Nuclear for a Net-Zero Canada

Pathways to scale by 2050

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CLEAN PROSPERITY

About Clean Prosperity

Clean Prosperity is a Canadian climate policy organization. We advocate for practical climate solutions that reduce emissions and grow the economy.

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Abbreviations

BWR	Boiling water reactor
CANDU	Canada Deuterium Uranium
CER	Clean Electricity Regulation
CfD	Contract for difference
CNSC	Canadian Nuclear Safety Commission
EITE	Emissions-intensive and trade-exposed
EPS	Emissions Performance Standards (Program)
IAA	Impact Assessment Act
IAAC	Impact Assessment Agency of Canada
IESO	Independent Electricity System Operator
IRA	Inflation Reduction Act
ITC	Investment tax credit
LCOE	Levelized cost of electricity
NWMO	Nuclear Waste Management Organization
OBPS	Output-based pricing system
PPA	Power purchase agreement
PTC	Production tax credit
SMR	Small modular reactor
TIER	Technology Innovation and Emissions Reduction (Regulation)
WACC	Weighted average cost of capital

W	Watt	1 W = 1 joule per second
kW	Kilowatt	(1,000 watts)
MW	Megawatt	(1,000,000 watts)
GW	Gigawatt	(1,000,000,000 watts)
TW	Terawatt	(1,000,000,000,000 watts)

Wh	Watt-hour	1 Wh = 3600 joules
kWh	Kilowatt-hour	(1,000 watt-hours)
MWh	Megawatt-hour	(1,000,000 watt-hours)
GWh	Gigawatt-hour	(1,000,000,000 watt-hours)
TWh	Terawatt-hour	(1,000,000,000,000 watt-hours)

Executive summary

Policymakers are eager to expand Canada's fleet of commercial nuclear reactors. Nuclear power has valuable attributes for provinces seeking to electrify their economies and decarbonize their grids: nuclear reactors are long-lived, large-scale, high-capacity assets that produce zero-carbon electricity with low land-use requirements and manageable risks related to safety, waste, and security.

Nuclear energy can be a significant contributor in achieving Canada's net-zero goals. Two distinct problems are undermining nuclear's potential in Canada.

First, commercial reactors have challenging economics. High upfront capital requirements, a global track record of cost overruns, and weak demand signals in electricity markets are pushing system planners and large industrial customers to alternative generating sources. Advanced and smaller reactor designs offer significant promise for cost reductions but lack a track record. We call this mix of project and financial challenges **the cost problem**.

Second, electrification is not inevitable. Canada's provincial and federal policy architecture is currently too unstable to drive levels of electrification needed to justify significant nuclear buildout. Constructing new reactors to help meet Canada's future electricity needs would be a multi-decade undertaking. Policymakers need a multi-decade vision to match. We call this **the certainty problem**.

These are problems worth solving. Ontario's on-budget and ahead-of-schedule refurbishments at its Darlington and Bruce nuclear generating stations offer promise that the cost problem can be solved in the Canadian context. Solving for both cost and certainty is vital for the expansion of Canada's nuclear fleet across three potential reactor classes: large, small, and micro. To fully leverage Ontario's recent successes and expand opportunities for reactors of all sizes, policymakers must take immediate action on the certainty problem, then attack the cost problem from multiple angles.

We propose three solutions to the cost and certainty problems in the Canadian context: 1) an ambitious and stable policy environment; 2) policy-based financial supports; and 3) pushing the cost curve for nuclear technologies downward.

To provincial and federal policymakers, we make three recommendations:

1. **Commit to an ambitious and stable package of electrification and decarbonization policies that define stringency beyond 2035.**

Ambitious nuclear policy doesn't make sense without ambitious climate policy. Our modelling suggests that rolling back or weakening existing electricity and decarbonization policies would significantly weaken the case for new reactors. Therefore, to aid the buildout of a fully-scaled fleet of dozens or hundreds of reactors, nuclear and nuclear-ambitious provinces should clarify their long-term electrification and decarbonization policy objectives — ideally beyond 2035.

We point in particular to the design of Canada's provincial industrial carbon markets, which put procurement of nuclear generation at a disadvantage. To correct this, provinces should set target dates for achieving a net-zero grid, set clear timelines for adjusting electricity performance benchmarks in their carbon markets to zero, and fully expose electricity generation to the carbon price.

2. **Gradually shift to financial supports that reward results rather than effort.**

Our analysis finds that Canada's investment tax credits (ITCs) and bespoke support for nuclear power across Canada are a rightsized competitive response to the US Inflation Reduction Act. Over the longer run, however, Canada should shift away from ITCs for nuclear. ITCs can be claimed before a facility is operating; they reward effort, not results. Shifting from effort-based models of support to results-based approaches can accelerate buildout. We discuss the tradeoffs across three results-based financial instruments that could replace ITCs: power purchase agreements, production tax credits, and contracts for difference.

3. **Prioritize fleet-based approaches to deploying commercial reactors.**

Advanced reactors need to become progressively less expensive to build over time. To accelerate this process, policymakers should prioritize approaches that seek to build as few reactor models on as few sites as possible, in large quantities. Canada may ultimately need a small portfolio of reactor models — large, small, and micro — to ensure that nuclear fills as many cost-effective use-case niches as possible.

Over the past year, Clean Prosperity has engaged and collected input from dozens of stakeholders and policymakers on the future of nuclear energy in Canada. We bring those perspectives to bear in this policy report. Assumptions underlying our analysis are in the appendices and footnotes.

Introduction: the cost and certainty problems

Expansion of Canada's nuclear fleet is drawing growing interest from a broad set of public and private stakeholders. Ontario has committed to a large-scale refurbishment of reactors at the Bruce and Darlington nuclear generating stations, with plans to construct new reactors at both sites. Bruce is proposing multiple large reactors, but has not made a final decision on its reactor design. At Darlington, the GE Hitachi BWRX-300 is on track to be a first-of-kind *advanced* reactor (see Box 1 below for terminology).

For significant expansion beyond these proposed additions to Ontario's grid, commercial reactors will need to deliver electricity at prices that are stable for households, and ideally decline over time in real terms. This condition must be satisfied both at the project level and at the consumer level. At the project level, capital expenditures ($ per MW of installed capacity) and operating expenditures ($ per MWh of electricity produced) should decline over time as successive reactors of the same model are constructed.

Household affordability must be central to electrification efforts, and that starts with effective management of capex and consistent execution across projects. In Ontario, home to 18 of Canada's 19 commercial reactors, nuclear power currently costs 10¢ per kilowatt-hour (kWh), as defined by the Ontario Energy Board's Regulated Price Plan.[1] Over the long run, this price point will need to hold steady on an inflation-adjusted basis as Canada's fleet expands. Stable retail prices will be all the more important as advanced reactors come online.[2]

This principle holds in retail electricity markets; although certain use cases and contexts may sometimes justify higher costs (e.g., provision of vital ancillary grid services, military applications, energy security considerations, large customers requiring power 24/7).

[1] All currency amounts in this paper are in 2024 Canadian dollars, except where otherwise noted.
[2] Inclusive of construction, financing, operations, and full lifecycle management. The median cost projection in Canada's SMR Roadmap for a first-of-kind 300 MW reactor is 16¢ per kWh; high-end estimates exceed 25¢ per kWh.

Box 1: Notes on terminology

This paper uses “advanced reactors” as an umbrella term to cover what other publications call small modular reactors (SMRs), as well as micro-reactors (under 20 MW). In popular use, “SMR” covers an array of reactor types ranging from 20 MW to 470 MW. The term can obscure more than clarify, as reactors of different sizes possess distinct project economics that bely direct comparison. This paper uses a 300 MW “small” reactor as its unit of analysis.

Reactors are differentiated into Generations (Gens) based on era, plant, and reactor design. Advanced reactors follow Gen I, II, and III, which were commercially deployed starting in the 1950s, 70s, and 90s, respectively. The first advanced reactors will be Gen III+. They improve on conventional light-water technology used in Gen II and III reactors, shrinking and simplifying the design and adding passive safety features that avoid the need for external power sources or human intervention in the event of malfunction. Gen IV reactors, very few of which are operating commercially, use novel and experimental fuels, moderators, and coolants. Their time horizon for widespread deployment is likely after 2040. Many Gen IV reactors promise additional applications, such as fuel recycling, and the production of zero-carbon industrial heat and hydrogen. For non-energy applications, some Gen IV reactors could also help Canada expand its production of medical isotopes.

Among the dozens of advanced reactors in development, none has yet shown that a fully modular construction process can work. At scale, modularity will require efficient, mature, and robust supply chains; economies of scale; and large, highly-skilled construction and operational workforces. No country is close to this stage in its development of advanced reactors, with many cost-related uncertainties surrounding all of these potential advanced reactors. Ultimately, reducing uncertainty requires successfully executing on first-of-kind projects.

The cost problem is different everywhere

Building commercial nuclear reactors is a complex[3] and historically expensive[4] undertaking. The cost problem covers project and financial risks inherent to reactor construction that are consequential for the final cost of electricity, for example:

- High upfront capital requirements and construction costs
- Inaccurate initial cost estimates
- Longer project timelines relative to other generating sources
- The snowball effect of project delays, where one delay leads to multiple delays
- Poor project management and/or inexperienced workforces
- Market distortions and weak price signals (e.g., low carbon prices for heavy industry)

Risks vary across projects. Particular policy and regulatory contexts make some jurisdictions more vulnerable to specific risks. Other risks are universal and cross-cutting, most notably high upfront capital requirements and the tendency for delays to snowball and cascade. These two risks in particular have left the nuclear sector prone to serious budget overruns[5] — notoriously so in Western democracies.[6] Cost overruns occur with megaprojects of all kinds, but nuclear projects overshoot their budgets with greater severity and frequency than any other type of megaproject. Confidence in the sector has eroded, which has in turn aged the global reactor fleet — 415 reactors as of this writing. At its peak in 1996, nuclear power met 17% of global electricity demand; in 2022, just 9%.

There are ways to address the cost problem

Not all countries are equally burdened by the cost problem. In fact, every nuclear and nuclear-aspiring nation faces its own distinct version of the problem. Some are able to build more cheaply than others. China, for example, builds large reactors with consistently low construction costs. Fuelled by strong market expectations for growing electricity demand, China will be responsible for 40% of the 58 new reactors (60 GW) expected to be

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[3] Shobeiri, E., Genco, F., Hoornweg, D., & Tokuhiro, A. 2023. Small modular reactor deployment and obstacles to be overcome. Energies, 16(8), 3468.
[4] Lovering, J.R., Yip, A. & Nordhaus, T. 2016. Historical construction costs of global nuclear power reactors. Energy policy, 91, 371-382.
[5] Flyvbjerg, B., & Gardner, D. 2023. How Big Things Get Done: The Surprising Factors that Determine the Fate of Every Project, from Home Renovations to Space Exploration and Everything in Between.
[6] Grubler, A. 2010. The costs of the French nuclear scale-up: A case of negative learning by doing. Energy Policy, 38(9), 5174-5188.

commissioned worldwide between 2024 and 2030. Several other nuclear nations have also demonstrated some ability to handle their distinct cost problems. Russia, India, South Korea, and Japan have had average construction costs of $3.4 million to $4.6 million per MW since 2000. In contrast, France and the US built reactors for $12.5 million and $17.5 million per MW, respectively, over the same timeframe.

