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Transforming energy taxation policy: A dual cooperative game and stochastic frontier approach for sustainable transitions in Canada

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ABSTRACT

A successful energy transition demands more than simply raising carbon taxes—it requires smart incentives that align environmental goals with economic resilience. This study introduces a novel Conditional Government Carbon Tax Rebate (CGCTR), which offers carbon tax reductions conditional on firms increasing salaries and expanding their workforce, fostering a dual benefit across environmental and labor dimensions within a government–industry energy network. We develop an integrated modeling framework that combines stochastic frontier analysis (SFA) with a dual-layer cooperative game theory approach to assess and optimize CGCTR adoption under multiple tax relief scenarios. The SFA component uses a policy-sensitive, time-varying Cobb–Douglas production function with workforce and salary as inputs and a policy-induced productivity shift from carbon tax to estimate firm-level energy output and inefficiency integrated with environmental performance, classifying firms as fully efficient, efficient, and less efficient. Strategic interactions among these tiers are modeled through intra-group and inter-group cooperation, enabling the identification of cooperative equilibria that support the acceptance of CGCTR. A Canadian case study using historical financial and operational data illustrates the practical utility of the framework. Results reveal that CGCTR can induce cooperative behavior even among heterogeneous firms, leading to (1) stable policy equilibria, (2) increased energy production and decreased emission intensity, (3) improved workforce sustainability through hiring and wage dynamics, and (4) broader social welfare gains reflected in rising wage-based GDP, increased employment, and enhanced productivity. This framework offers a novel decision-support tool for governments seeking to design adaptive, efficiency-driven carbon tax policies that align environmental goals with economic viability.

1. Introduction

1.1. Motivation and background

The global imperative to decarbonize energy systems has propelled carbon taxation to the forefront of climate policy. Despite its conceptual appeal, real-world implementation frequently encounters limited effectiveness stemming from diverse industry responses, inflexible policy designs, and inadequate integration of operational dynamics at the firm level. Current carbon pricing frameworks are inadequate in two significant areas. At first, firms are frequently regarded as independent entities reacting to policy, neglecting the potential for cooperative dynamics that may arise – either naturally or through intentional design – among companies pursuing mutual advantages. Secondly, there is a lack of integration of efficiency analysis within behavioral modeling, overlooking the impact of firms' technical capabilities on their policy preferences and adaptive potential. These limitations matter even more in fragmented sectors like energy, where firms vary widely in technology, resource use, and environmental impact—making it harder to move forward together and adopt effective carbon tax policies collectively.

In the Canadian context, the debate over carbon pricing has significant implications for Alberta's upstream energy sector, a cornerstone of both the provincial and national economy. Introduced in 2019 by former Prime Minister Justin Trudeau, the federal carbon tax was designed to reduce greenhouse gas emissions and accelerate Canada's transition to a low-carbon economy [1]. The policy has remained highly contentious for resource-rich provinces like Alberta, where the oil and gas industry constitutes major sources of employment and economic growths. Some analyses suggest that this policy "forced open the door" to investments in sustainable and cleaner energy sources, fostering innovative solutions in emissions reduction technologies [2,3]. On the other hand, Alberta has announced an indefinite freeze of the industrial

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carbon price under TIER at $95 per tonne, citing competitiveness concerns amid U.S. tariff uncertainty [4]. While this could provide meaningful relief for Alberta's energy companies, it remains uncertain whether the freeze will stand if Ottawa determines the system no longer meets federal benchmark stringency [5]. Also, in the broader Canadian debate, the Fraser Institute argues that higher carbon prices will leave households worse off, citing internal federal analysis and its own modeling that a $170/tonne levy would shrink GDP by about 1.8%, and lead to a permanent loss of roughly 185,000 jobs [6]. On the other hand, recent projections from Pembina institute indicate that Alberta stands to gain 364,000 clean energy jobs by 2050, accounting for 18% of the total new employment opportunities across Canada [7]. This suggests that, while traditional fossil fuel jobs may decline, carbon pricing policies and emissions caps could accelerate the province's transition to a clean energy economy, fostering job creation in emerging industries such as renewable energy, carbon capture, and energy efficiency solutions.

From the perspective of the federal government in Canada, there is a prevailing belief within climate policy circles that increasing carbon taxes will inherently reduce emissions and accelerate the transition towards renewable energy. However, this view simplifies the complex political and economic realities encountered by governments and industry stakeholders, particularly in energy-dependent regions such as Alberta [8]. Higher carbon taxes can lead to capital flight, workforce reductions, and heightened opposition to climate regulation, especially for firms with lower operational efficiency or narrower profit margins. In these contexts, tax increases without adequate incentives may polarize industries and jeopardize long-term climate objectives [9].

Carbon taxation is frequently misunderstood; it need not be punitive and can serve as a tool for negotiation. Governments can strategically mitigate carbon tax obligations under certain behavioral conditions rather than viewing increases as a blunt instrument. In response to potential negotiations between governments and energy companies, we introduced a new negotiation policy, the Conditional Government Carbon Tax Rebate (CGCTR). This framework provides firms with carbon tax reductions dependent upon their commitment to reallocating tax savings to enhance employment outcomes, specifically through increased worker salaries and workforce expansion. In doing so, CGCTR reframes climate policy as a mutually beneficial social contract: firms benefit from immediate financial relief, while governments ensure that the proceeds are reinvested into labor markets and long-term economic resilience. To foster potential cooperation among stakeholders and evaluate the economic growth implications of implementing CGCTR in the energy sector, this study introduces a novel integration of Stochastic Frontier Analysis (SFA) with a dual-layer cooperative game theory framework to assess both the adoption dynamics and overall impact of CGCTR. Unlike data envelopment analysis (DEA) and computable general equilibrium (CGE) models, which are often used in energy policy research, SFA provides a flexible and detailed approach that aligns well with economic theory and policy analysis, especially in uncertain situations like energy markets affected by fluctuating carbon prices. Classifying energy companies into fully efficient, efficient, and less efficient categories based on SFA-derived efficiency scores enables a more accurate attribution of internal inefficiencies, energy output, and carbon emissions, clarifying their individual and collective potential in the energy network. Building on this foundation, we model both intra-group (within efficiency tiers) and inter-group (across tiers) cooperation dynamics under four distinct CGCTR scenarios to evaluate coordinated responses and strategic alignment. This approach is not only methodologically innovative but also policy-relevant, as it captures the complex interplay between firm-level heterogeneity, strategic cooperation, and policy incentives. By integrating efficiency-based classification with game-theoretic modeling, the study provides a robust framework to anticipate how diverse stakeholders may align under different CGCTR implementations. This framework can assist policymakers in formulating adaptive, equitable, and effective carbon governance strategies that foster stakeholder cooperation, economic growth and economic sustainability in the region.

1.2. Literature review

1.2.1. SFA in energy production

SFA is a crucial econometric tool for evaluating energy efficiency across nations, sectors, and households. It separates inefficiency from statistical noise, providing insights into technical performance under real-world production constraints. Recent studies use SFA in modeling their efficiency frontiers to estimate productivity gaps and performance benchmarks within the energy sectors. SFA has been utilized to evaluate the impact of carbon pricing on energy efficiency at the provincial level in Canada [10]; however, its incorporation into frameworks that simultaneously address the emission–production trade-off and labor dynamics is still largely unexamined. At the national level, especially among OECD countries, SFA has demonstrated its utility in analyzing the relationship between sustainable economic growth and energy security [11]. Nonetheless, its potential may be improved by incorporating wider macroeconomic perspectives, extending beyond a limited emphasis on technological diversity and regulatory effects to encompass systemic dynamics in energy efficiency outcomes.

