CANADA'S **ECOFISCAL** COMMISSION
Practical solutions for growing prosperity

Technical Annex

for Case Studies in *Supporting Carbon Pricing*

This document provides additional details as to the approaches and assumptions used in *Supporting Carbon Pricing* to assess:

(1) Electric vehicle subsidies in Quebec
(2) Phasing out coal-fired electricity generation in Alberta

Technical Annex for Case Studies in *Supporting Carbon Pricing*

1. Electric vehicle subsidies in Quebec

OVERVIEW

This section provides the methodological details of our case study assessing Quebec's $8,000 subsidy on plug-in electric vehicles. The Ecofiscal Commission contracted modelling analysis from Navius Research for this case study. Below, we summarize the details of the reference and policy scenarios, describe our assumptions and the modelling framework, and outline the model's parameters and results.

SCENARIOS

To isolate the effects of Quebec's PEV subsidy, a policy scenario is compared to a reference case scenario in the model.

Reference case scenario:

The reference case scenario includes the carbon price on gasoline coming from Quebec's cap-and-trade policy. All other scenario drivers are defined in the "Key Parameters" section, below. For simplicity, this analysis does not include the impact of other transportation policies, such as the federal renewable fuel standard or the passenger automobile and light truck greenhouse gas (GHG) emissions standard.

Policy scenario:

The policy scenario is identical to the reference scenario, except that it includes Quebec's Drive Electric Program (Government of Quebec, 2012), represented as an $8,000 subsidy on the PHEV 64 and EV160 vehicle archetypes in the model (see below for more details). We have assumed the subsidy is in effect for a five-year period, from 2016 to 2020.

KEY ASSUMPTIONS

1. **No change in vehicle kilometres travelled**. Any policy could change the quantity of kilometres travelled by passenger vehicles. However, the impact of a PEV subsidy on driving behaviour is likely to be negligible.
2. **No change in the rate of vehicle retirement.** Similarly, we assume the policy does not change the rate at which vehicles are retired, nor does it change the rate at which new vehicles are acquired.
3. **Consumers have no foresight.** Consumers will not change or delay a vehicle purchase to take advantage of lower upfront costs in the future (i.e., waiting for electric cars to get cheaper); they choose to buy the vehicle at its current price.
4. **No impact on PEV costs.** We assume the incremental change in PEV adoption in Quebec caused by the subsidy has no impact on the cost of PEVs, which is driven by the global sales and global research and development.

ANALYTICAL APPROACH

For this analysis, Navius Research developed an agent-based version of its CIMS technology model. The CIMS model provides a detailed representation of the types of technologies available to meet different energy end-uses (including for passenger vehicles) and their costs. The model simulates how households and firms select different technologies (with different emissions associated with their use) under different policies or economic conditions.

CIMS accounts for three unique features that are relevant for this exercise and unique with respect to other technologically explicit models:

1. **Non-financial factors.** The model explicitly accounts for non-financial factors that influence decision-making. In particular, Axsen et al. (2015) find that electric vehicles currently have high perceived costs. However, Mau et al. (2008) also highlight that these costs are likely to decline over time if consumers gain greater familiarity with the technology (this is called the "neighbour effect").
2. **Realistic discount rates.** Empirical studies show that consumers use high implicit discount rates (i.e., much higher than the cost of capital or the opportunity cost of other foregone investments). Consequently, consumers are less likely to choose a vehicle with high upfront costs, even if its ongoing costs are much lower than those of other vehicles. Horne et al. (2005), for example, find that consumers use a discount rate of 22.3% when making transportation investments.
3. **Market heterogeneity.** The model recognizes that consumers are not homogenous with respect to their preferences toward different technologies and the costs they experience. Rather, households may select different technologies for many reasons, such as differences in preferences and differences in driving distances (and therefore sensitivity to fuel costs).

The model simulates consumer choices across six vehicle archetypes: a low-, medium-, and high-efficiency conventional internal combustion engine vehicle; a hybrid electric vehicle; a plug-in hybrid vehicle with a 64-km electric range (PHEV 64); and a battery electric vehicle with a 160-km electric range (EV 160). It simulates consumer choices from 2015 to 2030 in five-year time steps, producing a forecast of new vehicle stock in each model-year. New vehicle stock is added to the total stock of vehicles, replacing those that have been retired or satisfying additional demand for vehicles. Because the model explicitly simulates capital stock turnover for vehicles, the subsidy policy only affects new vehicles purchased in each year and has no impact on the existing stock of vehicles.

The CIMS model uses the following equation to allocate market share among technologies (Jaccard et al., 2003):

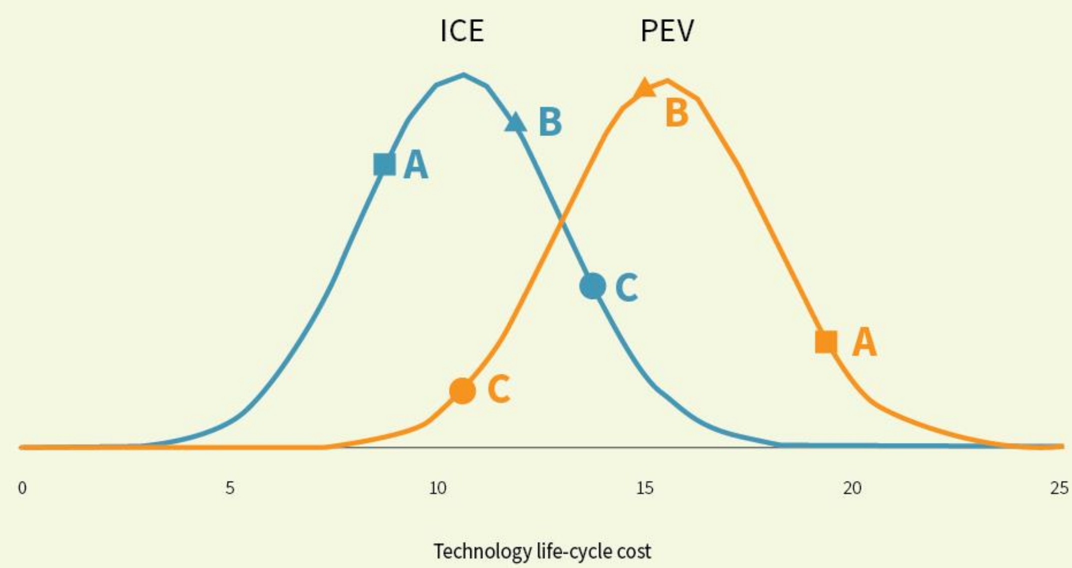
$$MS_t = \frac{{LCC_t}^{-v}}{\sum_{tt}^{T} {LCC_{tt}}^{-v}}$$

Where: MS_t is the market share for technology t; LCC_t is the life-cycle cost for technology t (calculated with non-financial costs using a realistic discount rate); v is a market heterogeneity parameter; T is the full technology set that competes with technology t; and tt is an alias for t.