Many nations are embracing the promise of advanced and smaller reactor designs (see Box 1 above). Smaller reactors promise to address multiple components of the cost problem, most importantly by lowering upfront capital costs and reducing project complexity through modularization.

Ontario's reactor refurbishments are a promising sign that it is developing the cost estimation ability, project management capacity, and workforce experience needed to successfully deploy new commercial reactors.

But Ontario's success is not guaranteed. Refurbishing large *conventional* reactors and constructing *advanced* reactors are different undertakings.[7] Here it is important to differentiate between operating experience and construction experience. The generation of workers that built Canada's existing fleets are no longer in the workforce. The refurbishments at the Bruce and Darlington stations have revived and rebuilt supply chains that will be essential for the buildout of Ontario and New Brunswick's next wave of reactors.

The certainty problem requires swift resolution

Uncertainty about future Canadian climate policy undermines the investment case for nuclear energy. This policy risk consists of two key components. First is "stroke of pen" risk, the possibility that currently implemented climate policies could be weakened or repealed. We point specifically to industrial carbon pricing. Uncertainty in Canada's provincial markets is delaying low-carbon investments in electrification for both heavy industry and households. At the same time, there are duplicative and overlapping provincial and federal policies, many with highly uncertain implementation timelines, which are making it more difficult for project proponents, utilities, system operators, and industry to properly assess their future electricity needs.

We point to three sources of uncertainty that are relevant for new commercial reactors.

[7] Steigerwald, B., Weibezahn, J., Slowik, M., & Von Hirschhausen, C. 2023. Uncertainties in estimating production costs of future nuclear technologies: A model-based analysis of small modular reactors. Energy, 281, 128204.

First is uncertainty about the future price of carbon in provincial industrial carbon markets — particularly in the four provinces that have signed the Strategic Plan for the Deployment of SMRs. The markets in question include Ontario's Emissions Performance Standards (EPS) program, Alberta's Technology Innovation and Emissions Reduction (TIER) regulation, and New Brunswick and Saskatchewan's output-based pricing systems (OBPS). The price path of carbon is ill-defined through 2030 and not defined at all past 2030. Carbon credits can be a significant source of revenue for utility-scale electricity projects and a robust industrial carbon price is an important demand signal for low-carbon electricity.

Further, the provinces have not set up their carbon markets in a way that internalizes the full value of zero-carbon electricity. Emitting sources of electricity have an unfair advantage over nuclear because they only pay a fraction of the headline carbon price. Unlike other industrial sectors, where carbon-price exposure is calibrated to protect international competitiveness, electricity generation can and should be exposed to the full carbon price. Fixing this would level the playing field for nuclear reactors and properly value their attributes as high-capacity, zero-carbon generating assets.

A second source of policy uncertainty is that design details and implementation timelines for the federal Clean Electricity Regulation (CER) remain unfinalized. This uncertainty, combined with overlap between the CER and industrial carbon markets, could impose new costs on project proponents that would weaken the case for new reactors.

Third, the 2019 Impact Assessment Act (IAA) was intended to speed up federal assessment processes for major infrastructure and resource projects, but may be having the opposite effect five years on. Legislative changes that respond to the Supreme Court's reference case on the IAA were introduced in the 2024 federal budget, which reiterated the government's "one project, one review" philosophy and intent to increase the flexibility in substitution of assessments as a way to avoid duplication. The implications of shared jurisdiction between the Impact Assessment Agency of Canada (IAAC) and the Canadian Nuclear Safety Commission (CNSC) with respect to new nuclear projects — and whether this arrangement will persist — remains a significant source of uncertainty.

Constructing a fleet of advanced commercial reactors — large-, small-, or micro-scale — is a multi-decade undertaking. For any particular reactor design to succeed, provincial and federal nuclear ambitions must sit within a stable climate policy architecture that provides long-term certainty for investors and households alike, with clear and predictable market signals, regulatory signals, and project approval processes. In practice, this means clearly defining policy packages to accelerate electrification and decarbonization efforts — ideally beyond 2035.

Success starts in Ontario — 2024 and 2025 are pivotal years

We embed our analysis in the following context:

Ontario is refurbishing two of its three commercial nuclear generating stations, and is considering refurbishments on the third. Six of eight reactors at Bruce and all four reactors at Darlington will be refurbished, with four of six reactors at Pickering under consideration for refurbishment.[8]

Ontario is also proposing up to 6,000 MW of new nuclear generating capacity by 2035, four 300 MW advanced reactors at Darlington and 4,800 MW worth of large reactors at Bruce. A final construction decision on Darlington's first 300 MW advanced reactor, GE Hitachi's BWRX-300, is expected in 2024. New Brunswick is exploring multiple advanced reactor designs at its Point Lepreau Station, targeting 600 MW of new capacity by 2035.

Quebec is considering new reactors at its Gentilly Station after briefly exploring recommissioning its lone commercial reactor, dormant since 2012. Non-nuclear provinces Alberta and Saskatchewan are conducting early-stage siting and engineering for their first commercial reactors (see Figure 2 below). Saskatchewan plans for a final construction decision on its own BWRX-300 reactor in 2029 but has not completed the siting process. In November 2023, the Saskatchewan Research Council awarded an $80 million grant to Westinghouse Electric to develop a demonstration project for its 5 MW micro-reactor known as eVinci.

Canada's nuclear sector is concentrated in Ontario (see Figure 1 below), which is setting the pace for advanced reactor development in Canada (see Table 1 below). The nuclear supply chain includes over 200 companies and 65,000 employees across the province, but there are a relatively small number of key players working closely with Crown corporation Ontario Power Generation (OPG) — a de facto private-public partnership. Darlington's first BWRX-300 is primarily a collaboration between four organizations:

- OPG is the CNSC license holder and maintains overall responsibility for the project, including operator training, commissioning, Indigenous engagement, stakeholder outreach, and oversight.
- Aecon is providing all construction services, including project management, construction planning, and execution.

[8] Canada's entire nuclear fleet consists of heavy-water Canada Deuterium Uranium (CANDU) reactors. Using heavy water to cool and moderate the nuclear reaction enables the use of unenriched uranium in the fuel bundles. There are 47 CANDU and CANDU-derived reactors operating globally. The advanced reactor proposed at Darlington — GE Hitachi's BWRX-300 — will use light water and enriched uranium.

- GE Hitachi is the technology developer responsible for the reactor design, and for procurement of major components, engineering, and support.
- AtkinsRéalis (the new trading name of SNC-Lavalin) is the architect and engineer providing design, engineering, and procurement support.

Beyond Ontario, OPG is actively facilitating new commercial activity in the nuclear sector — signing a three-year contract with New Brunswick's NB Power, co-sponsoring a feasibility study with Capital Power in Alberta, and collaborating with SaskPower. Outside of Canada, OPG has signed memoranda of understanding with Czechia, Poland, and Estonia to accelerate their deployment of advanced reactors. Ontario's success will set the stage for other provinces and countries.

Successfully executing the next wave of commercial reactors at Bruce, Darlington, and Point Lepreau could contribute to global decarbonization efforts by offering a model for small, advanced reactors — a template and a technology for nuclear and nuclear-aspiring nations to apply and scale. The first and best chance is at the Darlington station.

Table 1: State of provincial action on new commercial reactors

	AB	SK	ON	QC	NB
Interest from policymakers	Mostly/entirely in place	Mostly/entirely in place	Mostly/entirely in place	Mostly/entirely in place	Mostly/entirely in place
Access to federal ITCs	Partially in place	Partially in place	Partially in place	Partially in place	Partially in place
Workable regulatory frameworks	Not in place	Not in place	Mostly/entirely in place	Partially in place	Mostly/entirely in place
Final siting decisions	Not in place	Not in place	Mostly/entirely in place	Mostly/entirely in place	Mostly/entirely in place
Fuel and component supply chains	Not in place	Not in place	Mostly/entirely in place	Partially in place	Mostly/entirely in place
Long-term waste management plan	Not in place	Not in place	Mostly/entirely in place	Partially in place	Mostly/entirely in place
Workforce with construction experience	Not in place	Not in place	Mostly/entirely in place	Not in place	Partially in place
Workforce with operations experience	Not in place	Not in place	Mostly/entirely in place	Partially in place	Mostly/entirely in place
Order book for new reactors	Not in place	Not in place	Partially in place	Not in place	Partially in place