Further study has utilized SFA to assess renewable energy transitions via cooperative models, highlighting the significance of institutional and social infrastructure [12], or to benchmark environmental performance at national and regional levels to aid long-term energy planning [13]. Yet, policy-oriented climate strategies require a more profound theoretical integration, moving past benchmarking to support dynamic behavioral responses to regulatory interventions. SFA has been expanded to categorize regions according to production characteristics and to address heterogeneity in production technologies through latent class models, particularly in large and diverse economies like China, with the objective of enhancing energy efficiency outcomes [14]. However, these approaches could be enhanced by explicitly integrating environmental regulations or penalty structures into the SFA framework, rather than concentrating exclusively on technological investment patterns. Additionally, SFA has been extensively utilized in various sector-specific applications. For example, it has been employed to monitor total-factor energy efficiency in transportation systems, emphasizing emissions reduction [15]. It has also been used to assess the potential for household cooling savings, which informs targeted conservation policies [16]. Furthermore, SFA has been applied to identify electricity-saving opportunities in residential contexts, considering both technical and behavioral standards [17]. However, these models often lack structured policy integration, which restricts their direct relevance to practical decision-making and climate-responsive governance.

Furthermore, household energy consumption and income dynamics have been analyzed using SFA, especially considering structural changes in energy policies [18]. These models would benefit from a more comprehensive sensitivity analysis to better understand the complex decision-making behaviors in household energy use, which are frequently shaped by economic constraints and policy signals. In renewable energy, SFA has been employed in the wind power sector to evaluate technical efficiency, encompassing geographic diversity and operational practices [19], and to measure environmental benefits from recycling using multi-layered frontier frameworks [20]. Nevertheless, these applications frequently lack integration with firm-level behavioral responses to environmental policy, revealing a gap in the incorporation of dynamic production inefficiencies and regulatory mechanisms within a cohesive SFA-based policy evaluation framework.

1.2.2. Game theory in energy sector cooperation

Game theory has become an effective instrument for modeling cooperative frameworks in energy systems, particularly in decentralized or uncertain contexts. An illustrative case is the application of cooperative game-theoretic incentive schemes to optimize participation in local energy communities, showing that profit-sharing mechanisms can improve community engagement and encourage the utilization of renewable energy sources [21]. In addition, cooperative game frameworks have been utilized to create priority-based peer-to-peer trading mechanisms, frequently employing fair and stable allocations like the Shapley value, ensuring equitable energy access and efficient resource exchange among prosumers in decentralized markets [22]. While sharing schemes and the Shapley value offer a theoretical basis for equitable distributions, their efficacy is significantly influenced by the construction of cooperative game values. These values must align well with the system's dynamics to ensure realistic, context-sensitive, and stable outcomes in practice.

At a more complex system scale, game theory has been applied to manage uncertainties in regional multi-agent energy systems by facilitating coordination among local agents, while accounting for both cost and emissions factors [23]. In addition, recent studies have examined the decision-making dilemma regarding cooperation versus independent action to improve energy efficiency and economic performance in multi-agent systems [24]. Nevertheless, the construction of cooperative game models in such settings often requires each agent to be aware of others' strategic responses. This prerequisite complicates implementation in real-world energy sectors, which require adaptive and responsive stakeholder behavior to align with the evolving nature of energy systems as well as market conditions.

Systematic reviews indicate that game-theoretic approaches are increasingly utilized to model demand-side behaviors, facilitating dynamic decision-making under demand uncertainties [25]. Cooperative game theory has been essential at the system level for assessing the flexibility contributions of different actors in power grids, providing a cohesive framework for the equitable distribution of shared costs and benefits among stakeholders [26]. In remote or resource-limited contexts, game-theoretic strategies have been utilized to improve coordination in biomass supply chains by aligning economic returns with sustainability goals [27]. Yet, these models frequently neglect the existence of asymmetric power relations, in which certain agents exercise excessive authority over others. In realistic energy market interactions, the contributions of firms, particularly their marginal contributions, to overall system performance are influenced by asymmetries that conventional cooperative game applications often fail to capture or implement effectively.

On the other hand, non-cooperative modeling frameworks have been utilized to assess carbon reduction pathways and firm-level efficiency improvements independently from a policy perspective [28]. Moreover, optimization models that exclude strategic interactions among agents can still provide significant insights into overall system performance improvements [29]. Yet, real-world sustainability transitions necessitate collective coordination and shared responsibility, rather than merely isolated actions. In this regard, cooperative frameworks facilitating joint decision-making more accurately represent this reality, highlighting the interdependence of individual gains and collective outcomes in complex policy contexts.

1.2.3. Carbon tax impacts on energy sectors

Carbon taxation has become a crucial tool in climate policy, especially for the transformation of the energy sector. A recent study indicates that carbon pricing in Canada's electricity sector has significantly altered generation accounts by promoting renewable energy integration and reducing reliance on coal and other high-emission fuels [30]. This trend illustrates the potential of carbon pricing to drive structural changes in electricity systems. Nevertheless, carbon pricing in the agri-food sector has induced significant changes, resulting in higher food prices, thereby raising concerns regarding affordability [31]. This underscores the necessity for tax frameworks that encompass not only environmental goals but also economic equity.

Environmental taxation has been demonstrated to promote green innovations within Canadian firms, facilitating cleaner production and the adoption of energy-efficient technologies [32]. Yet, trade competitiveness concerns have prompted requests for border carbon adjustments [33]. Luckily, macroeconomic simulations indicate that these adjustments may decrease economic leakage while preserving incentives for domestic production [34].

In emissions trading systems, assessments demonstrate that carbon taxes offer clearer price signals, enhancing predictability and transparency for businesses [35]. For example, in China, using both renewable portfolio standards and carbon taxes together has been shown to reduce emissions more effectively than using either one alone [36]. However, those studies fail to consider firm-level heterogeneity, which restricts our understanding of how carbon taxes impact diverse energy firms with different abatement costs and capacities.

Studies of different carbon tax designs show that flexible options, like rebates or recycling revenue, are more likely to be accepted and supported by the public [37]. On the other hand, carbon taxation at the microeconomic level influences household energy consumption patterns, typically resulting in decreased consumption while simultaneously raising affordability concerns [38].

Decision-making frameworks demonstrate the impact of carbon taxation on supply chain strategies, especially within agri-energy sectors, from systems modeling perspective. The models highlight the significance of both cooperative and non-cooperative behaviors in attaining low-carbon outcomes, indicating that taxation should be incorporated into wider multi-agent decision frameworks [39,40]. Yet, uniform taxation-driven behaviors often overlook the conditional impact of how tax revenues are allocated towards key economic or environmental metrics.

Carbon tax schemes can cause negligible adverse effects on GDP [41]. This indicates that economic growth may occur alongside decarbonization when tax revenues are efficiently reinvested. Further research reinforces this point, showing that carbon taxes can lead to reductions in emissions while also enhancing energy system efficiency [42]. Additionally, these taxes can enhance overall welfare when paired with subsidies or rebates [43]. Nevertheless, in regions with fragile economic structures, such as Iran, the implementation of carbon taxes requires careful consideration, as improper design may result in regressive social outcomes [44].

1.3. Research gap

Although SFA has shown promise in energy systems efficiency analysis, there are still significant drawbacks to its present uses. The majority of research is limited to testing or static benchmarking, revealing little about company performance without accounting for changes in behavior brought about by policy interventions like carbon taxes. This ignores how companies dynamically modify their output in reaction to changing regulatory demands. Furthermore, current models often lack a policy-sensitive structure, leaving out tax-induced production trade-offs and feedback mechanisms in their frontier estimates.

Despite advancements, current cooperative game models in energy systems fall short in several important aspects. First, their realism and policy relevance are limited since models often leave out concrete economic and environmental indicators, such as workforce, wage, and carbon price. Second, the majority of models ignore how agents modify their tactics in changing policy contexts by failing to take stakeholder response to dynamic climate policies into account. Third, varied company efficiencies – especially those influenced by marginal production and emission behaviors – are not well integrated. As a consequence, the chance to capture the asymmetrical power dynamics that define collaboration in the actual world is lost. Lastly, there is a gap in illustrating how shared benefits arise via strategic, asymmetrical involvement since collective decision-making is often pictured rather than based on performance-driven contributions.