The agent-based version of the CIMS model, developed for this project, converts the market share equation into a more explicit representation of individual consumers. The model simulates 5,000 individual agents for which the life-cycle costs for a passenger vehicle are randomly drawn from a normal distribution around mean expected life-cycle costs. The standard deviation for the normal distribution, which is analogous to the *v* parameter in the equation above, is calibrated to yield a similar market share to that predicted by the CIMS model.

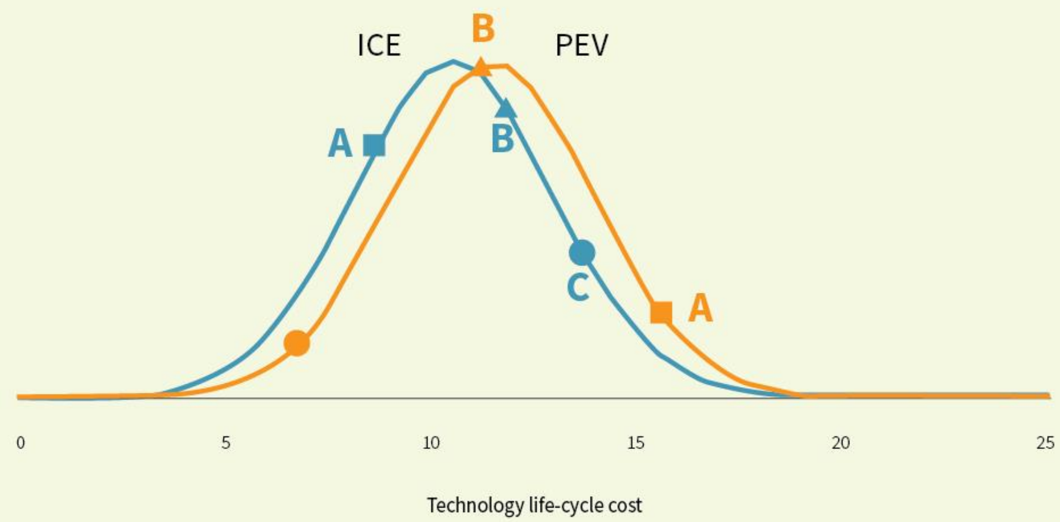
Figure 1 illustrates this process. As labelled in the figure, person A will have a specific life-cycle cost for a vehicle with an internal combustion engine (ICE), and a specific life-cycle cost for a plug-in electric vehicle (PEV). Likewise, persons B and C have specific costs for adopting an ICE vehicle or a PEV. In the absence of any policy constraint, each person will select the technology with the lowest life-cycle cost. In the example, persons A and B will select ICE vehicles, while person C will select a PEV. Once each agent's technological choice has been simulated, the market share for each technology can be estimated from the collective choices of all agents.

Figure 1: Market competition in the vehicle sector (reference case)



The subsidy on PEVs in Quebec reduces the cost of selecting a PEV, and therefore shifts the normal distribution for PEVs to the left (see Figure 2). As illustrated in the example in Figure 2, *in the absence of the policy,* person B would have purchased an ICE vehicle, but in the presence of the subsidy, the cost of selecting a PEV (after the subsidy) is lower than selecting an ICE vehicle. As a result, person B now selects a PEV.

Figure 2: Market competition in the vehicle sector (with subsidy)



The new stock and the total stock of vehicles that results from agents' modelled technological choices help define the costs and benefits of the policy, as well as energy consumption and resulting GHG emissions. The model considers all GHG emissions associated with the operation of light-duty passenger vehicles in Quebec.[1] It includes various costs and benefits that are used to estimate the policy's expected net social cost. These individual cost elements are summarized in **Table 1**. Not included in these costs and benefits are vehicle maintenance or depreciation costs, which could differ between ICE vehicles and PEVs. The costs and benefits also do not consider the net-human health impact of switching to an electric vehicle in Quebec.

Table 1: Types of costs and benefits modelled for the PEV subsidies in Quebec case study

Type		Description
Cost	Vehicle capital costs	The incremental cost of purchasing a PEV compared with an ICE vehicle. The total capital cost is the size of the incremental multiplied by the number of consumers who are induced to buy a PEV under the subsidy policy.
	Vehicle operating and maintenance (O&M) costs	The cost of gasoline and electricity used in vehicles over their lifetimes. These costs are taken against avoided fuel and carbon costs (seen below) to estimate the net change to O&M costs attributable to the policy.
	Market barriers	Sometimes called intangible costs, these preference-driven costs account for the real and perceived barriers to adopting PEVs, such as lack of information on benefits of the technology, lower performance (e.g., inconvenience of limited range and long charging times), and scepticism toward the technology due to a lack of familiarity. They capture both the effects of market barriers and market failures.

[1] Since the emissions intensity of electricity generation in Quebec is so low (95% of all electricity is sourced from hydropower), the model does not account for upstream emissions resulting from electricity generation, oil extraction, or oil refining (Hydro-Québec, 2015a).

Type		Description
	Cost of raising public funds	The subsidy that the government provides to consumers to purchase a PEV is paid for using *Fonds vert*, which is largely supplied by cap-and-trade revenue. As with all forms of taxation, there is an economic cost to raising these funds in the form of the economic distortion and the lost production or welfare that results. The cost is calculated using a "marginal cost of public funds" that is specific to a given jurisdiction and tax instrument.
Benefit	Avoided fuel costs	Consumers who buy a PEV instead of an ICE vehicle use less energy for transportation and avoid some of the fuel costs they would have otherwise experienced. This benefit reduces total net vehicle operating costs.
	Avoided carbon costs	Similar to avoided fuel costs, consumers who buy a PEV also avoid the cost of carbon applied to fossil fuels by the cap-and-trade policy. This benefit reduces total net vehicle operating costs.
	Benefit of addressing market failures	Increased adoption of PEVs helps overcome market failures that are inhibiting their adoption, which reduces net abatement costs. This benefit comes in the form of both PEV consumers experiencing lower costs than expected and greater PEV uptake in the broader market as a result of these changing perceptions (so-called neighbour effects).