Mostly/entirely in place | Partially in place | Not in place

Figure 1: The state of nuclear infrastructure in Eastern Canada

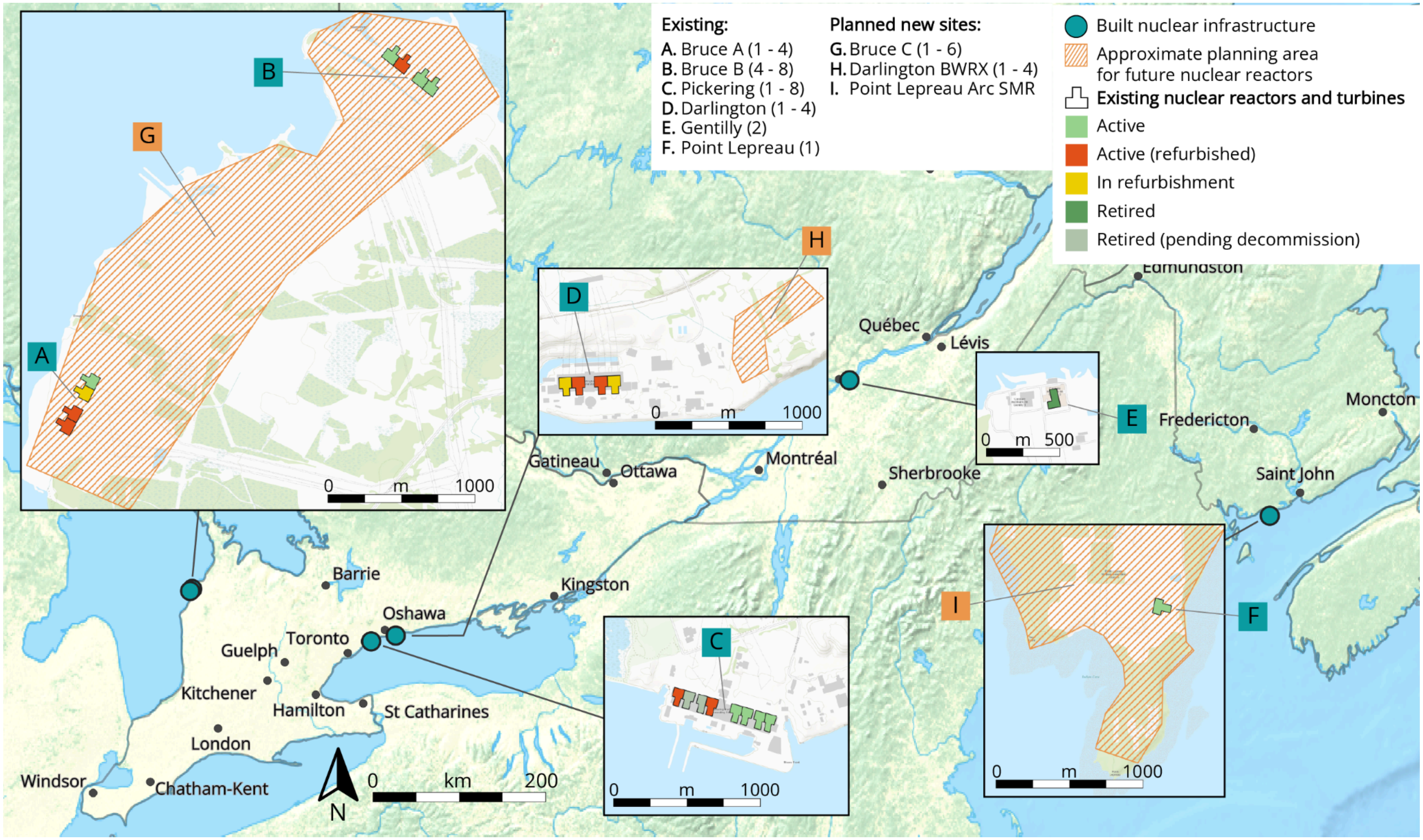
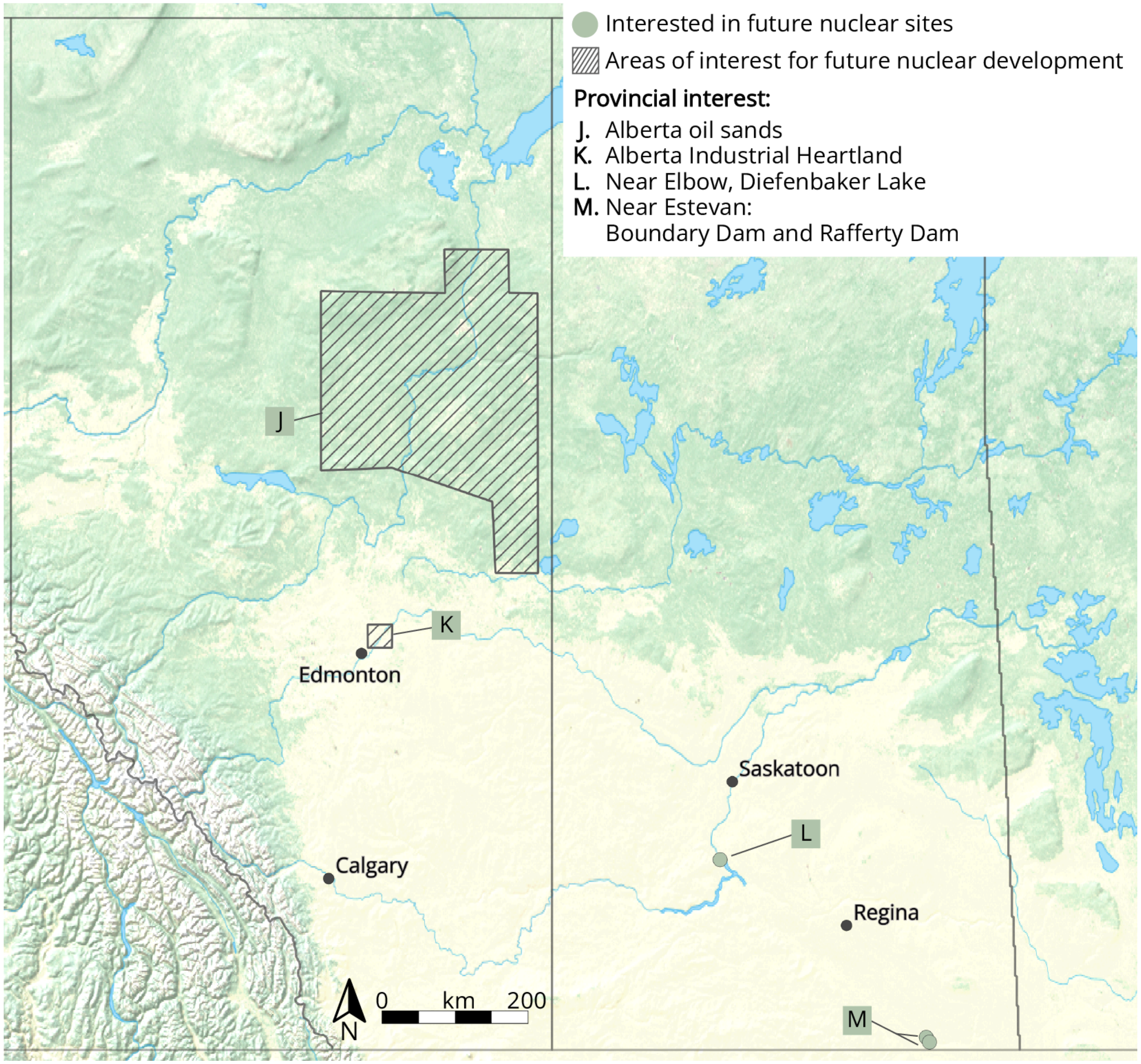


Figure 2: The state of nuclear infrastructure in Western Canada



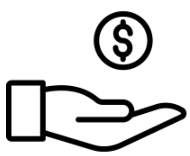
Three solutions to address cost and certainty

Realizing nuclear's potential requires a mix of stable policy and exceptional project execution.[9] We propose three solutions that will be vital to Canada's efforts and discuss them in detail in the next section. These solutions are mutually reinforcing; each expands the number of pathways to a fully-scaled fleet of commercial nuclear reactors.

Ambitious and stable policy

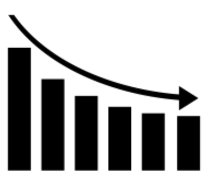
Ambitious climate and energy policies are necessary to create stronger demand forecasts for electricity, at a level that will support the business case for new nuclear reactors. Our modeling shows that ambitious policy could increase electricity demand by 60% compared to a scenario where climate policies are weakened or repealed.

Policy-based financial supports



Policy-based financial supports mitigate project risks and the high upfront capital costs for reactors of all sizes. We evaluate the effectiveness of different forms of policy-based financial supports for a "four-pack" of 300 MW commercial reactors, with particular attention to investment tax credits (ITCs), production tax credits (PTCs), and concessional financing (e.g., green bonds).

Pushing cost curves downward



To succeed in the long run, an advanced reactor design must descend a cost curve, where each successive build is less expensive than its predecessor. We analyze the drivers behind cost curves and use calculations to illustrate the effects of falling construction costs for a four-pack of 300 MW reactors, from first-of-kind to fourth-of-kind.

No solution is adequate on its own. All must play a role in efforts to scale deployment of advanced reactors. An ambitious and stable climate policy architecture is the foundation.

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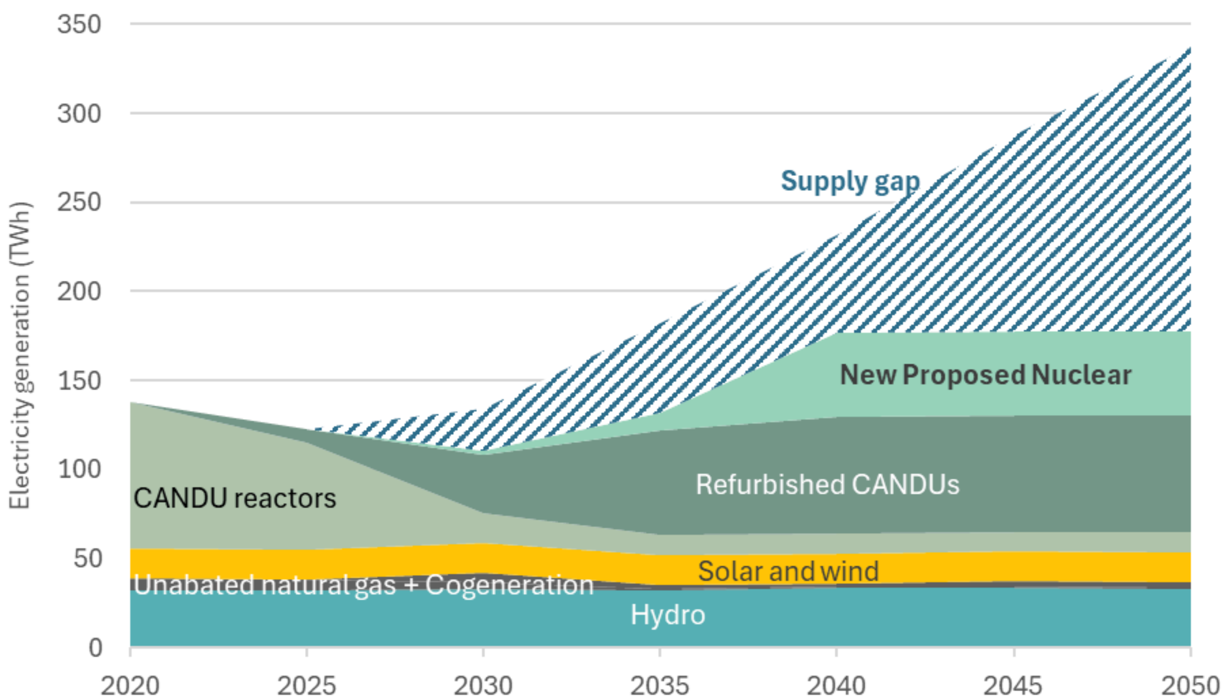
[9] There are of course legitimate issues with nuclear energy beyond cost and policy uncertainty. We believe these are manageable and secondary to the urgent imperative of decarbonization. We discuss these other challenges in the final section of this report.

Solution #1: Ambitious and stable policy

Electrification has become a key focus of decarbonization efforts across the Canadian economy.[10] Modeling we conducted with Navius Research for Clean Prosperity's Net-Zero Pathways Project suggests that 60% more electricity generation will be needed if Canada is to reach net zero by 2050 (337 TWh; see Figure 3 below) relative to an environment where climate policy is weakened (210 TWh; see Figure 4 below). In other words, climate policy needs to be ambitious and stable to create the right conditions for high levels of electrification.

Figure 3: Ontario's electricity supply with stable net-zero climate policy[11]



Ambitious and stable climate and energy policies make it safer to proceed with capital-intensive low-carbon projects, including commercial reactors. To illustrate the

[10] Preliminary results from Clean Prosperity's Net-Zero Pathways Project show electricity generation increasing by 43% to 74% between 2020 and 2050. Other net-zero modelling projects, including the Canada Energy Regulator's net-zero scenarios, show demand doubling by 2050.