The majority of the current work on carbon taxes focuses on uniform tax systems, which ignore sector-specific asymmetries and presume homogeneous firm responses. This overlooks the fact that without conditional allocation mechanisms, carbon taxes fail to reach their full potential. Most studies overlook the ways in which reinvesting carbon tax money into specific economic or environmental outcomes – like increasing the workforce, raising wages, or promoting the use of clean technologies – can encourage more fair and successful transitions. Furthermore, studies do not give enough consideration to the effects of strategic stakeholder interactions, behavioral change, and changing regulatory environments on the dynamics of tax responses over time. Last but not least, carbon tax models often see enterprises as passive users rather than strategic actors whose contributions to output and emissions change and may affect their involvement in overall results.

1.4. Paper contribution

This study contributes significantly to environmental and energy economics by presenting an integrated, policy-aware analytical framework.

First, this study presents a novel policy mechanism, CGCTR, which considers carbon taxation as a conditional incentive rather than a rigid fiscal obligation. In contrast to traditional carbon tax systems that uniformly impose emissions-based payments, CGCTR allows the government to strategically allocate portions of the tax liability back to energy companies, dependent upon the reinvestment of these funds in workforce expansion and salary enhancements. This framework is specifically designed for regulatory contexts with significant tax implications, such as Canada, where policies can jointly address multiple socio-economic objectives. Conditioning tax rebates on labor investments allows CGCTR to directly foster green employment growth, enhance wages, and improve social welfare, thereby connecting climate action to economic resilience. This approach promotes reductions in emission intensity while simultaneously supporting growth in firm-level energy production, thereby promoting an integrated pathway to sustainable development.

Second, this study employs a SFA framework to model firm-level energy production, considering traditional inputs such as workforce and average salary, alongside the influence of policy through carbon tax, which acts as a policy-induced productivity shift. Although recent literature has utilized SFA to evaluate technical efficiency among firms, its incorporation into policy-responsive modeling, particularly concerning environmental externalities, is mostly restricted. Our approach is distinguished by two novelties: (1) the integration of centered emission intensity within the inefficiency term to accurately represent firm-specific environmental performance, and (2) the adoption of strategic firm classification based on both output inefficiency and the relative trade-off between marginal energy production and carbon emissions. This classification system uses SFA to help distinguish between unexpected changes and ongoing inefficiencies, making it easier to compare companies that produce a lot but have poor emission records with those that produce less but are better for the environment. To the best of our knowledge, this study presents the first application of SFA that incorporates economic inputs, environmental inefficiencies, and tax-induced policy changes, while facilitating scenario-based forecasting of production outcomes.

Finally, this study introduces a new cooperative game-theoretic framework based on firm-level efficiency dynamics derived from the stochastic frontier model. The proposed framework differs from traditional static cooperative games by two novelties: (1) The payoff structure in the proposed cooperative game is not exclusively determined by financial returns; rather, it is dynamically associated with each firm's estimated inefficiency, marginal contributions to energy production, and emission levels. Embedding performance indicators from the Cobb–Douglas stochastic frontier model into the payoff design allows the game to more comprehensively represent each firm's role in the energy network. This integration enables coalition formation and policy adoption decisions to incorporate financial rewards alongside environmental responsibility and operational efficiency. (2) This study presents a two-layer coalition structure to facilitate the cooperative adoption of the CGCTR policy, thus enhancing strategic coordination among energy firms. In this formation, we separate between intra-group cooperation, which occurs among companies with equivalent efficiency scores, and inter-group cooperation, which is established between these efficiency-based groups. This dual-coalition framework presents a new perspective in energy economics, indicating that policy acceptance arises from consensus among performance-similar firms and system-wide alignment across the energy sector. This hierarchical coordination guarantees that adoption decisions consider local efficiency dynamics alongside broader collective interests, providing a more realistic and robust framework for cooperation in policy-sensitive energy networks.

1.5. Organization

The rest of this paper is organized as follows: Section 2 describes methods of the proposed study. Section 3 presents the results and discussions of the study, which includes the case study of Canada, comparative studies and policy implications. Section 4 concludes the study with additional remarks, limitations and suggestions for future research.

2. Methods

This section explores the methodological framework underpinning our analysis. Section 2.1 presents the CGCTR policy, outlining the relevant institutional and regulatory framework. Section 2.2 describes the development of a time-varying Cobb–Douglas production model aimed at forecasting future production levels in response to policy changes in the CGCTR. Section 2.3 presents a novel cooperative game-theoretic framework aimed at capturing firm-level strategic interactions and their alignment with the CGCTR policy. Section 2.4 introduces a dynamic model that connects social welfare outcomes to wage-based GDP, facilitating the assessment of macroeconomic implications. Section 2.5 outlines the dataset and describes the methodology applied to estimate missing carbon emission data for six prominent Canadian energy companies, thereby ensuring continuity and reliability in the analysis.

2.1. A novel carbon tax policy: CGCTR

This section introduces a novel carbon tax policy, CGCTR for an energy network consisting of the government and n number of energy companies. In this context, the government assumes a regulatory function by proposing a conditional carbon rebate: companies are required to allocate the whole of the tax relief funds towards enhancing their workforce and salaries within the work environment, as illustrated in Fig. 1. The proposed policy adjusts to annual variations in the priorities of government and energy companies, including carbon taxes, average salaries, workforce dynamics, and emission levels. The use of annually updated parameters facilitates a more realistic framework for the long-term analysis of energy transition and policy impacts. In this context, Tables 1 and 2 present the parameters of the government and energy companies, respectively concerning the proposed CGCTR policy for the jth year, where j represents a random year.

Table 1 illustrates four distinct rebate scenarios proposed by the government under CGCTR. Hence, we have

$$\hat{C}_{i,j}(k) = (1 - r_k)C_{i,j} \quad \text{for } k = 1, 2, 3, 4.$$

and the discount amount $r_k C_{i,j}$ is allocated for enhancing the workforce and salary of the ith company in the jth year under this policy.

In this setting, we assume that

$$0 < r_1 < r_2 < r_3 < r_4 < 1. \tag{1}$$

Table 1
jth year metrics of the government regarding four scenarios in CGCTR policy.

Parameters	Descriptions
r_1	Carbon tax reduction rate in the first scenario of CGCTR.
r_2	Carbon tax reduction rate in the second scenario of CGCTR.
r_3	Carbon tax reduction rate in the third scenario of CGCTR.
r_4	Carbon tax reduction rate in the fourth scenario of CGCTR.
$C_{i,j}$	Carbon tax of ith company without CGCTR.
$\hat{C}_{i,j}(k)$	Carbon tax of ith company in the kth scenario of CGCTR.

Table 2
jth year metrics of energy companies in relation to the CGCTR policy.

Parameters	Descriptions
$S_{i,j}$	Salary of each worker in the ith company without CGCTR.
$\hat{S}_{i,j}$	Salary of each worker in the ith company with CGCTR.
$W_{i,j}$	Total workforce of ith company without CGCTR.
$\hat{W}_{i,j}$	Total workforce of ith energy company with CGCTR.
$E_{i,j}$	Carbon emission amount of ith company.