We estimate the cost of Quebec's PEV subsidy policy as follows:

- When an agent selects a vehicle that the agent would not have purchased in the absence of the subsidy policy, the agent bears different capital and operating costs. Capital costs increase by the amount that the cost of a PEV exceeds that of an ICE vehicle (i.e., the *excess* cost of purchasing a PEV),[2] while operating costs fall by the amount that an ICE vehicle's fuel costs (over its lifetime) exceed a PEV's. The actual price of gasoline and electricity, as well as the price on carbon all inform this cost differential. Summing the change in agents' capital and operating costs estimates the direct private costs associated with the policy.
- In addition, each agent who alters his or her choice may—as a result of the agent's unique preferences—experience *intangible* costs. These costs represent the various factors that may be inhibiting PEV uptake, and estimate the impact of both genuine market failures and the larger set of market barriers. Summing the change in agents' intangible costs with the change in their net capital and operating costs estimates the total private costs attributable to the subsidy policy.
- The subsidy that the government provides to consumers to purchase a PEV has a cost to society in the form of the economic distortion and the lost welfare that results from raising the funds through higher taxes (Ferede & Dahlby, 2016). This social cost raises the policy's total estimated costs.
- Finally, some of the intangible costs discussed above may be due to market failures. Where the policy helps overcome these failures, it creates a social benefit. Because estimates of the quantitative impact that market failures have in the PEV sector are highly uncertain, we took the following approach in estimating the impact of overcoming market failures:
    - PEV-focused research by Axsen et al. (2015) indicated the importance of non-financial preferences for vehicle choice, but was less clear whether these non-financial preferences

[2] While a portion of purchase costs are covered by the subsidy, they remain a cost whether they are borne by the consumer or the tax payer.

are fully informed or not. This presented a dilemma of whether to leave these costs as part of intangible costs (and thereby implicitly suggest that these costs represent fully informed decisions by households) or to highlight that some of these costs may be due to market failures.
    - We chose the latter by making an assumption that 20% of the non-financial preferences may not be fully informed—in other words, 20% of the intangible costs that PEV buyers expect to incur are in fact not experienced. This change mirrors the change in a consumer's discount rate that occurs with better information, as found by Coller and Williams (1999). Clearly, there remains a considerable amount of uncertainty surrounding this estimate. However, it is taken to be a rough approximation of the magnitude of the subsidy policy's market failure-addressing benefit.
- To estimate the policy's expected total net social cost, the changes to net capital, operating, and indirect private costs are added to the cost to society of raising public funds, less the benefit associated with addressing market failures.

To communicate the resultant estimates of the policy's total cost in a single summative metric—the "implicit carbon price"—the model discounts costs and benefits (including projected future GHG reductions) to estimate a net present value (NPV) in terms of net social costs per tonne of emissions reduced. It assumes a social discount rate of 3%.

KEY PARAMETERS

Parameter	Modelled value	Source	Notes
Light-duty passenger vehicle activity	71 billion vehicle km travelled per year, growing at 0.9%/yr	NRCAN (2016)	Activity is calibrated to current activity estimated by NRCAN in the comprehensive energy-use database. Growth is based on the trend since 2005. New stock (i.e., new vehicle purchases) comes online to replace retired vehicles (retired on average after 16 years) and to allow increasing activity.
Implied discount rate used by consumers when making clean or alternative fuel transportation choices	25%	Horne et al. (2005)	Horne et al. (2005) estimate the discount rate at 22.3% using empirical choice modelling data. Ewing and Sarigöllü (2000) find the discount rate could range between 19% and 70%. We use 25% as a representative value, though the true value will vary among heterogeneous consumers.
"Optimal" discount rate consumers would use with perfect information—i.e., without market failures	20%	Coller and Williams (1999)	Coller and Williams (1999) estimate the implied discount rates within experimental consumer choices where current costs were traded off against future savings. With no prior information or discussion, discount rates were 20%-25%. After discussing the future benefits and typical returns on investment, discount rates fell to 15%-17.5%. We chose a 5% reduction from the "implied" rate above to represent the possible change in consumer behaviour with perfect information.

Parameter	Modelled value	Source	Notes
Starting (2015) incremental cost of PEVs, relative to an ICE vehicle	Hybrid: $5,000 PHEV64: $14,000 EV160: $20,000	Axsen and Kurani (2013); Nykvist and Nilsson (2015)	Vehicle battery costs are based on Nykvist and Nilsson (2015). How this translates into incremental cost is based on the method used in Axsen and Kurani (2013).
Trend in vehicle incremental costs	Hybrid (in 2030): $2,300 PHEV64 (in 2030): $6,200 EV160 (in 2030): $5,200	Axsen and Kurani (2013); Nykvist and Nilsson (2015)	We assumed vehicle battery costs continue to fall by 8% annually, the average historical change found by Nykvist and Nilsson (2015), until battery costs fall to $125/kWh, the U.S. government target for 2022 (US Department of Energy, 2013).
Trends in intangible costs	Intangible costs start equivalent to $8,000 (the value of the subsidy), but decline according to a logistic (S-shaped) trend once PEV new market share reaches roughly 10% of sales	Mau et al. (2008); Axsen and Wolinetz (2016)	The declining intangible cost relationship is based on Mau et al. (2008). The starting value and the rate at which the intangible cost changes in response to sales are calibrated so this model approximates the impact of a subsidy on PEVs simulated by Axsen and Wolinetz (2016). Again, based on the informed vs. uninformed discount rate used by consumers, we assume that 20% of the intangible cost is perceived costs, and not real costs experienced if they purchase the technology.
Energy intensity of PEVs	PHEV64: on average, 8 kWh/100 km and 1.8 L gasoline/100 km EV 160: 17 kWh/100 km	Axsen and Wolinetz (2016)	Values are based on typical energy intensities employed by Axsen and Wolinetz (2016). PHEV64 electricity vs. gasoline consumption is based on an average 66% of annual km travelled powered by electricity, with the remaining 34% at 4.8 L/100 km.
Fuel efficiency of ICE vehicles	Low, med, and high efficiency ranging from 9.1 to 6.4 L/100 km	Assumed values	Values for low-, med-, and high-efficiency ICE vehicle fuel efficiency are assumed and calibrated so the model matches current passenger light-duty vehicle energy consumption in Quebec (NRCAN, 2017).
Current price of petroleum-based fuel (e.g., gasoline)	$1.09/L in 2015	Statistics Canada (2016a).	CANSIM Table 326-0009: Average retail prices for gasoline and fuel oil, by urban centre, annual. Excludes the price impact of carbon pricing.
Trend in petroleum-based fuel (e.g., gasoline)	$1.10/L by 2030 (2015 CAD)	National Energy Board (2016)	Based on the reference oil price scenario.
Electricity price	7.2 cents/kWh throughout the forecast (2015 CAD)	Hydro-Québec (2015b)	Trend is based on National Energy Board (2016).
Carbon price on gasoline from cap-and-trade policy	$20/tonne (2015 CAD), rising to $39/tonne (2015 CAD) by 2030	Sawyer et al. (2016)	Rises by 5% in real terms each year, according to the price floor of the Western Climate Initiative cap-and-trade system.