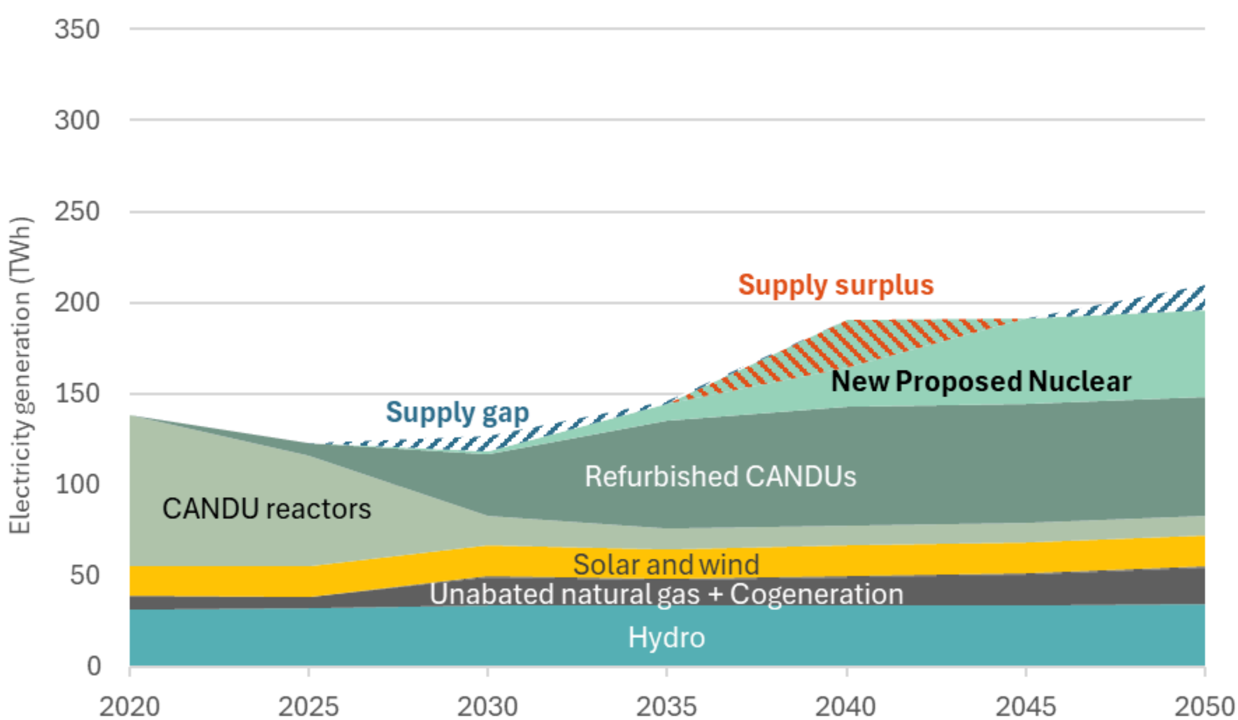
[11] Generation levels in Figure 3 are based on a net-zero policy scenario from modelling by Navius Research. This paper uses "ambitious and stable policy" as a proxy for net-zero policies. The final calculations reflect assumptions made by Clean Prosperity (methodology available by request to the authors). The supply gap in Figure 3 is illustrative; Navius' modelling analysis prevents supply gaps or surpluses from emerging, instead fully meeting electricity demand through generation and trade.

potential scale of this change, the 2050 supply gap in Figure 3 (above) would accommodate approximately 67 BWRX-300 reactors.[12] Conversely, policy gaps muddy the long-term signals for the nuclear sector, which must already contend with longer time horizons for both project execution and operating lifespan.

Electrification is not inevitable — it requires ambitious policy

Because most net-zero electricity modelling selects for the cheapest generation sources available when procuring new generating capacity, new commercial reactors do not tend to show up in these forecasts. In Figure 4 (below), we add the planned expansions at Darlington and Bruce to a Navius Research scenario that models the impact of weakened climate policies.[13]

Figure 4: Electricity generation in Ontario under weak[14] climate policies



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[12] For reference, the Canada Energy Regulator's net-zero scenarios project 154 TWh of electricity from SMRs across Canada by 2050, equivalent to 66 BWRX-300s operating at a capacity factor of 90%. We describe this quantum of reactors elsewhere in the paper as a *fully-scaled fleet.*

[13] Or alternatively, any scenario where private firms do not behave with confidence that climate policies will both stay in place and become more stringent over time.

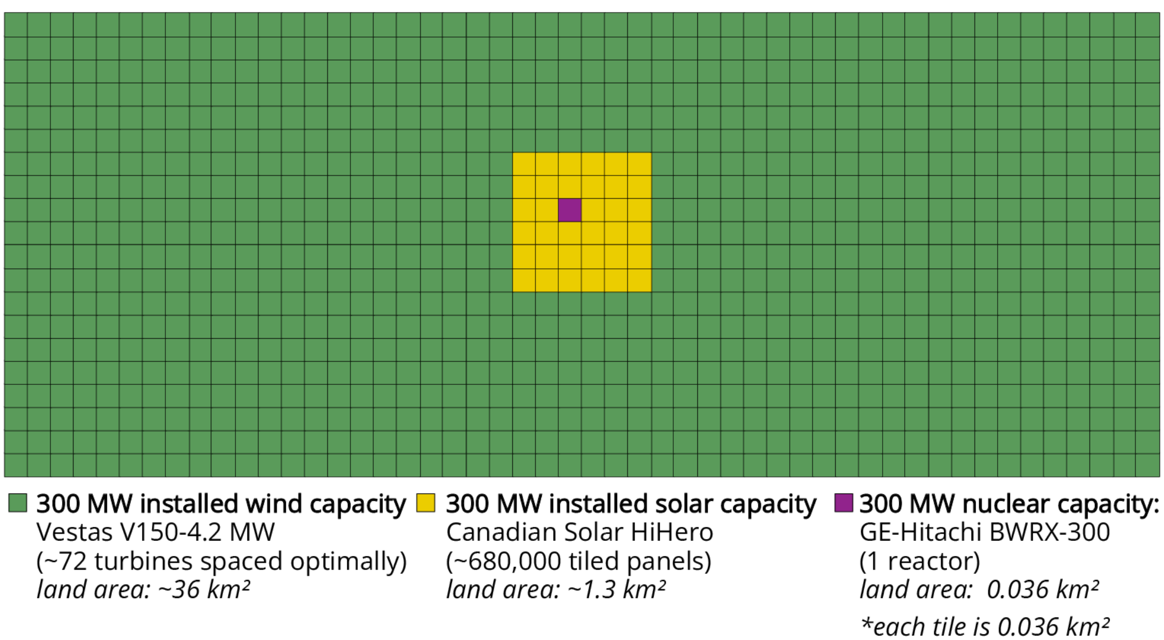
[14] Generation levels in Figure 4 are based on a Policy Rollback scenario from modelling by Navius Research. "Weak policy" in this paper describes the Rollback scenario. Final calculations reflect assumptions made by Clean Prosperity (methodology available by request to the authors).

Adding just 6,000 MW at these two sites produces an oversupply of electricity between 2035 and 2045. In other words, low-electrification scenarios dampen the economic imperative to add additional reactors to Ontario's grid — or any other province's grid.

Ambitious policy can alleviate other decarbonization bottlenecks

If situated within a stable provincial-federal framework, ambitious nuclear policy can address other bottlenecks that are slowing electrification. For instance, larger numbers of reactors (ideally on as few sites as possible) can reduce the level of buildout needed on provincial grids. In net-zero pathways with high levels of electrification and high levels of renewable energy, buildout requirements are significant. For instance, Princeton's Net-Zero America Project projects that US transmission capacity would need to increase by 400% between 2020 and 2050 in its high-renewable, high-electrification scenario. It is not a certainty that provincial regulators and utilities can achieve the buildout needed to reach net-zero by 2050 based on a grid with high levels of weather-dependent renewables.

Figure 5: Relative scales of siting zero-carbon electricity sources[15]



[15] Note: this figure only shows the land footprint of the generating site. Nuclear is also the most land-dense energy source on a lifecycle basis. For more information see: Ritchie, Hannah. 2022. How does the land use of different electricity sources compare? Our World in Data.

Building new transmission infrastructure is increasingly expensive, which increases the need to optimize and augment existing assets (i.e., operational generating sites and transmission infrastructure), with brownfield expansion as a second-best option and greenfield development as a third-best option. We point to South Korea, which has internalized and applied this principle to help solve its cost problem. South Korea has 26 reactors operating across just four nuclear stations, which allows operators to better optimize for fixed operating costs, such as refueling, monitoring, and security.

Solution #2: Policy-based financial supports

Canada has leveled the playing field for the next wave of commercial reactors

Canada is developing a series of ITCs and other tax measures to respond to the competitiveness pressures created by the US Inflation Reduction Act (IRA). Several new federal supports will be available to new commercial nuclear projects:

- A 15% technology-neutral clean electricity ITC for non-taxable entities, such as Crown corporations and Indigenous communities
- A 30% clean technology manufacturing ITC that covers fuel reprocessing and heavy water recycling activities (but not the original production of uranium or heavy water)
- A 30% clean technology ITC that covers zero-emissions electricity generating technologies, including SMRs
- Tax reductions for zero-emission technology manufacturers, including nuclear energy equipment manufacturing, fuel processing and recycling, and heavy water

Clean Prosperity's internal modelling finds that these federal supports, which are broadly accessible across the nuclear supply chain, are highly competitive with the incentives in the US IRA.

The US IRA offers new commercial reactors a choice between a production tax credit (PTC) valued at US$0.015 per kWh[16] and a 30% ITC. The ITC comes with two 10% bonus credits, first if the project meets domestic content requirements for steel, iron, and manufactured products; second if the project is sited in an "energy community".[17] All in, these bonus

[16] This PTC value assumes that prevailing wage and apprenticeship requirements are fulfilled.
[17] The IRA defines "energy communities" as either brownfield sites; communities that previously had a high dependence on fossil fuel extraction for employment or local tax revenues, but that now face high unemployment; or places where coal mines or coal-fired power plants have closed down in recent years.

credits available in the IRA allow proponents to earn tax credits worth up to 50% of eligible capital costs. The US is also offering existing conventional nuclear sites a PTC to encourage aging plants to stay online through the 2020s.

Canada is offering ITCs only. When the federal ITCs become law, they will unlock significant financial benefits for Canada's coming wave of nuclear reactors. At our proposed optimistic price of $10 million per megawatt,[18] a 30% ITC would be worth $900 million for a single BWRX-300 reactor:

$10 million/MW X 300 MW = $3 billion per reactor
30% of $3 billion = $900 million

Different portions of Ontario's proposed nuclear projects will be eligible for different federal ITCs. The ITCs are not stackable, so proponents will seek to maximize the 30% clean technology ITC over the 15% clean electricity ITC wherever possible. Ultimately, projects will be able to claim a total investment tax credit somewhere within this range.

An ITC-only approach comes with tradeoffs. Longer project timelines relative to other electricity projects mean that the cash-flow value of ITCs are more attractive. Canada's ITCs have an advantage over the IRA's PTCs in that they will allow proponents to write off eligible capital expenditures in the year the equipment is acquired. In the event of cost overruns, the public would share the fiscal downside. PTCs on the other hand cannot be claimed until a facility is completed and producing electricity.