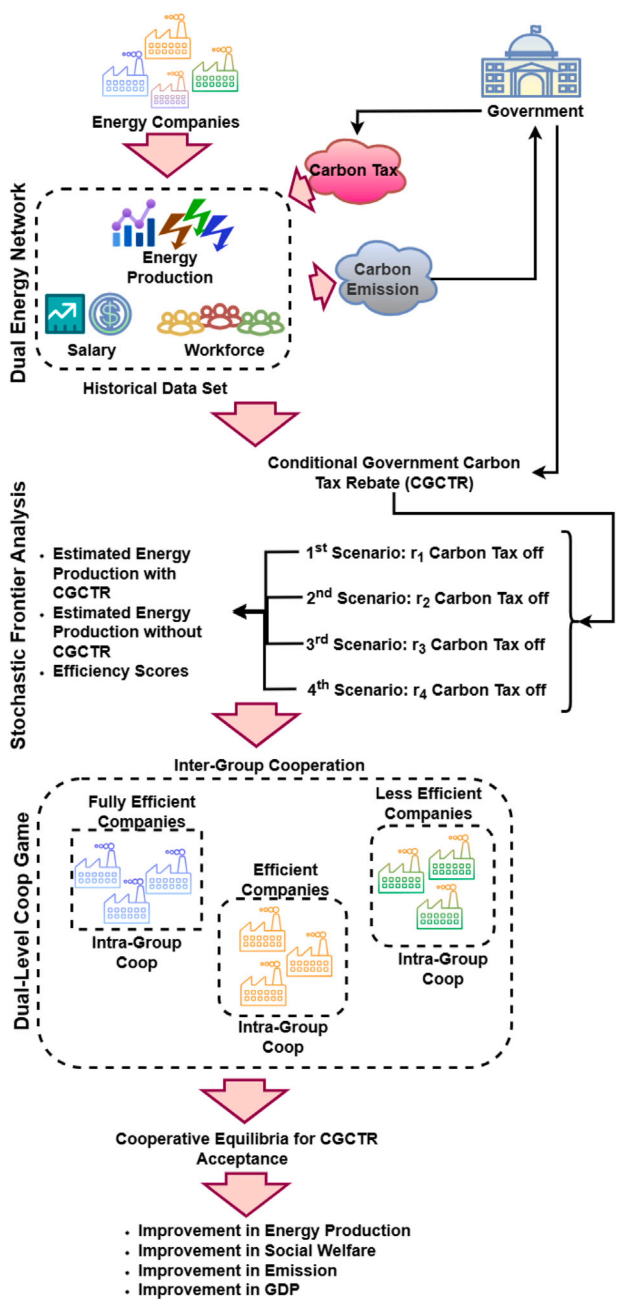

Fig. 1. CGCTR integration framework within the dual energy network.

The CGCTR policy is to be executed by allocating 80% of the carbon tax rebate to workforce capacity expansion and 20% for salary enhancement. This division corresponds with Canada's Sustainable Jobs framework, highlighting that in the shift to a low-carbon economy, the creation as well as preservation of jobs is more essential than simply raising wages [45]. Furthermore, employment data from Canada's energy sector highlight the importance of workforce stability, as sectoral employment continues to exhibit volatility despite relatively high salary levels. This suggests that job creation yields significant social and economic benefits [46]. Hence, the 80/20 allocation represents a policy-oriented, empirically supported, and economically sound strategy aimed at converting carbon tax savings into broad societal and economic benefits, rather than increasing profits for shareholders or growing capital. Based on this discussion, CGCTR allocates the rebate as follows: for $k \in \{1,\dots,4\}$, $\frac{4}{5}r_kC_{i,j}$ is designated for workforce improvement, while $\frac{1}{5}r_kC_{i,j}$ is allocated for salary enhancement of the ith company in the jth year. More precisely, we present the following arrangement for the values of $\hat{W}_{i,j}$ and $\hat{S}_{i,j}$:

$$\hat{W}_{i,j} = W_{i,j} + \frac{4}{5}\frac{r_kC_{i,j}}{S_{i,j}} \quad \text{and } \hat{S}_{i,j} = S_{i,j} + \frac{1}{5}\frac{r_kC_{i,j}}{W_{i,j}}.$$

Here, we check that

$$\hat{W}_{i,j}\hat{S}_{i,j} = W_{i,j}S_{i,j} + r_kC_{i,j} + \epsilon. \tag{2}$$

It is evident from (2) that companies must enhance their working environment by allocating not only $\frac{4}{5}r_kC_{i,j}$ to the workforce and $\frac{1}{5}r_kC_{i,j}$ to salaries, but also investing an amount ϵ in the working environment to fully leverage CGCTR policy. In this context, ϵ approaches zero for small r_k, while it increases for larger r_k values, indicating that small-scale companies with higher carbon emissions should allocate more investment under CGCTR.

2.2. A stochastic frontier function

This study uses a policy-aware stochastic Cobb–Douglas production function to analyze the relationship between inputs – total workforce and average salary of each company – while the total carbon tax for each company is characterized as a policy-induced productivity shift, with output defined as the energy production of that company. In our setting, we consider the following stochastic production function with time-varying exponents and stochastic inefficiency:

$$P_i(t) = W_i(t)^{\alpha_1(t)}S_i(t)^{\alpha_2(t)}\eta_i(t)^{\alpha_3(t)}e^{-u_i(t)}, \tag{3}$$

where $W_i(t)$, $S_i(t)$, $\eta_i(t)$ are step functions defined as

$$W_i(t) = W_{i,j}, \quad S_i(t) = S_{i,j}, \text{ and } \eta_i(t) = \lambda C_{i,j},$$

when $j \le t < j+1$, and $\lambda > 0$. For simplicity, we take $\lambda = 1$ in our setting. Here, $\alpha_k(t)$ are time-dependent exponents for $k \in \{1,2,3\}$, and $u_i(t)$ is a firm-based and time-specific inefficiency function, for $i \in \{1,\dots,n\}$. In this setting, to capture nonlinear growth or decline, we assume the coefficients $\alpha_1(t)$, $\alpha_2(t)$, and $\alpha_3(t)$ evolve with time according to:

$$\alpha_1(t) = a_0 + a_1\sqrt{t - t_0 + 1},$$
$$\alpha_2(t) = b_0 + b_1\sqrt{t - t_0 + 1},$$
$$\alpha_3(t) = c_0 + c_1\sqrt{t - t_0 + 1},$$

where $t_0 > 0$ is the initial starting year in the model. Moreover, inefficiency of ith company, $u_i(t)$ is modeled by using the firm-specific characteristics function $z_i(t)$

$$u_i(t) = \log\Big(1 + \exp(\tau z_i(t) + \gamma I_i(t))\Big), \tag{4}$$

where $\tau, \gamma \in [0,1]$ are defined within the interval $[0,1]$, representing the structural inefficiency and the environmental deviation, respectively, and

$$I_i(t) = \log\left(\frac{E_i(t)}{P_i(t)}\right) - \frac{1}{N}\sum_{j=1}^{N}\log\left(\frac{E_j(t)}{P_j(t)}\right). \tag{5}$$

Here, $I_i(t)$ represents the centered log emission intensity, which measures the relative environmental inefficiency of the ith company in terms of emissions per production unit against the industry average. This metric identifies firms that either outperform or underperform in emissions efficiency, measuring the degree of deviation from the sector's average carbon productivity.

Our objective is to minimize the average squared error between the actual and predicted log-productions from initial starting year $t = t_0$ to final year $t = t_f$:

$$\min_{\theta}\Big[\sum_{t=t_0}^{t_f}\frac{1}{N}\sum_{i=1}^{N}\Big(\log P_i(t) - \log \widehat{P}_i(t)\Big)^2\Big], \tag{6}$$

where $\theta = \{a_0, a_1, b_0, b_1, b_2, c_0, c_1, \mathbf{z}\}$ includes all global and firm-specific parameters and the predicted production given as

$$\log \widehat{P}_i(t) = \alpha_1(t)\log W_i(t) + \alpha_2(t)\log S_i(t) + \alpha_3(t)\log \eta_i(t) - u_i(t), \tag{7}$$

where functions $W_i(t)$, $S_i(t)$, and $\eta_i(t)$ are defined as step functions, with their values specified in the dataset spanning from year t_0 to year t_f.

To estimate the coefficients of the production function, a dataset is utilized that spans from the initial year t_0 to the final year t_f, including data on production, workforce, salary, and emissions. The nonlinear quasi-Newton optimization algorithm L-BFGS-B [47] is employed, as it is particularly effective for high-dimensional, smooth, and bounded problems, thus serving as an efficient and reliable method for calibrating production models under environmental and economic constraints.

