however.

Table 6: The wind policy interaction under alternative treatments

	Carbon Price	Policy × LCOE	N
Primary rule (decreases dropped)	0.486 (0.009)	−6.398 (0.059)	85
Alternative rule (decreases to zero)	0.185 (0.171)	−2.740 (0.372)	90

Under the alternative rule the interaction falls from -6.398 to -2.740 and its p-value rises, it removes the significance but still points to carbon price mattering more once the technology is cheap. Each is a year in which a province held a substantial carbon price and reported no growth in wind capacity. Only British Columbia's is a decline of any size: thirty megawatts in 2018, against a fleet of roughly seven hundred, in a year when its carbon price stayed at forty dollars a tonne. The other four declines are between 0.1 and 3.6 MW. This is small enough that those years are flat.

The second check asks if the results come from one province alone. The model is re-estimated ten times with one province removed each time. The interaction is negative in all ten, so no single province is responsible. Only two reach conventional significance, and omitting either British Columbia ($p = .364$) or Quebec ($p = .293$) on its own is enough to remove it. Those two are the only provinces that did not follow the federal schedule.

A third limitation concerns what the individual coefficients can show. The carbon price follows a common federal schedule, so in most provinces it takes the same value in the same year, and the model already contains a dummy for every year. Those dummies absorb almost all of the movement in the carbon price and leave little province-specific variation behind. The variance inflation factor reaches 138.7 on the carbon price and 43.6 on the interaction even in the reduced specification. The carbon price and its interaction with cost therefore cannot be interpreted one at a time, which is why Table 5 reports the two combined rather than either coefficient on its own.

The other checks agree. Table 7 collects them for the wind LCOE specification, including the paper's main result.

Check	Policy × LCOE	p
Baseline	−6.398	0.059
Alternative decrease rule	−2.740	0.372
All-province peer measure	−4.471	0.095
Raw kilowatt dependent variable	−198,332	0.104
Leave-one-province out	Negative in all 10	Significant in 2 of 10
Structural-zero fill removed	Not applicable	Not applicable

Table 7: The wind policy interaction under the six robustness checks

The sign is negative in every specification examined. Also the estimate fails to reach the 5% threshold in every specification. After replacing the neighbour-based measure with the all-province peer measure, it moves the interaction to $-\ 4.471$ with $p\ =\ 0.095$; as well as the peer main effect to $p\ =\ 0.114$, this shows neither of the results actually depends on the geographic definition, but none is strengthened by the alternative. The log form here is contested when a large number of observations are at zero; so the model is estimated in raw kilowatts (Chen and Roth 2024). The interaction remains negative with $p\ =\ 0.104$, so the sign does not depend on the transformation. Leverage explains why the estimates are so easily moved. The mean hat value is 0.282, but five observations exceed 0.45, the highest being British Columbia in 2023 at 0.697. All five are province-years with zero new capacity. So having a lot of zeros in high-carbon-price years therefore carries a disproportionate share of the identifying variation. Policy-channel estimate is directionally consistent but also statistically fragile.

4.4 Solar

The solar estimates reproduce the structure of the wind estimates with greater apparent strength: every term of interest in the LCOE specification is significant. None of that strength is treated as informative, for reasons already given. The sample covers six years and fits twenty-one parameters to forty-five observations, and the coefficients move materially between the fill and no-fill samples. The carbon price main effect falls from 1.297 at $p\ =.011$ to 0.436 at $p\ =.489$. The no-fill sample has six clusters rather than ten, so its reference distribution is $t(5)$. Solar points the result in the same way as wind, where the carbon price interaction is negative in both technologies. But six years and 45 observations is too limited to establish anything on its own, so it supports the wind pattern, however it does not confirm it.

5. DISCUSSION

A major problem in renewable energy policy is that governments set carbon prices without knowing whether a price produces more new capacity while a technology is still expensive or cheap. Previous analyses have treated cost, peer influence and policy stringency as independent determinants of deployment, each entering a model on its own. That approach cannot address the possibility that the three are interdependent. The three literatures reviewed support the three factors separately: learning curves, diffusion, regulation literature does not examine how they interact. To examine the question, this paper assembled a panel of the ten Canadian provinces from 2010 to 2023 from government sources and estimated a two-way fixed-effect model where each non-economic factor enters on its own and multiplied by cost competitiveness.

For the peer channel, there is no evidence of moderation. On the policy channel, the evidence supports and points with complete directional consistency toward complementarity, which is when carbon pricing is associated with deployment only once the technology becomes cheap, but it stops short of statistical significance. Substitution, on the other hand, finds no support anywhere in the estimates.