Parameter	Modelled value	Source	Notes
Marginal cost of public funds (MCPF) from cap-and-trade system	0.29	Modelling using EC-PRO model	The PEV subsidy is funded through *Fonds vert*, which in turn is primarily funded by the cap-and-trade revenues. The MCPF used is specific to this taxation instrument in Quebec. Computable general equilibrium modelling of the Canadian economy using the EC-PRO model was used to estimate this figure (Boehringer et al., 2015).

RESULTS

Emissions reductions

The model estimates GHG reductions by comparing the total level of emissions in the reference case and policy scenarios. The difference between the two is the emissions reduction attributable to Quebec's PEV subsidy policy.

Differences between the two scenarios stem from the policy's effect on vehicle purchases. Some consumers who would opt to purchase an ICE vehicle in the absence of the subsidy may instead buy a PEV under the subsidy policy. The aggregate reduced emissions that result is the policy's estimated GHG mitigation. Some consumers would choose to purchase a PEV with or without a subsidy. These buyers are said to "free-ride" on the subsidy policy. Because these consumers' emissions are the same across both scenarios, free-riding does not affect estimated emissions reductions (however, it does affect the policy's costs).

The model calculates annual emissions reductions and sums them over the model's time horizon to estimate total cumulative GHG mitigation. By 2030, the cumulative GHG reductions that result from the purchase of PEVs instead of ICE vehicles as a result of the subsidy are estimated by the model to amount to **3 Mt CO_2e**.[3]

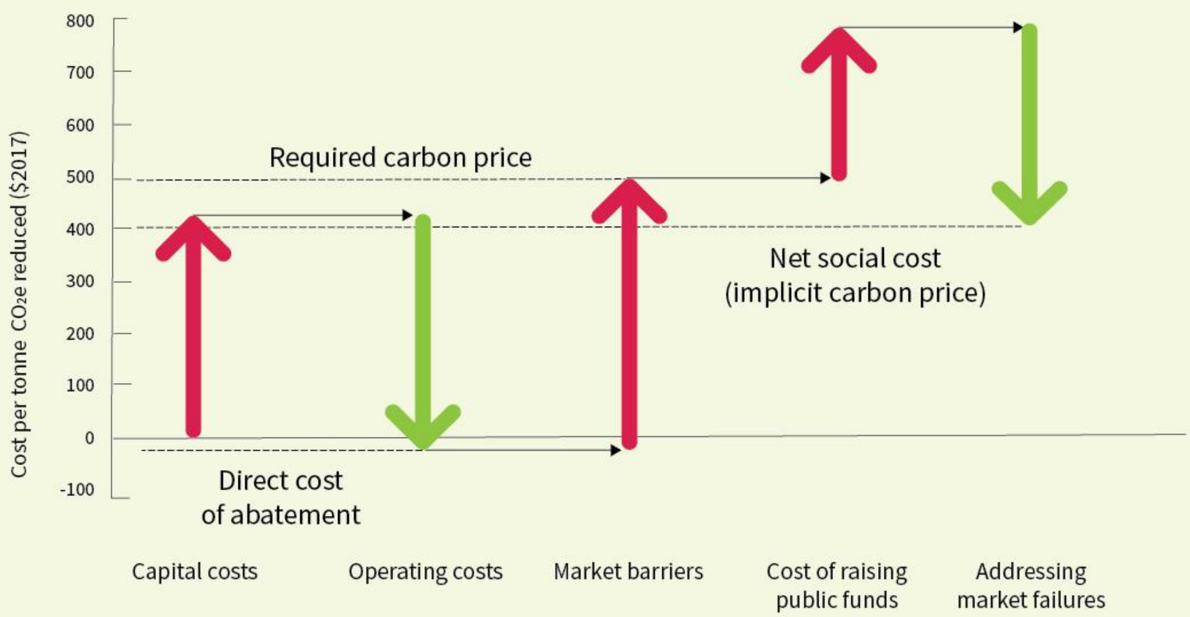
Costs

Differences in costs across the two scenarios stem from the excess capital cost of PEVs to consumers as compared with an ICE vehicle, the benefit of PEVs' lesser operational costs, the economic cost of providing the PEV subsidy, and the benefit of addressing market failures via the policy. We estimate the policy's mitigation costs in the form of its "implicit carbon price" by discounting net annual costs and dividing by net annual GHG mitigation. The model estimates that the policy's GHG mitigation is delivered at a cost of **\$395/tonne CO_2e**.

Figure 3 decomposes this total net social cost into its separate cost elements, which are described in detail below.

[3] This estimate assumes that the emissions cap in the Quebec's cap-and-trade system continues to not bind. The policy's net mitigation would in fact be less if the cap-and-trade system's permits began to sell above the price floor (i.e., if the cap binds).

Figure 3: Breakdown of net social mitigation costs for Quebec's PEV subsidies



This figure decomposes different costs and benefits (each described in the text) associated with Quebec's PEV subsidy program. Each cost (upward arrow) or benefit (downward arrow) is expressed as net costs divided by total emissions reductions expected from the policy (i.e., all costs and benefits are displayed in "per tonne" terms). Both net costs and emissions reductions are incremental: they reflect the difference between a case in which only carbon pricing is implemented and a case in which both carbon pricing and the PEV subsidy are implemented. To better summarize the modelling results, time-series estimates for the cost and benefit variables seen here have been converted to single-point estimates using present value discounting, in line with Environment and Climate Change Canada's approach to calculating policies' social cost per adjusted tonne of CO_2e.

Capital costs represent the average additional cost of purchasing a PEV compared with an ICE vehicle. PEVs cost more to purchase than ICE vehicles; therefore, capital costs appear in the figure as a net cost.