To evaluate the comparative performance of each company in terms of production and emissions, as well as the inefficiency factor, we introduce a dynamic efficiency score that incorporates not only the inefficiency terms but also the marginal contribution ratios of emissions and production levels for the ith company during the interval $j \le t < j+1$ as

$$\rho_i(t) = \exp\left(-\phi_0 u_i(t) + \phi_1\frac{P_i(t) - \bar{P}(t)}{\bar{P}(t)} - \phi_2\frac{E_{i,j} - \bar{E}_j}{\bar{E}_j}\right), \tag{8}$$

where

$$\bar{P}(t) = \frac{1}{n}\sum_{i=1}^{n}P_i(t), \quad \text{and} \quad \bar{E}_j = \frac{1}{n}\sum_{i=1}^{n}E_{i,j},$$

are means corresponding to production and emission, respectively. In addition, weights $\phi_0, \phi_1, \phi_2 \ge 0$, represent contributions of the inefficiency term, production, and emissions to the score, respectively, and satisfy the equation $\phi_0 + \phi_1 + \phi_2 = 1$.

In our setting, we define fully efficient, efficient and less efficient companies at jth year according to (8) as follows:

$$i\text{th Energy company is}\begin{cases}\text{Fully efficient}, & \xi_f \le \rho_i(j),\\ \text{Efficient}, & \xi_e \le \rho_i(j) < \xi_f,\\ \text{Less efficient}, & \rho_i(j) < \xi_e,\end{cases} \tag{9}$$

for some $0 < \xi_e, \xi_f$.

2.3. A dual cooperative game

This section presents a new dual cooperative game, outlining its rules to systematically assess collaborative behavior among energy companies in the context of conditional government incentives. This model combines SFA outputs with coalition-based decision-making to identify the optimal acceptance of CGCTR within the energy network, as depicted in Fig. 1. The game examines intra-group and inter-group cooperation among companies, classified into three efficiency-based clusters: G_1, a group of fully efficient companies; G_2, a group of efficient companies; and G_3, a group of less efficient companies, where $G_i \cap G_j = \emptyset$ for $i \ne j \in \{1,2,3\}$. Now, we present the following playability conditions for the proposed game:

1. Cooperation initially occurs within each group G_i where its members $g_{i,j}$ collaborate to adopt CGCTR or reject it, where $j = \{1,\dots,\alpha_i\}$, with $|G_i| = \alpha_i$.
2. In a cooperative context, members in each group G_i collectively decide to either accept or reject CGCTR, rather than maximizing their individual interests under different coalitions.
3. The probability of the jth member in the ith group accepting CGCTR is represented as $p_{i,j}$, whereas the probability of rejecting CGCTR is $1 - p_{i,j}$.
4. The probability of a group accepting CGCTR is the average of the probabilities of individual group members accepting CGCTR.
5. The payoff for the jth company within G_i, denoted as $\hat{P}_{ij}$ for accepting CGCTR (or P_{ij} for rejecting CGCTR), is determined by multiplying the efficiency score ρ_j by the overall work power, defined as the product of the workforce and salary, and subsequently subtracting the total carbon tax associated with CGCTR (or without CGCTR).
6. The payoff for the ith group under CGCTR (or without CGCTR), denoted as P_{iY} (or P_{iN}), is determined by summing the payoffs of all its members.

Fig. 2 illustrates the complete flowchart of the dual cooperative game. To achieve optimal cooperative decision-making for the acceptance of CGCTR, we optimize the total payoff defined as the sum of expected payoffs across all groups, subject to the constraints $0 \le p_{i,j} \le 1$.

Now, we formulate the dual cooperative game payoffs of each group player and all groups according to the game rules. In this regard, we construct the possible costs associated with each player's decision to accept or reject CGCTR based on parameters presented in Tables 1 and 2. For the sake of simplicity, we designate the year as t throughout the game.

For intra-group collaboration, the jth member $g_{i,j}$ in G_i receives

$$\hat{P}_{ij} = \rho_j(t)p_{i,j}\Big(\hat{W}_{j,t}\hat{S}_{j,t} - \hat{C}_{j,t}\Big), \quad \text{if it says YES to CGCTR,}$$

or

$$P_{ij} = \rho_j(t)(1 - p_{i,j})\Big(W_{j,t}S_{j,t} - C_{j,t}\Big), \quad \text{if it says NO to CGCTR.}$$

For inter-group cooperation, G_i receives

$$P_{iY} = \sum_{j=1}^{\alpha_i}\hat{P}_{ij}, \quad \text{if it says YES to CGCTR,}$$

or

$$P_{iN} = \sum_{j=1}^{\alpha_i}P_{ij}, \quad \text{if it says NO to CGCTR.}$$

Then, expected inter-group cooperation payoff of G_i becomes

$$P_{i,exp} = P_{iY}\frac{1}{\alpha_s}\sum_{j=1}^{\alpha_s}p_{i,j}\frac{1}{\alpha_m}\sum_{j=1}^{\alpha_m}p_{i,j} + P_{iN}\Big(1 - \frac{1}{\alpha_s}\sum_{j=1}^{\alpha_s}p_{i,j}\Big)\Big(1 - \frac{1}{\alpha_m}\sum_{j=1}^{\alpha_m}p_{i,j}\Big),$$

where $s \ne m \in \{1,2,3\}/\{i\}$. Hence, we formulate the following maximization problem:

$$\max_{0\le p_{i,j}\le 1}\Big[P_{1,exp} + P_{2,exp} + P_{3,exp}\Big]. \tag{10}$$

Here, we employ particle swarm optimization (PSO) [48] to maximize the objective function (10). This method is recognized as a robust

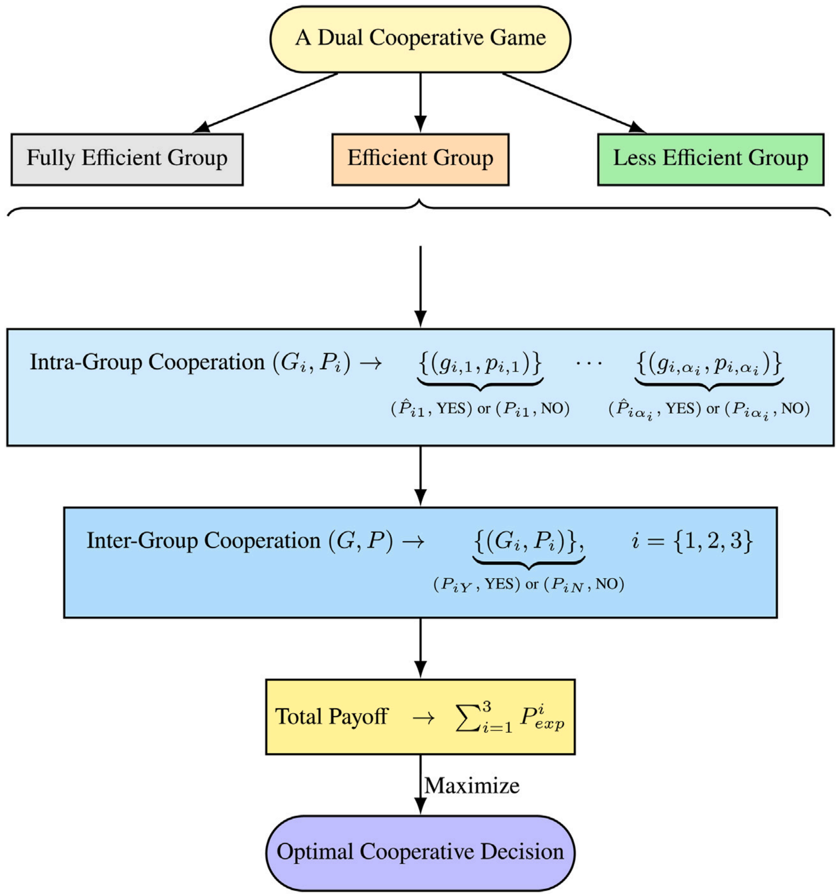

Fig. 2. Flowchart of the dual cooperative game with group structure and cooperation layers.

meta-heuristic for estimating the optimal responses of all group members, thereby facilitating cooperative decision-making regarding the acceptance of CGCTR within the energy network.