Three considerations limit how much weight this pattern will have. The first is that the Canadian LCOE series decline correlates with the year at -0.975 USD/kWh for wind. The interaction of policy with cost is almost the same with the interaction of policy with elapsed time. Anything else that improved over those same years would produce the same estimate, such as maturing supply chains, the growth of the corporate power-purchase market, or accumulated procurement experience. The design cannot separate these from falling cost. The second is the specification dependence recorded in Table 4. The wind policy interaction is present under the LCOE specification and absent with the COMP specification. The LCOE and COMP specification is different because COMP adds provincial electricity prices and an index construction to the national cost series; yet, both of them do not have a clear claim to being the correct one. The sensitivity is the third consideration. There were five observations that moved the estimate from p = 0.059 to 0.372 (Table 6). Each is a province-year in which a substantial carbon price coincided with no new wind capacity.

On the other hand, there's two considerations against these cautions. Under the LCOE specification the direction of the policy interaction will not reverse. It has a complementarity sign in all 24 estimates we looked at. Under the COMP specification the pattern is mixed, but there the wind coefficient is almost zero with -0.002, p=990; a coefficient that close to zero could be positive or negative without meaning. These results relate most directly to Xu and Yang (2024), who find that carbon pricing generally promotes renewable development across countries. Overall, the results suggest that carbon pricing's effect on renewable deployment could have the most impact where renewable technologies are already cost-competitive.

5.1 Limitation

The central limitation of this experimental study is the cost series. National LCOE varies only by year. That causes provincial cost variation by construction and correlates with time too much; for wind the series correlates with the year at -0.975. The interaction of policy with cost is close to an interaction of policy with elapsed time. Here, if a provincial cost series were available, it would help reduce the effect of this limitation by having the cross-province variation that this model lacks.

The carbon price enters in the same year as the deployment it is meant to explain, but projects completed in a certain year were pre-planned several years earlier. The policy estimates in this model would describe association but not effect due to this. The peer variable is lagged one year due to this, but carbon price is not.

Inference is based on ten clusters with one per province. P-values are computed against the t(9), but not the normal distribution because being ten is a small number of clusters, the normal distribution gives p-values that are too small. Even so, inference and estimates near conventional thresholds is therefore weak and should not be read as decisive.

The solar panel only has a span of six years, the time is too limited to test if cost competitiveness moderates either channel. Much of the solar is assumed. Of the sixty province-years in that window, 41 had a published capacity figure, 12 were structural zeros, and 6 were unavailable. The assumption creates much limitation as the carbon price main effect drops from 1.297 ($p=0.11$) with the fill to 0.436 ($p=0.489$) without it. The solar estimates are therefore read as exploratory. The constraint is the length of the record: Canadian solar LCOE begins only in 2018, and the same specification run on a longer series would be capable of testing if cost competitiveness moderates the two channels and would show more than merely indicating it. COMP's main effect measures only the provincial electricity price. Since the year fixed effects absorb its cost component, then there is no component that estimates a level effect of cost competitiveness. In this paper, deployment means utility-scale capacity. Therefore, this paper is not focusing on household adopters, and the limitation here is that these estimates do not address household channels.

6. CONCLUSION

The paper asked if cost competitiveness moderates the effect of peer diffusion and carbon pricing on renewable deployment across Canadian provinces. The question was answered by multiplying each channel by cost competitiveness, allowing an effect to differ at different cost levels. For peer diffusion, the estimate from the model showed no evidence of moderation. For carbon pricing, every version of the model points to the price level associated with more new capacities once the technology is cheap, but none of them reaches statistical significance. The results show that the policy's association with wind deployment is negative while the technology is expensive and positive when price decreases. The pattern correlates with the complementarity pattern. To prove this pattern, it would require more clusters than ten

provinces supply, a cost series with variation in provinces, and also a policy instrument that is less collinear with time.

Two groups have a stake in this research direction. In the case of governments, a carbon price whose effect depends on the cost of the technology is worth different amounts as time changes. The same price per tonne buys less new capacity while one technology is expensive, and purchases more when the price decreases. When a government introduces a price, therefore, matters just as much as how high the price was originally set. Among utility companies and agencies responsible for procurement, the current consensus is that the relationship between the price of carbon and new installed capacity is not stable over time. Planning assumptions developed based on one cost environment cannot be directly applied to another. While the scope of this paper is confined to the Canadian provinces, the design is not. Extending the estimation to other nations would provide more clusters that this panel lacks, this would test whether the cost-dependence proposed here only appears in Canada or a general feature of how carbon pricing works.

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