We evaluate the effect of ITCs, PTCs, and concessional financing on the internal rate of return (IRR) for a project that involves four 300 MW reactors constructed in two-year increments, starting in 2029 (see Figure 6 below). This illustrative modelling exercise shows the relative impact of each form of policy support. We find that measures that directly reduce upfront capital requirements or the overall cost of capital, such as ITCs and

[18] We primarily use $/MW as our unit of analysis, rather than the levelized cost of electricity (LCOE). If Canada's nuclear sector is to make an outsized impact on global decarbonization efforts, the final construction cost of the first BWRX-300 (e.g., the $/MW sticker price) will be more influential than the LCOE. A low final cost would send a strong market signal to nuclear and nuclear-ambitious nations. Our optimistic assumption uses the capital cost estimate of $10.16 million per MW from our Net-Zero Pathways for Canada project, rounded for simplicity. LCOE calculations for advanced reactors require assumptions that cannot be known *ex ante* and require years of real-world data to evaluate. LCOE is therefore less informative for this analysis and does not offer a clean comparison between commercial reactors and other generating sources. Lifespan and discount rate are two prominent examples. Many LCOE forecasts (e.g., Lazard's 2023 Levelized Cost Of Energy+) assume lifespans of 40 years for new reactors. Estimates for the BWRX-300's lifespan are as high as 60 years. Using steep discount rates in LCOE calculations mutes the effect of that additional 20 years of zero-carbon generation. The question of how to value 20 years of additional zero-carbon electricity generation between 2070 and 2090 cannot be answered with LCOE.

concessional financing, have a greater influence on the project economics *ex ante* than PTC-style instruments.

Figure 6: Effect of various policy-based supports on cash flows for hypothetical Canadian 4x300 MW advanced reactor project ($3 billion to $6 billion per reactor)[19]

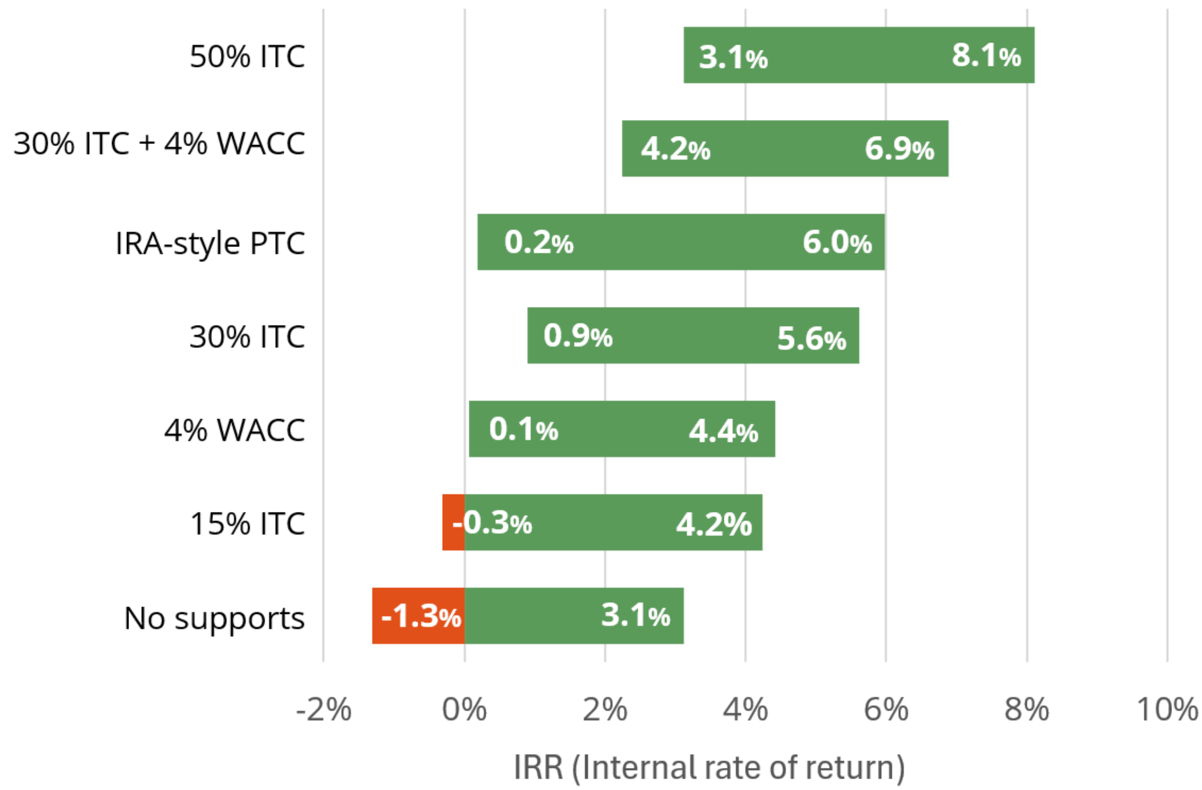


Figure 6 shows the ex-ante effect of various policy supports — including reductions in the weighted average cost of capital (WACC) from 5.5% to 4% attributable to concessional financing — on the expected IRR for a hypothetical "four-pack" of 300 MW nuclear reactors, like those proposed at Ontario's Darlington Station. The range shown encompasses optimistic (low-cost) and high-cost scenarios. The optimistic upper bound shows the expected IRR in the presence of specific policy supports if the reactors cost $3 billion each. The higher-cost lower bound shows the expected IRR if the reactors cost $6 billion each.

[19] See Appendix A for a list of assumptions underlying this analysis.

Other supports are bridging the gap

Canada's nuclear sector has access to a growing pool of additional supports. Beyond ITCs, and a $970 million loan from the Canada Infrastructure Bank, policymakers in Ontario, federally, and internationally are using other supports to help solve the cost problem. Green investment taxonomies and frameworks historically excluded nuclear, but that is quickly changing. Nuclear energy projects will now be eligible for the federal government's Green Bond Framework after their initial exclusion in 2022.[20] As of February 2024, Ontario has followed suit. In Figure 6 (above), we simulate the effects of concessional financing by reducing the weighted average cost of capital (WACC) from 5.5% to 4% in two scenarios.

As Figure 6 shows, we find that the overall package of policy-based supports for the nuclear sector in Canada is competitive with the US IRA. This makes nuclear power an outlier across low-carbon sectors.[21]

Policy-based supports are vital but only a partial solution — execution is key

Canada has mounted a highly competitive response to the US IRA in the nuclear sector. ITCs are the centrepiece. They will bridge Canada's nuclear cost problem in the short run, but are only a partial solution. These policy-based supports must be situated within a larger policy architecture and remain time-bound. An expiry date for policy incentives must serve to pull investments in nuclear generation forward in time, driving cost reductions from one reactor to the next as quickly as possible. As we discuss in our recommendations, policymakers should recalibrate these policy-based supports over time — particularly if Canada's cost problem proves to be more stubborn than expected.

Over the long run, the nuclear sector must execute on time and on budget with consistency. Ontario should be the first province to bring an advanced reactor to market if the first Darlington BWRX-300 is completed on time in 2029. Delivering the first advanced reactor at the low end of cost estimates would position the BWRX-300 as an option for other nuclear nations to consider. This project could make an outsize contribution to the pursuit of cost-competitive nuclear power. Executing on the second, third, and fourth reactors would establish the BWRX-300 as a reactor that Canada's nuclear sector is capable of building on time and on budget.

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[20] Includes investments in new reactors, refurbishment of existing facilities, research and development, and specific supply chain investments.

[21] Clean Prosperity's Canadian Advantage series of working papers has found that the IRA has opened up a "bankable gap" in policy-based economic incentives that make the United States a more attractive place to invest than Canada, in a range of low-carbon projects and sectors.

Solution #3: Pushing cost curves downward

Cost curves (also called learning curves[22] or learning rates) refer to cost declines from a first-of-kind product to an *n*th-of-kind.

The global nuclear sector's failure to execute projects with consistency has prevented the development of cost curves for large reactors. This is a key component of the cost problem. Historically, constructing a commercial reactor has been a custom engineering project, which resulted in poor knowledge transfer from one project to the next.

Policy can help the nuclear sector organize and emphasize repetition across successive projects of various reactor sizes. The final construction cost of the first BWRX-300 at the Darlington generating station will define what is possible for future cost reductions, and the development of cost curves for new nuclear reactors in the 2030s.

Repetition and standardization are key to reducing costs

Learning by doing is like building muscle: repetition is key. The IRA, along with the Bipartisan Infrastructure Act and the CHIPS and Science Act, is part of a US attempt to relearn how to build megaprojects, as a way to grow strategic sectors in specific regions of the country. Relearning how to do megaprojects of all kinds on time and on budget is crucial to building the industrial capacity needed to effectively scale many low-carbon technologies, including advanced reactors.

The benefits of repetition and learning by doing can be substantial. To illustrate this, we model a 10% cost curve for four reactors (see Figure 7). A 10% curve is optimistic, but within the range of possibilities for advanced reactors.[23] With Darlington's proposed four-pack of BWRX-300s, following this curve would result in the capital cost of each successive reactor declining by 10% relative to the preceding reactor.

As a rule of thumb for this project, our modelling indicates that each percentage of cost reduction along the cost curve is equivalent to a one-percent ITC.

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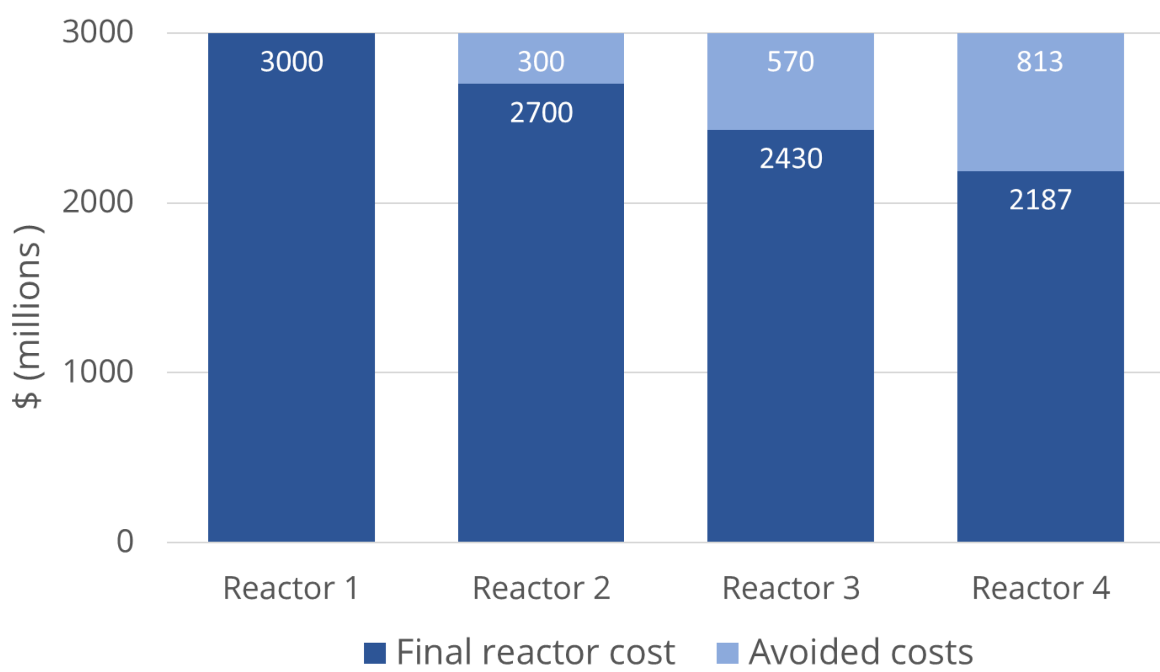
[22] Grubb, M., Jamasb, T. & Kohler, J. 2008. "Learning curves for energy technology and policy analysis: A critical assessment." Delivering a low carbon electricity system: Technologies, economics and policy. Cambridge University Press.