2.4. Social welfare

In this section, we model a social welfare dynamics H that accounts for wage-based Gross Domestic Product (GDP), workforce, and energy production output using the following log-linear form:

$$H = \psi_0 \log(D) + \psi_1 \log(W) + \psi_2 \log(P), \tag{11}$$

where D is wage-based GDP in the country, W represents total number of employed individuals and P is energy production in the company, and $\psi_0, \psi_1, \psi_2 \in [0, 1]$ are weights with $\psi_0 + \psi_1 + \psi_2 = 1$.

The wage-based GDP in the region is calculated by multiplying the aggregate wage income of the population by the total workforce within the region. This study examines the impact of CGCTR on wage-based GDP within the energy network. Let W_0 and S_0 denote the baseline values for workforce and average salary, while W_1 and S_1 represent the updated values for workforce and average salary under CGCTR in the company, respectively. Now, we define the gain in wage-based GDP as the following ratio

$$\Delta D = \frac{W_1 S_1 - W_0 S_0}{D}. \tag{12}$$

This section explores the procedure for assessing the variation in social welfare dynamics, as defined in (11), within the region of interest. Let D_0, P_0 represent baseline values for GDP and energy production, respectively, with H_0 denoting the initial social welfare value. On the other hand, D_1, P_1 are the updated values for GDP and production under CGCTR, corresponding to the social welfare value H_1. The gain in social welfare is calculated as follows:

$$\Delta H = H_1 - H_0 = \psi_0 \log\left(\frac{D_1}{D_0}\right) + \psi_1 \log\left(\frac{W_1}{W_0}\right) + \psi_2 \log\left(\frac{P_1}{P_0}\right). \tag{13}$$

In (13), the first term reflects economic gains from wage-based GDP growth, the second term addresses labor market inclusion, and the third term assesses increased energy output.

2.5. Data description

This study examines a dataset derived from six leading Canadian energy companies, chosen for their contributions to national production, employment, and emissions levels: Canadian Natural Resources (CNQ.TO), Cenovus Energy (CVE.TO), Baytex Energy (BTE.TO), Tourmaline Oil (TOU.TO), Peyto Exploration (PEY.TO), and Paramount Resources (POU.TO). The dataset carefully assembled from publicly accessible sources and corporate energy disclosures, focusing primarily on annual financial and sustainability reports.

To maintain model effectiveness and ensure fair evaluation of the CGCTR policy, we assume that workforce size and average annual salary remain constant from 2024 to 2025. This decision is supported by labor market data indicating overall employment stability in Canada's energy sector, with minimal fluctuations in hiring and layoff rates during this period [46]. Due to Canada's rigorous emissions reporting standards, the confirmed emission data in the 2025 National Inventory Report is limited to 2023, with the values for 2024 and 2025 awaiting verification and consolidation [49]. In this context, machine learning methods including ridge regression with order one [50] and

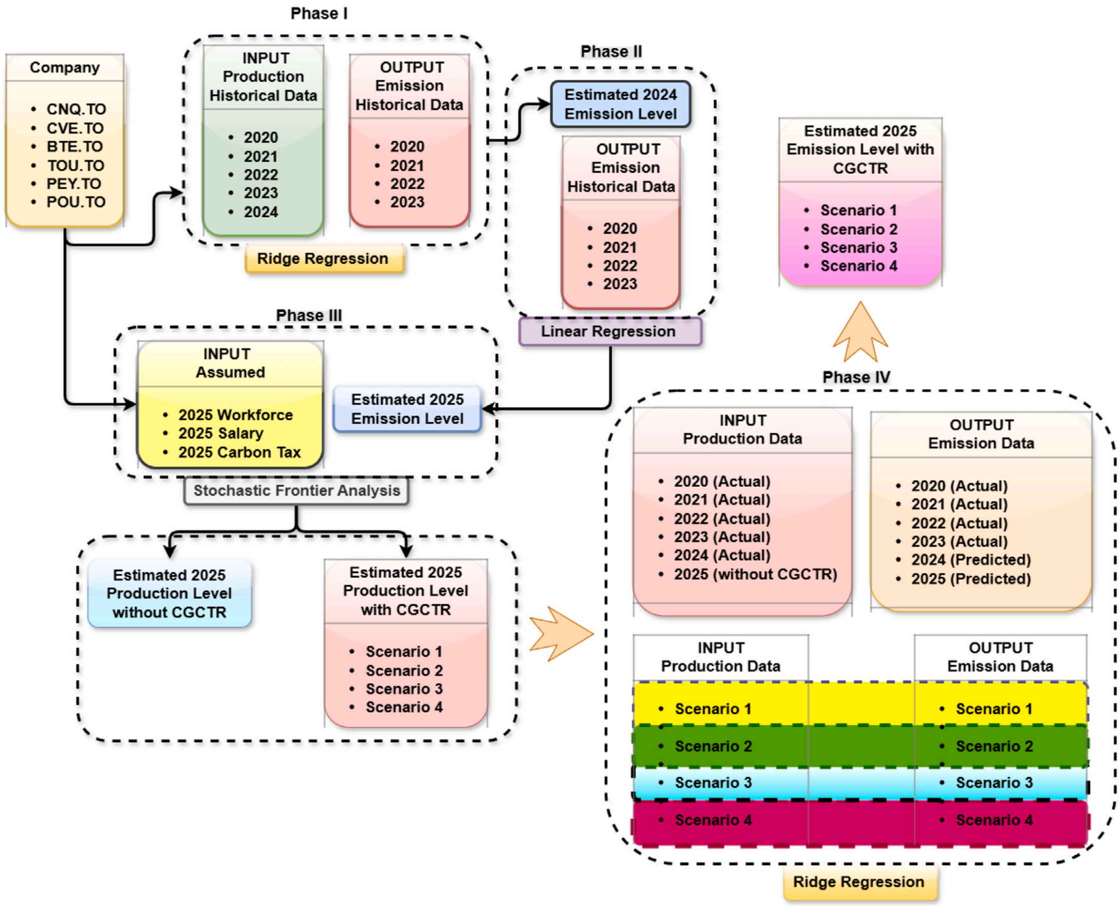

Fig. 3. Emission estimation by using ridge and linear regressions under the CGCTR.

linear regression [51] are used to approximate the missing data for 2024 and 2025.

Fig. 3 presents a structured flowchart outlining the multi-phase methodology used to estimate firm-level carbon emissions for 2024 and 2025, as well as projected emissions under the CGCTR policy scenarios for 2025.

Phase I involves the collection of actual emissions data from 2020 to 2023 and corresponding production levels from 2020 to 2024. Ridge regression is then used to project 2024 emissions based on these historical patterns.

Phase II utilizes linear regression on the emissions data from 2020 to 2023, augmented by the projected 2024 values from Phase I, to predict baseline emissions for 2025 in the absence of policy action.

Phase III involves simulating the Cobb–Douglas production function five times using 2025 inputs, which include workforce, average wage, and emissions, to project production levels both without CGCTR and under four policy scenarios defined by increasing rebate rates with CGCTR.

Phase IV models 2025 emissions for each CGCTR scenario with a recursive ridge regression approach. The model begins with six historical input–output pairings to assess emissions under Scenario 1. The predicted output is then incorporated into the dataset to iteratively expand the training set—moving from 7 to 8 and then 9 data points—to estimate emissions for Scenarios 2, 3, and 4, respectively.