Operating costs represent the additional cost of operating a PEV compared with an ICE vehicle *over its lifetime.* As illustrated in the figure, the costs are negative, meaning there are net operating *savings* associated with owning a PEV over its lifetime, given its lower relative fuel costs.

Direct costs of abatement are the sum of capital costs and operating costs. They express the total additional cost of owning a PEV instead of an ICE vehicle, indicating the abatement costs associated with PEV uptake. The modelled *negative* direct cost of abatement suggests that the purchase of an ICE vehicle should offer a net *return* over its lifetime under the province's cap-and-trade system. However, market barriers in the PEV sector (as discussed below) inhibit the uptake of this seemingly cost-effective mitigation action.

Costs of market barriers reflect non-financial factors that affect consumers' preferences. They are important in the PEV sector: Since PEVs are a new technology, some consumers may be unaware of the net lifetime savings they can offer. Consumers may also perceive the costs of PEVs to be higher as a result of inconveniences such as limited charging infrastructure or the required charging time. This element is estimated based on empirical findings regarding how consumers actually behave when considering purchasing PEVs. Importantly, it captures both the market *barriers* (range anxiety, consumer preferences, etc.) and the genuine market *failures* (incomplete information, uncertain future carbon prices, etc.) that may be limiting PEV uptake. While the analysis is based on survey data that captures driver preferences, the extent to which these preferences are driven by market barriers or market failures is highly uncertain.

Required carbon price indicates the cost of mitigating GHG emissions by purchasing PEVs as *perceived* by potential PEV consumers. It combines their direct capital and operating costs (relative to an ICE vehicle), as well as both the real and perceived *additional* costs that they anticipate when considering purchasing a PEV. It implies the level of carbon price that would have been necessary (over and above the existing explicit carbon price) to overcome the market barriers that are impeding consumers' wide-scale adoption of PEVs.

Cost of raising public funds reflects the economic costs of the government subsidy for the purchase of PEVs. The subsidy is largely funded by cap-and-trade permit auction revenue via *Fonds vert*. Raising funds through most forms of taxation adds distortions to the economy and has an economic cost (Ferede & Dahlby, 2016). As illustrated in the figure, the economic costs of raising public funds are considerable.[4] These costs are measured using an estimated marginal cost of public funds (MCPF) for revenue collected from Quebec's cap-and-trade system.

Benefits of addressing market failures are the social benefits of overcoming true market failures. The market barriers variable described above signals the effect that features of the PEV market can have on how consumers perceive PEVs' costs. For example, buyers might have *perceived* higher costs owing to a lack of information about new technologies, such as the range and reliability of batteries. If this problem is a true market failure, once the vehicle is purchased as a result of the subsidy policy, the buyer will realize he or she overestimated these costs. Furthermore, other potential buyers may have fewer misgivings about PEVs the more they see others buying them (Mau et al., 2008). This variable estimates the benefit that the subsidy offers with respect to its effect on reducing market failures—namely, its "signal-boosting" effect.

Net social cost is an estimate of the policy's net costs to society. It is estimated as the total of all previous cost elements. These social costs reflect the policy's *implicit carbon price*. The arrow seen in the figure only *estimates* the policy's true social cost: other, non-modelled costs and benefits might change the results shown above; for example, health benefits from reduced air pollution as a result of increased PEV use, or the benefits of knowledge spillovers in the PEV sector. Because of the small size of Quebec's PEV sector, these effects are expected to be small and uncertain, and so are not modelled here. If included, they would marginally lower the social costs that we estimate.

[4] Owing to associated uncertainty, these costs are difficult to estimate with precision. They should be seen as *indicative* of the expected cost of raising public funds.

2. Phasing out coal-fired electricity generation in Alberta

OVERVIEW

This section provides the methodological details of our case study assessing the Alberta government's planned 2030 phase-out of coal-fired electricity generation. For this case study, we developed a model of electricity supply costs and firm decision-making in Alberta. Below, we summarize the details of the reference and policy scenarios, describe the model's assumptions and framework, and outline its parameters and results.

SCENARIOS

To isolate the effects of Alberta's coal phase-out policy, a policy scenario is compared to a reference case scenario in the model.

Reference case scenario:

The reference case scenario includes Alberta's planned Carbon Competitiveness Regulation (CCR) policy. The design of the CCR is still being finalized, but in this case study, we assumed the CCR to be consistent with the design suggested by Alberta's Climate Leadership Team (2015): a carbon price of $30 per tonne, with Output-Based Allocations (OBAs) provided to regulated electricity generators on the basis of "good-as-best-gas" emissions performance.

The reference case also includes the 2012 federal regulations on coal-fired electricity, which stipulate that coal plants must close (or be retrofitted such that their emissions are consistent with good-as-best-gas generation) at their end-of-useful-life," as defined by the regulation (usually 50 years) (Environment Canada, 2012).

To permit an isolated analysis of the effect of Alberta's planned coal phase-out policy, this analysis does not include the impact of the recently announced federal phase-out of coal (Government of Canada, 2016a). In November 2016, the federal government proposed a federal coal phase-out policy that would shutter all Canadian coal-fired electricity plants by 2030, unless an affected province reached an equivalency agreement with the federal government. Because this 2030 phase-out timeline is roughly consistent with the Alberta policy modelled in the policy scenario, we have excluded it from the reference case scenario. The reference case scenario also does not include the effect of Alberta's proposed Renewable Energy Program policy.

Policy scenario:

The policy scenario is identical to the reference scenario, except that it includes Alberta's planned phase-out of emissions from coal-fired electricity generation by 2030, as called for in the provincial government's current Climate Change Leadership Plan.