[23] Lewis, C., MacSweeney, R., Kirschel, M., Josten, W., Roulstone, T., & Locatelli, G. 2016. Small modular reactors: Can building nuclear power become more cost-effective. National Nuclear Laboratory: Cumbria, UK.

Figure 7: Capital cost of a hypothetical 4x300 MW advanced reactor project with a 10% cost curve



The light blue bars in Figure 7 (above) show avoided project costs associated with a 10% cost curve from first-of-kind to fourth-of-kind. If Darlington's first reactor can be constructed at our optimistic $3 billion cost estimate and a 10% cost curve develops, the cumulative sum of avoided costs would total $1.68 billion in capital expenditures relative to no cost curve (2024 dollars).

Descending the cost curve is not guaranteed

Cost curves can be disruptive or gradual. Practically speaking, cost curves are the aggregate of governments and private actors (e.g., startups, established firms, and consortiums) in a particular sector pursuing solutions to cost problems for specific technologies. Analysts tend to simplify this dynamic process by aggregating it into one smooth line on a chart. But the goal of any technology company is to be a disruptive and nonlinear force that can accelerate the rate of cost reductions.

Advanced commercial reactors have less potential for disruption and will likely not descend the cost curve as quickly as other key decarbonization technologies have in recent years. Reactors with stronger track records will have a built-in advantage over pre-commercial reactors and nuclear technologies. Pushing cost curves downwards requires a strategic focus on reactor types that are capable of scaling as quickly as possible.

Globally, many forecasts remain optimistic about cost reductions for commercial reactors. High-end estimates from the World Nuclear Association and, more recently, CIBC Capital Markets, suggest up to 50% cost reductions are eventually possible for an *n*th-of-kind reactor relative to first-of-kind. Others suggest that advanced reactors could experience 5% to 10% cost reductions for every doubling of global capacity.[24] The Canada Energy Regulator's net-zero scenarios are more conservative, suggesting $-per-kWh reductions from first-of-kind to *n*th-of-kind between 10% and 30% by 2050 in Canada.

Reactors face two important physical limitations: size and complexity

Even small reactors are large and complex relative to other zero-carbon electricity sources. Wind turbines and solar panels were a remarkable low-carbon success story in the 2010s, reducing costs by an average of 23% and 20% with every doubling of global capacity, respectively. These technologies have followed Wright's Law, where each doubling of installed capacity reduces costs at a more or less constant rate.

The relatively less complex components and ease of replication for wind turbines and solar panels have afforded them a large number of doubling times.[25] [26] Faster-than-expected deployment has become self-reinforcing, driving massive cost reductions.

The physical limitations of size and complexity will prevent nuclear from benefiting from Wright's Law in the same way as other zero-carbon electricity technologies. Even if repetition and automation are optimized to the fullest extent, specific reactor models will take longer to double their installed capacities compared to other technologies. Orders of magnitude separate the best-case scenario for new commercial reactors installed by 2050 (thousands) versus wind turbines (millions) or solar panels (billions), for example. Though they are the least advanced of the three size classes, micro-reactors will actually have the greatest opportunity to realize cost reductions via a greater number of doubling times, by virtue of their smaller size.

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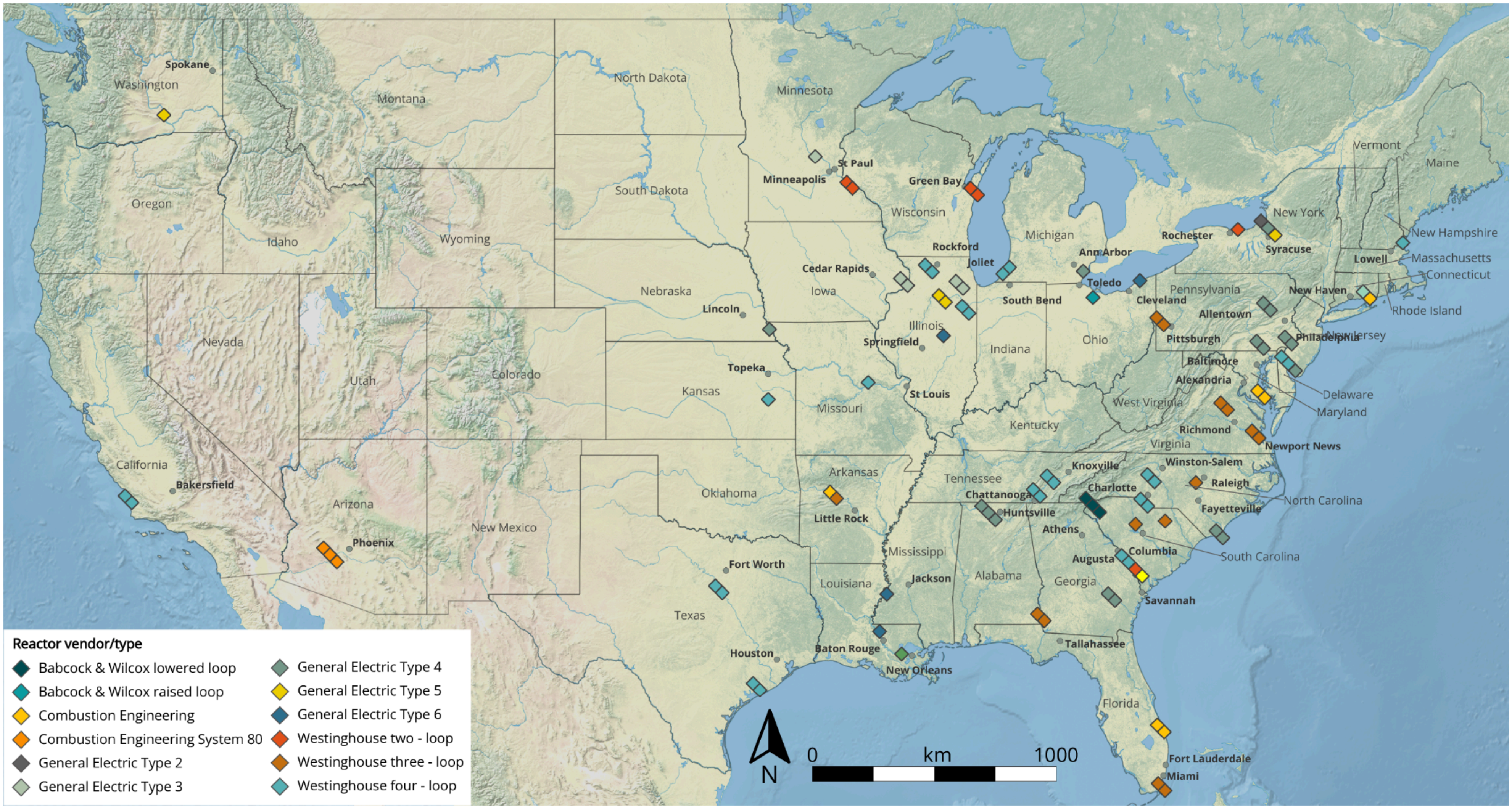
[24] Colterjohn, C., Nagasaki, S., & Fujii, Y. 2024. Optimizing the Implementation of Small Modular Reactors into Ontario's Future Energy Mix. Nuclear Technology, 210(1), 23-45.
[25] Sweerts, B., Detz, R.J., & van der Zwaan, B. 2020. Evaluating the role of unit size in learning-by-doing of energy technologies. Joule, 4(5), 967-970
[26] Wilson, C., Grubler, A., Bento, N., Healey, S., De Stercke, S., & Zimm, C. 2020. Granular technologies to accelerate decarbonization. Science, 368(6486), 36-39.

Figure 8: Reactor makes and models in the United States



Steep cost curves are good, low costs for first-of-kind are better

Size and complexity reduce the likelihood of steep or disruptive cost curves for commercial reactors, which only increases the importance of establishing a low cost floor for the first new advanced reactor at Darlington.

Cost curves will only become possible for the BWRX-300 in Ontario and beyond with a final price tag that is low enough to compel additional expansion. This would set the stage for pushing down the cost curve over the long run.

There are many potential ways that advanced reactors could descend the cost curve. The US Department of Energy's Liftoff Report for Advanced Reactors points to modularization as just one of six factors that will allow advanced reactors to develop and descend cost curves. The Liftoff Report suggests that over 80% of cost reductions will be driven by consistent application of best practices and learning by doing. In the Canadian context, this points to the importance of leveraging the Ontario workforce that builds the first BWRX-300 reactor.

Other challenges

Nuclear faces challenges beyond the cost problem and the certainty problem. We believe these challenges are manageable and secondary to the imperative of decarbonization. To build new nuclear reactors it is not sufficient to say that these challenges are manageable; the public must believe that they are manageable.

Operational safety

Canada's nuclear sector has a strong safety record. High-profile accidents at Chernobyl, Three Mile Island, and Fukushima have created significant psychological impacts and shaped public opinion about nuclear safety. But nuclear generation is in fact among the safest sources of electricity on a per-unit production basis.

The nuclear industry is one of Canada's most tightly monitored sectors. The CNSC has a rigorous licensing process that covers a range of safety and control areas from system design to siting and personnel certification, with robust frameworks for public health and safety at all steps of the energy production cycle, from uranium mining to waste management. Notably, all three of the major nuclear accidents mentioned above have been widely attributed to a mix of poor safety culture; regulatory failures, including insufficient design[27] and siting assessments; underqualified personnel; and, in the case of Chernobyl, broad non-adherence to international safety standards.[28]

Investigations into these disasters continue, with many of the findings still heavily debated.[29] [30] The common finding is that such accidents are largely preventable with responsible regulation.[31] This underscores the importance of Canada's continued leadership by example as a responsible operator in the global nuclear industry.

An informed debate about the benefits, tradeoffs, and safety features of commercial nuclear power can help to build public confidence in and support for future nuclear development.[32] Community, stakeholder, and Indigenous rights-holder participation in decision-making processes are vital to the success of future nuclear projects.

Long-term waste management

Nuclear waste is not the overwhelming problem it is commonly perceived to be, either in terms of long-term safety or overall volume of high-level wastes. Canada's Policy for Radioactive Waste Management and Decommissioning, administered by Natural Resources Canada, describes roles and responsibilities and detailed protocols for managing high-level, intermediate-level, and low-level radioactive waste.