This cumulative modeling method guarantees uniform learning and enhanced predictive precision at every phase. The approach produces detailed emission estimates for 2024, baseline 2025, and all four 2025 CGCTR scenarios, establishing a solid foundation for policy assessment and environmental-economic forecasting.

3. Results and discussions

3.1. Canada case

This case study examines Canada's major energy companies and the federal government as stakeholders in the energy network. This analysis utilizes a historical dataset encompassing production levels, carbon emissions, carbon tax amounts, workforce size, and average worker salaries from 2020 to 2024. In addition to data description in Section 2.5, Table A.1, Table A.2, Table A.3, Table A.4, Table A.5 present the historical data for the six companies, CNQ.TO, CVE.TO, BTE.TO, TOU.TO, PEY.TO, and POU.TO from 2020 to 2024, which is utilized in the Cobb–Douglas production modeling to estimate the production function (3). In this setting, the initial year of this study is $t_0 = 2020$, and the final year is $t_f = 2024$. The carbon tax in Canada commenced at 30 CAD per tonne in 2020, subsequently increasing to 40 CAD in 2021, 50 CAD in 2022, 65 CAD in 2023, and reaching 80 CAD per tonne by April 1, 2024, with a projected rise to 95 CAD by 2025 [52].

To ensure the reliability and practical relevance of the proposed production model, we conducted a sensitivity analysis on the coefficients (τ, γ) associated with inefficiency terms. This analysis aims to evaluate how variations in these parameters affect the model's capacity to yield meaningful production gains. A heat map, presented in Fig. B.1, visualizes the relationship between both structural inefficiency (τ) and environmental deviation (γ) values and corresponding production outcomes, including relative increases or decreases compared to the 2024 baseline.

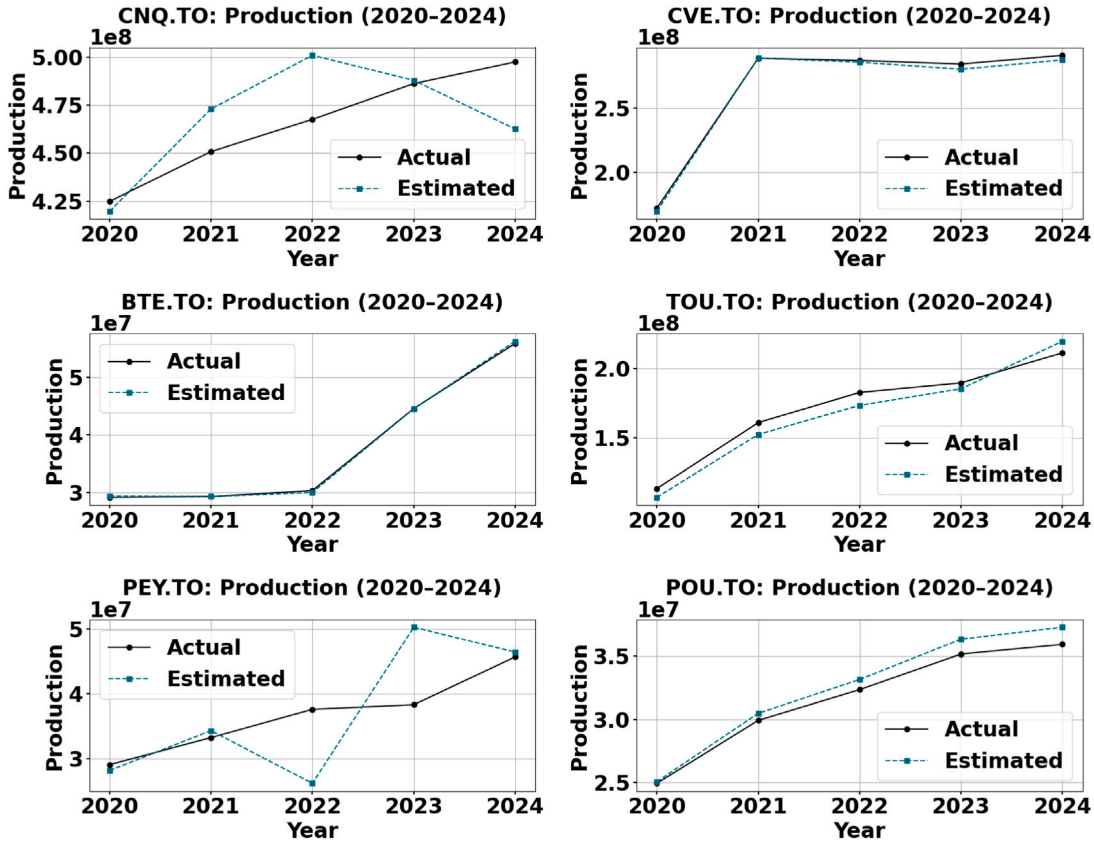

Fig. 4. Fitting the estimated production function to historical production data when $\tau = 1$ and $\gamma = 0.88$.

Sensitivity analysis indicates that high-emission, small-scale firms like PEY.TO demonstrate significant sensitivity to lower values of τ and γ. For example, with $\tau = 0.14$ and $\gamma = 0.22$, PEY.TO achieves a 35.45% increase in production. This indicates that soft penalization allows emission-intensive firms to attain considerable output growth, demonstrating their adaptability to relaxed environmental regulations. Furthermore, CVE.TO, despite being emission-intensive, demonstrates the gain of 5.98% under $\tau = 0.34$ and $\gamma = 1$. This indicates that its structural inefficiency and environmental penalization enhances its growth potential. Furthermore, owing to their low emission intensity, CNQ.TO and POU.TO demonstrate operational efficiency in the context of high environmental penalization (i.e., when $\gamma = 1$). This stability underscores their resilience to inefficiency penalties and confirms their commitment to environmentally efficient practices. Additionally, BTE.TO exhibits non-linear sensitivity and achieves the better results when the environmental deviation is in medium level ($\gamma = 0.44$) and the structural inefficiency is at its lowest ($\tau = 0.14$), recording −12.36%. Finally, TOU.TO shows production increase peaks of 29.59% at $\tau = 0.14$, with the highest environmental deviation of $\gamma = 1$, yet it also records severe drops of −25.00% at ($\tau = 0.74, \gamma = 0.22$). This dual behavior reflects a structurally efficient yet environmentally sensitive profile.

Based on the overall performance across firms, the parameter set $\tau = 1$, $\gamma = 0.88$ emerges as the most balanced choice—producing stable and equitable production gains while achieving a mean estimation accuracy of 95.6% when applied to historical production data, as shown in Fig. 4.

In this simulation, we estimate the production function exponents and inefficiencies as follows:

$$\alpha_1(t) = 1.2302975 - 0.2775257\sqrt{t - 2019},$$

$$\alpha_2(t) = 0.9826153 + 0.1582611\sqrt{t - 2019},$$

$$\alpha_3(t) = -0.0000001 - 0.0000793\sqrt{t - 2019},$$

and

$$u_1(t) = 1.0001 - 0.2106(t - 2019), \quad u_2(t) = 2.1812 - 0.1378(t - 2019),$$

$$u_3(t) = 1.6344 + 0.1401(t - 2019), \quad u_4(t) = 0.7068 + 0.0583(t - 2019),$$

$$u_5(t) = -0.2667 + 0.1551(t - 2019), \quad u_6(t) = 1.5721 + 0.0105(t - 2019),$$

where exponent and inefficiency values are illustrated in detail in Fig. 5.

Following a policy-sensitive Cobb–Douglas model, Fig. 5 shows firm-level micro-production patterns. Here, the contribution of workforce input, $\alpha_1(t)$, decreases over time, indicating labor saturation or limited employment growth. The increased trend in salary coefficient, $\alpha_2(t)$, suggests that wage-related inputs, such as labor quality or technology-enabled productivity, are more important in driving firm output. Importantly, the carbon tax parameter $\alpha_3(t)$ becomes progressively negative, indicating its growing role as a regulatory restriction that reduces production, especially for emission-intensive companies.