KEY ASSUMPTIONS

1. **Alberta's Carbon Competitiveness Regulation (CCR) will take the form articulated by the Climate Leadership Panel in its Report to the Minister.** Alberta's carbon pricing policy for its large industrial emitters is still being finalized. As a result, we have assumed that it will function in the way suggested by the expert panel appointed by the government (Government of Alberta, 2016a).
2. **Alberta's carbon price remains at $50 after 2022.** The federal government has stated that national minimum carbon prices will rise in $10 increments, from $30 in 2020 to $50 in 2022. Because no price trajectory beyond this point has been provided, we have assumed that carbon prices will remain at $50 per tonne CO_2e.
3. **The payout to coal producers approximates the lost economic value of coal plants.** The coal plants affected by Alberta's coal phase-out had an economic value associated with their post-2030 operation that is reduced to zero by the policy. The $1.3-billion payout negotiated between the Alberta government and coal producers is taken to be a reasonable proxy for the economic value of the coal plants affected by the regulation.
4. **Output-Based Allocations remain in place through the model horizon.** The CCR suggested by the Climate Leadership Panel forgoes carbon tax revenues from the electricity sector for the portion of a facility's emissions from generation that is equivalent to good-as-best-gas. We have assumed that this policy remains in place over the long term.
5. **The costs of natural gas and coal rise in line with International Energy Agency projections.** Estimates of the future price of fossil fuels obviously come with a high degree of uncertainty. We relied on U.S. Energy Information Administration projections (2017) for fuel prices.
6. **The health impacts from both gas and renewables are negligible.** We assume that any health expenditures resulting from the operation of gas-fired and renewable electricity generation capacity are marginal, and do not quantify them in the model.

ANALYTICAL APPROACH

The model developed by the Ecofiscal Commission estimates expected GHG reductions and net social costs associated with Alberta's planned 2030 phase-out of coal-fired electricity. The model considers costs and benefits over a period from 2017 until 2061—the last possible year in which the province's last coal plant would have closed in the absence of new policy. **Table 2** summarizes these costs and benefits.

Table 2: Types of costs and benefits considered for phasing out coal-fired electricity generation in Alberta case study

Type		Description
Cost	Capital costs	The cost of constructing new electricity generation capacity to replace lost coal-fired generation.
	Operating and maintenance (O&M) costs	The cost of operating and maintaining coal plants and/or the plants that replace them. These include costs such as fuel, labour, scheduled maintenance, planned part replacement, and land or lease. Renewable generation sources also carry a grid integration cost (to deal with their intermittency, and other issues). These costs are taken against avoided costs (seen below) to estimate the net change to O&M costs attributable to the policy.
	Lost economic value of coal plants	The early shuttering of the coal plants that will be affected by Alberta's coal phase-out policy represents a cost in terms of their lost economic value.
	Cost of raising public funds	The province negotiated a payout of $1.3 billion (to be paid in annual instalments) to firms that own the coal plants affected by the regulation, as compensation for the lost economic value of the plants. The raising of tax revenue to fund these payments represents a cost to the economy in the form of the economic distortion and the lost production or welfare that results. The cost of raising public funds is calculated using a marginal cost of public funds that is specific to a given jurisdiction and tax instrument.
Benefit	Avoided O&M costs	Had the coal plants affected by the phase-out continued to operate, there would have been O&M costs associated with their continued operation. By shuttering the facilities, these costs are avoided. *Avoided* costs are captured in the model as benefits.
	Health benefits of phasing out coal	Coal-fired generation is associated with air pollution, and this air pollution comes at a cost to Albertans in the form of greater expenditure on health care. This variable captures the health benefits that will be enjoyed by Albertans due to the coal phase-out, and is measured in terms of the reduced health expenditures that result.

The model simulates electricity-producing firms' decision-making. Firms deliver a fixed amount of annual generation over the model's time horizon, corresponding to the historical average generation of the six coal plants affected by the regulation. They deliver this generation using either their existing coal-fired generation capacity, new gas-fired capacity, new renewable capacity, or a mix of these sources.[1] The decision-making of firms is modelled across four possibilities:

1. Firms continue to operate coal plants after 2030 at the historical average capacity factor[2]
2. Firms continue to operate coal plants after 2030 but reduce their capacity factor
3. Firms shutter the coal plants and build new gas-fired generation capacity to replace the lost generation
4. Firms shutter the coal plants and build a mix of gas and renewables, in line with the province's target of 30% of generation being renewable by 2030

[1] When coal plants reach their end-of-useful life, the model assumes that plants are decommissioned and enough new capacity is built in its place to replace the lost generation. Firms are assumed to build what they perceive to be the lowest-cost mode of generation, based on expected long-term changes in capital and operating costs.
[2] A plant's capacity factor is its total annual generation divided by its total annual *potential* generation.

Firms select the option they perceive to have the lowest cost. They weigh the short- and long-term costs of the four possibilities using a private discount rate, and select the option with the lowest net present value (NPV).

Using the model, we estimate the total net cost of the Alberta government's planned 2030 phase-out of coal-fired electricity generation as the sum of the following costs:

- When coal plants are shuttered early due to the phase-out policy, firms incur a cost in the form of the plants' lost economic value. Before the policy, these plants could have continued to operate until they reached their end-of-useful-life, as defined by the federal regulation. The plants, therefore, had an economic value associated with their post-2030 operation that is reduced to zero by the policy. This represents a net cost.
- The compensation of these firms in the form of the $1.3-billion payout negotiated by the Alberta government carries a social cost in the form of the cost of raising public funds. Raising this $1.3 billion through taxes creates a distortionary effect on the economy, which also contributes to the policy's total attributable costs. The relevant cost here is the economic cost of raising the $1.3 billion through taxation, rather than the $1.3 billion itself. The $1.3 billion is a transfer to the private sector and is therefore not considered a cost in the model; it enters the model as a cost in the form of plants' lost economic value, discussed above.
- When plants affected by the regulation go offline, new generation capacity must be built to replace the total lost generation. Firms construct new generation capacity that they perceive to represent the least-cost mode of generation. The construction of this capacity has additional capital costs.
- The new capacity will have operating and maintenance costs (O&M). If the O&M costs of the new generation capacity are less than that of what would have existed in the absence of the policy, then net O&M savings can result (if not, then there will be net O&M costs).
- Finally, the phase-out of coal-fired generation is expected to reduce health expenditures, creating a benefit (i.e., negative cost).

The model estimates costs and benefits for each modelled year (2017 to 2061). To communicate a single metric—the implicit carbon price— the model discounts costs and benefits (as well as projected future GHG reductions) to estimate an NPV in terms of net social costs per tonne of emissions reduced. We assume a social discount rate of 3%.

KEY PARAMETERS

Parameter	Modelled value	Source	Notes
Coal plants' end-of-useful-life under the reference case	Sheerness 1: 2036 Genessee 2: 2039 Sheerness 2: 2040 Genessee 1: 2044 Genessee 3: 2055 Keephills 3: 2061	Government of Alberta (2016b)	These are the years in which the six coal plants affected by the phase-out would have had to shut down under 2012 federal regulations.
Payout to coal producers	$1.26 billion	Morgan (2016)	The payout negotiated between the Alberta government and coal producers will be made in annual payments of $97 million from 2017 to 2030.