Canada's planning for long-term nuclear waste storage is ongoing and keeping pace with other advanced democracies. Long-term geological storage for high-level nuclear waste in Canada is the purview of the Nuclear Waste Management Organization (NWMO), which has led the site selection process for long-term geological storage since 2010. Hosting sites have voluntarily expressed their interest, engaging with NWMO, undertaking consultations with Indigenous communities, and conducting independent site and environmental reviews.

In 2024, two communities in Ontario are expected to decide whether and under what conditions they are prepared to host a long-term storage site: Ignace (250 km northwest of Thunder Bay) and South Bruce (50 km inland from the Bruce Nuclear Generating Station,

[27] Rosztoczy, Z.R. 2019. Root causes of the Three Mile Island accident. Atw. Internationale Zeitschrift fuer Kernenergie, 64(11-12), 521-524.
[28] Kortov, V. and Ustyantsev, Y. 2013. Chernobyl accident: causes, consequences and problems of radiation measurements. Radiation Measurements, 55, 12-16.
[29] Holt, E. 2010. Debate over health effects of Chernobyl re-ignited. *The Lancet*, *375* (9724), 1424-1425.
[30] Ritchie, H. 2017. What was the death toll from Chernobyl and Fukushima? Our World in Data.
[31] Synolakis, C. and Kanoglu, U. 2015. The Fukushima accident was preventable. The Royal Society, 373 (2053).
[32] Kim, Y., Kim, W., and Kim, M. 2014. An international comparative analysis of public acceptance of nuclear energy. Energy Policy 66, 475-483.

on the shore of Lake Huron). Willingness to host must be community-driven, with Indigenous support a crucial precondition.

Geostrategic considerations

Security is an essential component of existing and emerging nuclear supply chains, particularly as Canada decides whether to allow fuel reprocessing on Canadian soil. Some argue that the expansion of the global commercial nuclear fleet increases the amount of precursors available to produce nuclear weapons.[33] We remain skeptical of both the causal pathway and the scale of this risk, particularly in the context of Canada's nuclear supply chain. There are easier paths to weapons development than stealing fuel or waste streams from secured commercial sites or storage facilities.[34] [35]

CANDU reactors do not require enriched uranium. This innovation emerged in part due to Canada's pledge against domestic enrichment under the Treaty on the Non-Proliferation of Nuclear Weapons (NPT). Canada's ratification of the NPT is not in conflict with the pursuit of new commercial reactors, but it does impose some near-term constraints. The BWRX-300 requires enriched uranium.

Canadian policymakers are exploring the potential for domestic enrichment. In 2023, OPG partnered with Cameco, Urenco USA, Orano, and Global Nuclear Fuel-Americas to secure enriched fuel supplies for the new Darlington reactors. Policymakers should develop deeper technology roadmaps to better understand the tradeoffs associated with continuing to rely on other countries for uranium enrichment, maintenance, and fueling, versus developing those supply chain links domestically.

Speed of deployment

Licensing has been flagged as a significant hurdle to global deployment of advanced reactors.[36] But the fact that nine reactor designs are in pre-licensing with CNSC suggests that all of the proponents believe they can successfully navigate licensing and regulatory affairs with CNSC and other regulators. Clean Prosperity's stakeholder engagement to date provides little indication that points of friction like the financial costs of pre-licensing,

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[33] Bluth, C., Kroenig, M., Lee, R., Sailor, W. C., & Fuhrmann, M. (2010). Civilian nuclear cooperation and the proliferation of nuclear weapons. International Security, 35(1), 184-200.
[34] Singh, S., & Way, C. R. (2004). The correlates of nuclear proliferation: A quantitative test. Journal of Conflict Resolution, 48(6), 859-885.
[35] Sagan, S. D. (2011). The causes of nuclear weapons proliferation. Annual Review of Political Science, 14, 225-244.
[36] Shobeiri, E., Genco, F., Hoornweg, D., & Tokuhiro, A. 2023. Small modular reactor deployment and obstacles to be overcome. Energies, 16(8), 3468.

regulatory duplication, and regulatory uncertainty are enough to meaningfully slow Canada's coming wave of announced nuclear capacity from 2025 to 2035.

Long project timelines are a common argument against nuclear power development. To address the drag that project approval timelines currently place on megaprojects, governments are studying options to reform and expedite project approvals in Canada. Current forums include the Ministerial Working Group on Regulatory Efficiency for Clean Growth Projects and the Regional Energy and Resource Tables, to name two. The 2024 federal budget proposes setting a three-year target for nuclear project reviews specifically. The budget language specifically mentions reducing duplication between the IAAC and CNSC. Clarifying the roles and responsibilities of these actors would address a crucial source of uncertainty for nuclear project proponents — present and future.

Conclusion: Take immediate action on the certainty problem, then attack the cost problem from multiple angles

Between 2024 and 2050, Canada's nuclear story will unfold in three overlapping phases.

Phase I began with Ontario's reactor refurbishments, which have primed supply chains and seeded the long-term labour force required for Phase II.

Phase II, still in its early stages, is the delivery of Canada's next wave of reactors at the Darlington, Bruce, and Point Lepreau generating stations — roughly through 2035. Executing Phase II on time and on budget is Canada's opportunity to make an outsized contribution to global efforts to triple nuclear capacity by 2050, as it pledged to do at COP28 in Dubai, and pave the way for Phase III domestically.

The federal ITCs and other federal policy supports pushed Phase II projects forward in Ontario and New Brunswick and offered clear, time-bound incentives for non-nuclear provinces to accelerate the development of their nuclear frameworks. For Phase II to translate into success in Phase III, Canada needs ambitious and stable provincial and federal policy frameworks that can set a responsible trajectory for high levels of electrification alongside broader decarbonization efforts.

Phase III is the development of a fully-scaled nuclear fleet for a high-electrification outcome in Canada. For Phase III to even be possible, cost curves must develop in Phase II. Simultaneously, provinces, regulators, utilities, private actors and the federal government must cooperatively build stable, long-term frameworks that can support the multi-decade project that will follow.

Each phase requires a rightsized approach that can lay the groundwork for additional scaling. Policymakers must strengthen the information channels, partnerships, and clarity of roles and responsibilities needed for nimble decision-making in the face of multiple possible futures.

An orderly transition from Phase II to Phase III becomes possible if policymakers commit to developing ambitious and stable policies that can provide predictable market signals and operate on timelines that are consistent with the construction of new reactors.

We make three recommendations to policymakers:

Recommendation #1: Develop ambitious and stable electrification and decarbonization policies that define stringency beyond 2035

Ambitious nuclear policy doesn't make sense without ambitious climate policy. Weakening or rolling back existing electrification and decarbonization policies severely damages the macroeconomic case for new reactors. A fully-scaled fleet of dozens or even hundreds of reactors requires a package of electrification and decarbonization policies that are built for the long term and that increase in stringency over time. The use of policy to enable high-electrification outcomes is a key lever to fuel the macroeconomic case for a fleet of reactors.

Given the timelines involved in building new commercial reactors, nuclear and non-nuclear provinces alike must start looking beyond 2035 in their policymaking. Ambitious, durable, and complementary policies at the provincial and federal levels are preconditions for the transition from Phase II to Phase III.

Phase III will not succeed without collaborative federalism to address policy and regulatory uncertainty, and clear signals from governments to utilities, regulators, and system planners that Canada and Ontario in particular are intent on pursuing high-electrification pathways.

In the short run, this requires clarifying the long-term trajectory of policies that are already up and running in the provinces, most notably industrial carbon markets. Provinces should define the price path for carbon beyond 2035 and establish firm timelines for developing fully net-zero grids. Provincial governments intent on pursuing ambitious nuclear policy cannot rely on business as usual to reach Phase III. Ambitious policy is needed to clarify intentions to system operators, industry, and households, and push provincial grids towards higher-electrification pathways.

We point specifically to the need for stringent carbon markets for heavy industry, which can help level the financial playing field for new nuclear projects. Most provincial carbon markets — including Ontario — apply emissions performance benchmarks to emitting sources of electricity that significantly reduce their exposure to the full headline carbon price. This gives emitting generation an unfair advantage over nuclear power and undervalues nuclear as a source of high-capacity, zero-carbon electricity.

To correct these issues with the carbon-price signal, provinces should establish a clear timeline for setting their emissions performance benchmarks for all forms of electricity generation to zero. Provincial carbon pricing systems use benchmarks to avoid exposing emissions-intensive and trade-exposed (EITE) industries to the full carbon price. Benchmarks are set at levels that accommodate the international competitiveness pressures that these industries face in the presence of carbon pricing. Electricity currently receives EITE treatment in industrial markets, but the electricity sector as a whole does not meet the definition of EITE in Canada. Setting electricity generation benchmarks to zero paired with ratepayer rebates would correct this issue.

Policymakers should fully expose their electricity sectors to the carbon price, but should avoid crediting nuclear facilities within carbon markets without carefully considering implications for the carbon credit market as a whole. By virtue of its high capacity factors and negligible emissions, nuclear has the potential to generate large volumes of carbon credits, which could easily tip markets into oversupply. Robust energy-economy modelling could establish how to accommodate the large volumes of carbon credits that nuclear facilities might generate.

Affordability is central to electrification efforts. Both businesses and households are highly sensitive to electricity costs. As they begin to use electricity for more applications, the direct financial benefits of fuel switching must fully offset the direct financial costs of consuming more electricity. Therefore, adjusting electricity benchmarks to zero should be paired with rebates to ratepayers. All of the additional carbon-pricing revenue can directly reduce consumer electricity charges such that the cost of electricity to ratepayers is completely unaffected by this policy change. There is very little that ratepayers can do to influence the carbon intensity of their electricity consumption. Full exposure to the carbon price for electricity, paired with rebates, would remove one of nuclear’s key disadvantages in electricity procurement while protecting affordability for households and realigning incentives for industry, utilities, and system planners.

Recommendation #2: Gradually shift to policy-based financial supports that reward results rather than effort

There are adequate policy-based financial supports in place for Phase II across the nuclear supply chain. The federal ITCs, once fully implemented, will constitute a strong response to the IRA. Paired with bespoke supports, they effectively address several aspects of the cost problem for the forthcoming wave of reactors at the Darlington, Bruce, and Point Lepreau stations. Federal policymakers must act with the urgency that the moment demands and finalize the ITCs as swiftly as possible.

Developing a fully scaled nuclear fleet will require both policy-based financial support and a plan to eventually remove this scaffolding. The ITCs are the appropriate tool for Phase II, the moment Canada finds itself in. But the ITCs are ill-suited for Phase III because they reward effort rather than results. Ontario and Canada need results.

Should the cost curve for the BWRX-300 and other small and micro reactors descend quickly in Phase II, no policy-based financial supports may be needed for Phase III. The public cost of Canada's ITC approach is manageable for a small handful of projects. But if Canada is to scale commercial reactors at a reasonable fiscal cost, policymakers must reward results rather than effort.

If supports are required for Phase III, policymakers must leverage alternatives to ITCs. In Table 2 below, we compare three alternative policy supports, noting that they can be combined and stacked with one another or with ITCs.