Parameter	Modelled value	Source	Notes
Marginal cost of public funds from Alberta's carbon tax	0.25	Modelling using EC-PRO model	Computable general equilibrium modelling of the Canadian economy using the EC-PRO model was used to estimate this figure (Boehringer et al., 2015)
Avoided health expenditure	$14,000 / GWh	Anderson et al. (2013)	This Pembina Institute study of the health benefits of Alberta's coal phase-out converts estimates from Environment Canada's regulatory impact analysis statement of its 2012 regulation on coal-fired electricity to be specific to the provincial context.
Social discount rate	3%	Treasury Board of Canada Secretariat (2007)	The Treasury Board of Canada Secretariat recommends using a 3% discount rate in the cost–benefit analysis of regulatory proposals.
Private discount rate	11%	Consultation with industry stakeholders	Discussions with industry stakeholders indicated that firms in the electricity sector can be expected to use a discount rate of 10%-12% in their investment decisions. The midpoint of 11% was used in the model.
Capacity factor for coal and natural gas	83%	Statistics Canada (2016b)	The capacity factor for coal is applied to natural gas plants as well, since these plants will be replacing coal's baseload and ramping function.
Capacity factor for wind	35%	AESO (2016)	The capacity factor for renewables are lower than that seen for coal or natural gas because of the intermittency of renewable resources.
Capacity factor for solar	15%	NREL (2016)	The 20% figure provided by NREL was adjusted to 15% to account for the greater relative abundance of solar resources in the U.S.
Capital costs: 2030	Natural gas: $1,321,567/MW Wind: $2,536,382/MW Solar: $3,513,900/MW	EIA (2016a); Schröder et al. (2013)	Estimates are for the cost of construction in year 2030, converted to 2017 Canadian dollars.
Capital costs: future	Natural gas: $1,321,567/MW Wind in 2055: $2,417,745/MW Solar in 2050: $3,195,806/MW	EIA (2016a); Schröder et al. (2013)	Current costs are taken from EIA figures (2016a); future cost decreases are taken from Schröder et al. (2013). Wind costs in 2055 are estimated using expected average cost decreases between 2030 and 2050 and extending them to 2055.
Cost of capital	7%	Consultation	A cost of capital of 7% for construction of electricity generation capacity was used to annualize expected capital costs over project lifetimes.
O&M costs for coal plants	Fixed: $4.54/MWh Variable: $4.94/MWh Fuel: $27.10/MWh	EIA (2016a, 2016b, 2016c, 2017a)	Fuel costs are for year 2017 and are projected to increase based on EIA projections at an average rate of 2% per year to 2050, at which point they are held constant (since no post-2050 estimates were available).
O&M costs for natural gas plants	Fixed: $1.70/MWh	EIA (2016a, 2017b, 2017c)	Fuel costs are for year 2017 and are projected to increase based on EIA projections at an average

Parameter	Modelled value	Source	Notes
	Variable: \$4.73/MWh Fuel: \$22.13/MWh		rate of 3.5% per year to 2050, at which point they are held constant (since no post-2050 estimates were available).
O&M costs for renewables	Wind: \$6.12/MWh Solar: \$3.55/MWh	EIA (2016a)	These include costs such as labour, scheduled maintenance, planned part replacement, and land or lease.
Renewable energy integration costs	\$15,000/GWh	Estimated	No official data or estimate of these costs was available; therefore, integration costs were inferred by evaluating the excess cost of renewables compared with capital costs as signalled by the value of Alberta's subsidy toward renewable procurement.
Emissions intensity of coal-fired generation	1.016 tonnes CO_2e/MWh	Government of Canada (2016b)	This emissions intensity is held constant over the model's time horizon—i.e., we assume no retrofit of coal plants.
Emissions intensity of gas-fired generation	0.339 tonnes CO_2e/MWh	Government of Canada (2012)	This figure estimates the emissions intensity of plants built in 2030 (rather than current plants) and assumes that the gas-fired capacity that replaces coal in 2030 uses combined-cycle generation. This figure takes the 2016 good-as-best-gas figure of 0.42 tonnes CO_2e/MWh and extrapolates out to 2030, with efficiency improving 1.5% per year.
Good-as-best-gas GHG intensity reference number (under Alberta's Carbon Competitiveness Regulation)	0.42 tonnes CO_2e/MWh of gas generation	Government of Canada (2012)	The reference number provided by Environment Canada applies in 2018, the year the CCR takes effect (the regulation then decreases it by 1.5% per year).
Life-cycle emissions of renewable capacity	Wind: 0.012 tonnes CO_2e/MWh Solar: 0.05 tonnes CO_2e/MWh	Nugent and Sovacool (2014)	These figures represent the small amount of emissions associated with the construction and operation of renewable capacity.

RESULTS

Emissions reductions

The model estimates GHG reductions by comparing the total level of emissions in the reference case and policy scenarios. The difference between the two scenarios is the level of emissions reductions that the model estimates to be attributable to Alberta's coal phase-out policy.

The model considers all GHG emissions associated with the generation of electricity, including emissions from the continued operation of coal-fired capacity, the operation of new natural gas capacity, as well as a small amount of emissions associated with the construction of the renewable capacity. The difference between scenarios in terms of the type of generation sources that are built and operated—and their resultant mixes in total generation—determines the total mitigation that the model estimates for the coal phase-out policy.

In the reference case scenario, modelling results indicate that firms' most likely response to the Carbon Competitiveness Regulation (CCR) would be to continue to operate coal plants beyond 2030, but at a much-reduced capacity factor.[3] This response is estimated to be—from their perspective—the least-cost alternative.[4] In terms of the generation that would be lost when coal was phased down, analysis indicates that firms could be expected to build new gas-fired capacity in its place (rather than a mix of gas and renewables), since they would perceive gas as the least-cost mode of generation.[5] However, the extent of this new capacity construction is uncertain (since the precise capacity factor that firms would choose for their coal plants is itself uncertain).

In the policy scenario, firms shutter their coal-fired capacity in 2030 as a result of Alberta's phase-out policy. Modelling analysis suggests that gas-fired capacity would be perceived as the least-cost mode of generation and would therefore be built in coal's place.

Both scenarios involve constructing gas-fired capacity to replace coal. The key difference between the two scenarios is how much new capacity would be built in the reference case when firms phase down their coal-fired generation in response to the CCR policy: the higher the capacity factor adopted in the reference case, the more the GHG mitigation will result from the phase-out policy. But because there is uncertainty in the capacity factor, there is also uncertainty associated in the model's estimate of GHG mitigation. We therefore estimated a range of possible emissions reductions from the policy based on an upper-bound capacity factor of 15% and a lower bound defined by no continued coal operation (i.e., a capacity factor of 0%).

The model sums annual emissions reductions over its time horizon to estimate total cumulative GHG mitigation. A post-2030 capacity factor of 15% would result in 49 Mt CO_2e of mitigation (cumulatively) between 2030 and 2061. Lower capacity factors imply lesser mitigation. If coal plants were expected to shutter in the reference case, there would be zero mitigation attributable to the coal phase-out policy. This suggests a range of **0 to 49 Mt CO_2e** of cumulative GHG mitigation attributable to the coal phase-out policy.

Costs

Differences in costs across the two scenarios stem from the different capital and operating costs that the alternative generation mixes present, as well as social parameters such as the cost of raising public funds and health benefits. We estimate the mitigation costs of the policy in terms of its implicit carbon price by discounting net annual costs and dividing by net annual (discounted) GHG mitigation.

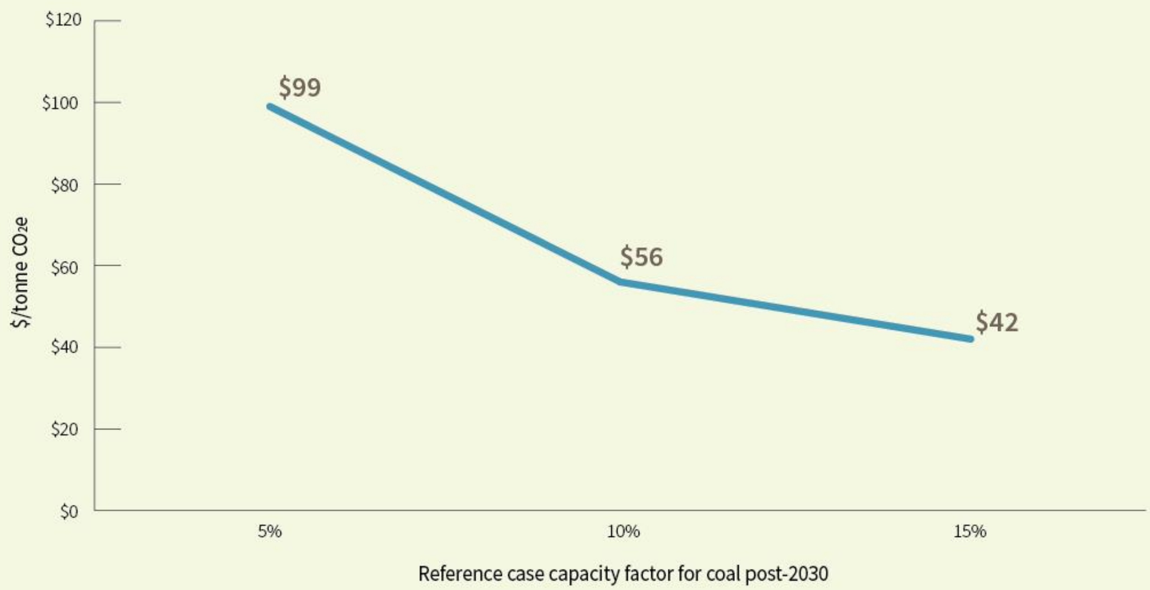
[3] The precise capacity factor they would choose is uncertain. Each possible level of output would imply different variable costs, and firms would operate at whatever capacity factor allowed them to both recover costs and maximize profits. If no economical capacity factor existed, electricity production from coal would no longer be economical, and all coal plants would close in the reference case.

[4] Private and social perspectives on the least-cost mode of generation may differ due to alternative discount rates and cost scoping. A social perspective would likely call for a lower discount rate and would consider coal-fired generation's impacts on public health. It would not consider the CCR's carbon price as a cost, since it would only be a transfer from a social perspective. It would, however, consider the cost of raising public funds associated with the tax. A full social accounting would also consider the social cost of carbon emissions.

[5] It is possible that some lost generation would be replaced by greater generation from existing gas plants (i.e., increases on the intensive margin). However, our case study is focused on long-term dynamics in the electricity sector and assumes that generation shortfalls are met with new capacity (i.e., increases on the extensive margin). We also do not model the possibility of retrofitting coal plants with carbon capture and storage or converting them to biomass or gas.

As discussed above, the capacity factor that firms would adopt for their coal plants in response to the CCR policy is uncertain. This creates uncertainty in the model's estimates of emissions reductions as well as costs. As seen in **Error! Reference source not found.**, different capacity factors correspond to different mitigation costs (and thereby different implicit carbon prices for the coal phase-out policy). These capacity factors correspond to different levels of generation and generation costs. Plants would have continued to operate at the highest operating capacity that allowed them to receive an average price for their total generated power that exceeded their costs and maximized their profits. With a 5% capacity factor, we estimate costs to be $149/kWh and annual generation at 1,103 MWh. At 10%, we estimate costs to be $112/kWh and 2,207 MWh; at 15%, $99/kWh and 3,310 MWh.[6]

Figure 4: Possible mitigation costs under Alberta's coal phase-out policy



This figure shows a sensitivity analysis around our estimates of the costs (per tonne of GHG emissions reduced) of Alberta's coal phase-out. It illustrates that the costs of the policy depend on the capacity at which coal-fired plants would have operated in a scenario that includes carbon pricing under the CCR, but excludes the coal phase-out. The more that carbon pricing would have led to coal plant closure anyway, the higher the estimated incremental costs per tonne of the coal phase-out.

The capacity factor that firms would adopt for their coal plants would depend on what the market for power was like in 2030, which—especially in light of the complexity and uncertainty that the province's planned shift to a capacity market for electricity introduces—is beyond the scope of our analysis. Costs are therefore estimated in a range, where a 15% capacity factor describes the upper bound and the lower bound is defined by coal plants shutting down altogether in the reference case (i.e., a 0% capacity factor). This leads to an estimated implicit carbon price of **between $42 and $99/tonne CO_2e.** If coal operation was not economical at any level of output, coal plants would shutter in the reference case. In this case, the cost of the payout to coal producers would not be associated with any GHG mitigation, and mitigation costs would be undefined (i.e., they would have a zero denominator).

[6] Per-megawatt costs are higher at low capacities, because plants' fixed costs are being spread over a smaller amount of total generation.

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