These supports merit further study to quantify their potential private and public costs across both Phase II and Phase III, as well as their potential influence within provincial electricity markets (e.g., potential market distortions). We call attention in particular how well suited each instrument is for reactors of different sizes.

Table 2: Tradeoffs across results-based incentives for nuclear power

Policy support	How it works	Strengths	Weaknesses
Power purchase agreements (PPAs)	A contract between an electricity generator and private or public customer, where the customer agrees to buy a specific amount of electricity at a fixed, pre-negotiated price. This can provide greater certainty to the generator and the customer before construction begins.	Simple, well-understood by industry, and bankable. PPAs already exist in provincial power markets that have independent power producer participation.	Policy instrument is only available to provincial governments and private actors, not the federal government. Power prices are not directly market tested, and increased market exposure creates risks that vendors may not be willing to take on given large initial construction risk associated with nuclear power.
Production tax credits (PTCs)	Electricity generators receive a direct per-unit subsidy for electricity production (i.e., $ per kWh) for a fixed period of time (e.g,. five or 10 years).	Simple, clear, and bankable for project proponents. Issues of market distortions and public cost can be mitigated through certain delivery models, such as capping the total program size in advance and reverse auctions.	PTCs can distort energy markets. These "out of market" payments have resulted in negative energy prices, which have forced higher-cost merchant power plants in North American jurisdictions to pay to sell their power or prematurely cease operations. The public costs of PTCs can be high if the program is broadly accessible by all projects.
Contracts for difference (CfDs)	Similar to a PPA. Instead of a fixed price, there is a pre-negotiated "strike price". The generator pays its contract counterparty (most often a business or government) the difference if market prices for electricity exceed the strike price. The counterparty pays the generator if the market price falls below the strike price.	Locks in a profitable price for generators. Keeps costs better privatized in the event of overruns. Successful recent examples in provincial markets (e.g., Alberta wind/solar procurements). Recent example from the UK of CfDs signed with a nuclear generating station, with relevant learnings for policymakers.	While several countries have successfully used CfDs for wind and solar deployment, none have used CfDs to support active nuclear (the UK's CfD for nuclear is not yet operational). Potential contingent liability issues given long project lead times.

Recommendation #3: Prioritize fleet-based approaches to deploying commercial reactors on as few sites as possible

For advanced reactors to descend the cost curve in Canada and abroad, policymakers should prioritize fleet-based approaches for commercial reactors. For micro-reactors, this means organizing around as few designs as possible to facilitate widespread deployment. For large and small reactors, this means organizing around as few designs on as few sites as possible to take full advantage of nuclear's low land-use requirements.

Canada may ultimately need a small portfolio of reactor models. Practically, this should include one large, one small, and one micro reactor capable of generating both electricity and industrial-grade heat. For the small reactor class, the BWRX-300 is the strongest candidate to descend the cost curve in Canada by 2050. Provinces should embrace the BWRX-300 in their economic and industrial strategies, but prepare to embrace cost-competitive alternatives should they emerge. Advanced designs in development at Point Lepreau and in the US are natural backup candidates. Successful execution of the Darlington BWRX-300s would pay dividends, increasing the likelihood that other nuclear and nuclear-aspirant nations proceed with the BWRX-300 themselves. This would in turn help ensure that Ontario benefits from other nations' descent down the cost curve.

In contrast, the large and micro-reactor classes do not have clear frontrunners. The technology selected for the Bruce expansion will have a natural advantage in the large reactor class. Other reactors with well-understood designs and operating histories, such as the EPR and AP-1000, are also candidates. The micro-reactor class is the least advanced. Canada should continue to experiment with micro-reactors at Chalk River, but the most cost-competitive micro-reactor is more likely to originate beyond Canadian borders.

In addition to domestic R&D, policymakers can lay the groundwork to enable expeditious adoption of winners that emerge across different reactor classes and sizes in the 2030s and 2040s. Canada should closely monitor the progress of reactor designs approaching commerciality in the US. As Saskatchewan piggybacks off Ontario, Canada should piggyback off the burst of economic activity and demonstration projects enabled by the US IRA.

It is not a guarantee that the cost problem will resolve in time for Canada to take a fleet-based approach for 2050. Policymakers should prepare for high-electrification scenarios that do not feature large amounts of nuclear power, and build off-ramps for grid architectures that rely on other generating sources.

Appendix A: Nuclear project modeling assumptions

This appendix outlines the major assumptions made in modeling the relative impacts of different policy supports, cost curves, and various regulatory costs for a 4x300 MW advanced reactor project. We parameterized our model and developed ranges for various cost categories based on a mix of academic literature, grey literature, and stakeholder input. This is not an exhaustive list of assumptions. For questions about the methodology, please contact the authors.

- Nameplate capacity of 300 MW
- Capacity factor of 90%
- Our "optimistic" cost scenario of $3 billion is based on overnight capital cost estimates from a 2021 SMR feasibility study by provincial power utilities, a figure that has been reiterated in public statements by Canadian policymakers.
- Costs of impact assessments, licensing, and decommissioning costs informed by averages from the World Nuclear Association, as well as stakeholder input
- Average capital expenditures and operating expenditures informed by Lazard's 2023 Levelized Cost of Energy+ report and Navius Research's gTech model assumptions
- First reactor comes online in 2029, followed by reactors 2-4 in 2031, 2033, and 2035
- Revenues from wholesale electricity sales and PPAs are informed by assumptions used by other modellers, including Navius Research, Lazard, Ontario's Independent Electricity System Operator, and the Canada Energy Regulator. Our median estimate displayed in Figure 6 is $90/MWh. As a point of reference, the current off-peak rate for regulated electricity in Ontario is 8.7¢ per kWh.
- Inflation indexed to 2%
- All publicly announced federal policy-based financial supports are considered in our model (see Appendix B). The Clean Electricity Regulations are not considered.
- $1.35 CAD to USD exchange rate
- Discount rates are 8% unless otherwise specified
- Projects are 75% debt financed after federal ITCs are applied

Appendix B: List of federal policy supports for nuclear energy

- **Investment tax credits:** Budget 2023 proposed refundable tax credits that will support nuclear energy, including the 15% Clean Electricity ITC that covers conventional nuclear, SMRs, and transmission equipment; the 30% Clean Technology Manufacturing ITC, which covers nuclear energy equipment and the processing or recycling of nuclear fuels and heavy water; and a 30% Clean Technology ITC that covers zero-emissions electricity generating technologies, including SMRs.

- **Reduced tax rates for zero-emission technology manufacturers:** Budget 2023 proposes extended eligibility for reduced business tax rates to include the manufacturing of nuclear energy equipment and the processing and recycling of nuclear fuels and heavy water, beginning after 2023.

- **Regulatory streamlining:** Budget 2024 set a three-year target for nuclear project reviews by working with the CNSC and IAAC to consider how to reduce duplication across the agencies.

- **Canada Infrastructure Bank (CIB):**

  - Budget 2022 broadened CIB's role in private sector-led infrastructure projects that will accelerate Canada's transition to a low-carbon economy. This will allow the CIB to invest in SMRs.

  - CIB invested $970 million to aid OPG in Phase 1 of construction for the first GE Hitachi BWRX-300, which includes project design, procurement of long lead-time equipment, utility connections, site preparation, and project management requirements.

- **Strategic Innovation Fund/Net Zero Accelerator (Innovation, Science and Economic Development Canada):** $20 million to Terrestrial Energy (2020); $49 million to Moltex (2021); $27.2 million to Westinghouse Electric (2022)

- **Natural Resources Canada (NRCan) Budget 2022 SMR funding:**

  - **Waste management, safety and nuclear cooperation:** $69.9 million for NRCan to undertake research to minimize waste generated from future SMRs; support creation of a fuel supply chain; strengthen international nuclear cooperation agreements; and enhance domestic safety and security policies and practices.

    - **Pre-development activities:** Budget 2022 proposes to provide $250 million over four years, starting in 2022-23, to NRCan to support pre-development activities of clean electricity projects of national significance, such as inter-provincial electricity transmission projects and small modular reactors.
    - **Enabling Small Modular Reactors Program (NRCan):** Launched in February 2023, the Enabling Small Modular Reactors Program lays out $30 million of the $69.9 million in funding over four years for supply chain development and waste management.
- **Small Modular Reactors Research Grant Initiative (NSERC):** The Natural Sciences and Engineering Research Council of Canada issued a call for proposals in 2022 (with another to come in 2025) from universities to study various components of the SMR supply chain, including chemistry and materials, environmental and radiological protection, human and organizational factors, safeguards and security, and novel fuel compositions. The program is worth $15 million over five years.
- **Atomic Energy of Canada Ltd. (AECL):**
    - A nearly 50% increase to AECL's budget since 2020 (pg 20). In part to pay for the 10-year, $1.2 billion renewal of Canadian Nuclear Laboratories' Chalk River facility, including the installation of a microreactor, with Global First Power the most advanced applicant as of 2021.
    - Budget 2024 proposes $3.1 billion over 11 years, starting in 2025-26, with $1.5 billion in remaining amortization, to AECL to support Canadian Nuclear Laboratories' ongoing nuclear science research, environmental protection, and site remediation work.
- **Regional economic development agency funding (various):** The Point Lepreau reactor has received more than $5 million in support through the Atlantic Canada Opportunities Agency (ACOA). Moltex received $3 million through ACOA's REGI program in 2021.
- **Canadian Nuclear Safety Commission (CNSC):** Budget 2022 allocated $50.7 million, and $0.5 million ongoing, for the CNSC to build the capacity to regulate SMRs and work with international partners on global regulatory harmonization.
- **Green Bond Framework:** The 2023 Fall Economic Statement announced that Canada's Green Bond Framework will make certain nuclear expenditures eligible.

Appendix C: List of commercial reactors in Canada

Reactor	Model	Capacity (MWe)	First grid connection	Refurbishment scheduled completion
Bruce 1	CANDU 791	732	1977-01-14	2012
Bruce 2	CANDU 791	732	1976-09-04	2012
Bruce 3	CANDU 750A	750	1977-12-12	2027
Bruce 4	CANDU 750A	750	1978-12-21	2028
Bruce 5	CANDU 750B	822	1984-12-02	2030
Bruce 6	CANDU 750B	822	1984-06-26	2024
Bruce 7	CANDU 750B	822	1986-02-22	2032
Bruce 8	CANDU 750B	795	1987-03-09	2034
Darlington 1	CANDU 850	881	1990-12-19	2026
Darlington 2	CANDU 850	881	1990-01-15	2020
Darlington 3	CANDU 850	881	1992-12-07	2023
Darlington 4	CANDU 850	881	1993-04-17	2027
Pickering 1	CANDU 500A	508	1971-04-04	NA
Pickering 4	CANDU 500A	508	1973-05-21	NA
Pickering 5	CANDU 500B	516	1982-12-19	2035
Pickering 6	CANDU 500B	516	1983-11-08	2035
Pickering 7	CANDU 500B	516	1984-11-17	2035
Pickering 8	CANDU 500B	516	1986-01-21	2035
Point Lepreau	CANDU 6	660	1982-09-11	2012
Gentilly 2	CANDU 6	675	1983-10-01	NA