Emission intensity, defined as the ratio of total carbon emissions to production output, serves as a key indicator of both environmental efficiency and the effectiveness of policy interventions. As illustrated in Fig. 6, all firms demonstrate reductions in emission intensity under the CGCTR, with high-emission and high-output firms like CVE.TO exhibiting the most elastic response, indicating rapid declines in emission intensity as rebates increase—suggesting substantial marginal benefits from policy investments. Lower-intensity firms like TOU.TO, POU.TO, PEY.TO demonstrate slower responses to the policy while still achieving modest benefits. Alongside individual firm trajectories, Fig. 6 presents the average emission intensity for all companies, offering a comprehensive view of sector-wide environmental performance under each scenario of the CGCTR. A numerical comparison of emission intensity

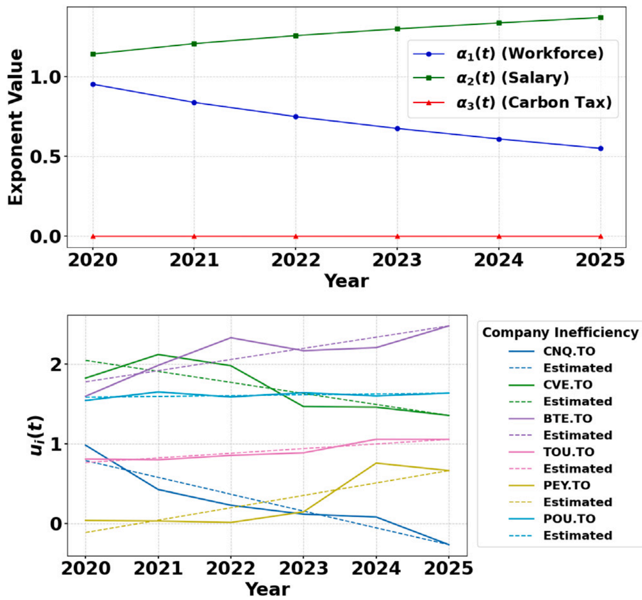

Fig. 5. Production exponent functions and estimated inefficiencies of each energy company from 2020 to 2025.

values, comparing model projections with historical data, is provided in Table E.1.

Fig. 7 demonstrates that the implementation of the CGCTR policy leads to higher production levels among all firms relative to the baseline projections for 2025. The simulation assesses four tax rebate scenarios: $r_1 = 0.05$ (Scenario 1), $r_2 = 0.1$ (Scenario 2), $r_3 = 0.2$ (Scenario 3), and $r_4 = 0.5$ (Scenario 4), demonstrating varied effects among firms. PEY.TO, a smaller-scale operator with relatively higher emission intensity, exhibits the most significant production gains, achieving increases of 16.3%, 33.2%, 68.9%, and 193.5% under the respective rebate scenarios. In addition, CNQ.TO, a larger firm with a more carbon-efficient production base and greater workforce capacity, shows high increases of 15%, 30.5%, 63.1%, and 175%. In addition, Fig. C.1 presents a detailed comparison of projected production levels for 2025 across all companies, comparing outcomes with and without the CGCTR policy under four rebate scenarios, all benchmarked against 2024 output data. Additional visualizations based on production changes relative to the 2024 true baseline, with and without the CGCTR policy, are presented in Appendix C (see Fig. C.1).

The numerical results indicate that the CGCTR policy yields significant increases in workforce size and average annual salaries among participating firms, as illustrated in Fig. 8. In this regard, CVE.TO and CNQ.TO demonstrate the most significant workforce growth among all other firms, doubling its baseline level in the highest rebate scenario. The outcome is largely influenced by both substantial carbon tax obligations; under CGCTR, rising rebate rates facilitate enhanced reinvestment in labor and compensation. A comparable trend is noted for BTE.TO, the second most emission-intensive company, which similarly observes substantial increases in workforce and wage levels.

In our game-theoretic model, firms are categorized according to a composite efficiency score that indicates their operational and environmental performance. We assign weighted contributions of 75%, 15%, and 10% to the inefficiency term, energy production level, and carbon emissions, respectively. This weighting scheme emphasizes internal inefficiencies as the main factor in firm classification, while also considering production scale and environmental impact, thus providing a balanced and policy-relevant evaluation of firm performance. In this regard, we let $\phi_0 = 0.75$, $\phi_1 = 0.15$ and $\phi_2 = 0.1$ in the ρ function in (8). In the end, we obtain the following efficiency scores for each company illustrated in Fig. 9.

In this study, we assume that $\xi_f = 0.8$ and $\xi_e = 0.4$ in efficiency score table (9). According to the score table, CNQ.TO is the sole member that belongs to the fully efficient group. TOU.TO and PEY.TO are identified as members of the efficient group, while CVE.TO, BTE.TO, and POU.TO are categorized in the less efficient group. Hence, we define three groups in the dual cooperative game as $G_1 = \{\text{CNQ.TO}\}$, $G_2 = \{\text{TOU.TO, PEY.TO}\}$ and $G_3 = \{\text{CVE.TO, BTE.TO, POU.TO}\}$. For simplicity, we present a comprehensive construction of firm-level payoffs, along with the intra-group and inter-group cooperation structures, illustrated in the game flow diagram in Fig. D.1. This visual framework explores the strategic interactions among firms within the CGCTR policy, demonstrating the formation of collective decisions and the impact of cooperative dynamics on economic outcomes and environmental performance.

Fig. 10 illustrates that all firms choose to implement the proposed CGCTR policy in the final scenario, in which carbon tax rebates of 50% are reinvested directly into workforce expansion and employee salaries. In the first two scenarios, where rebates are 5%–10%, collective policy acceptance does not occur: the sub-coalition of TOU.TO, CVE.TO, and PEY.TO accepts the policy, whereas CNQ.TO, BTE.TO, and POU.TO reject it.

To evaluate social welfare under CGCTR, we consider the latest wage-based GDP for Canada in 2025. According to Statistics Canada [53], the average weekly earnings in February 2025 were 1298.22 CAD, representing a 5.4% increase over the same month in the previous year. This implies an average annual wage of CAD 67507 per worker in Canada, denoted, w_a.

Based on Statistics Canada [54], the employment rate, represented as e, in April 2025 is estimated as $e = 0.615$, and the working-age population (aged 15 and older), denoted as P_w, is estimated as $P_w \approx 33,000,000$. The total employed labor force, L_e, is then evaluated as

$$L_e = P_w \times e,$$

which gives $L_e \approx 20,295,000$. Finally, the wage-based GDP of Canada in 2025, denoted as D_0, is calculated as

$$D_0 = L_e \times w_a,$$

yielding $D_0 \approx 1.37$ trillion CAD.

Fig. 11 demonstrates the positive impact of the CGCTR policy on social welfare and wage-based GDP under four different rebate scenarios. The findings indicate a significant correlation between rising carbon tax rebates and improved social welfare outcomes, beginning with a 0.0632 increase at the 5% rebate level and resulting in a notable 0.4644 gain at the 50% rebate level. The policy's impact on wage-based GDP growth is relatively modest yet positive, with incremental increases ranging from 0.00017% at the 5% rebate to 0.00215% at the maximum rebate rate. The outcomes, resulting from the economic contributions of six major firms, highlight the dual potential of effectively designed carbon rebate mechanisms to promote environmental sustainability and macroeconomic advantages, facilitating a fair and productive transition in Canada's energy sector.

3.2. Comparative analysis

CGCTR policy diverges from traditional carbon tax systems by reallocating tax revenues to support employment and wage growth within the energy network. More precisely, CGCTR supports economic sustainability by reinvesting carbon tax rebates directly into the energy workforce, enhancing employment levels and wage structures. Unlike the revenue-neutral carbon tax analyzed by Yamazaki [55], which emphasized the balance between emissions reduction and labor market neutrality via tax shifting in British Columbia, Canada, CGCTR presents

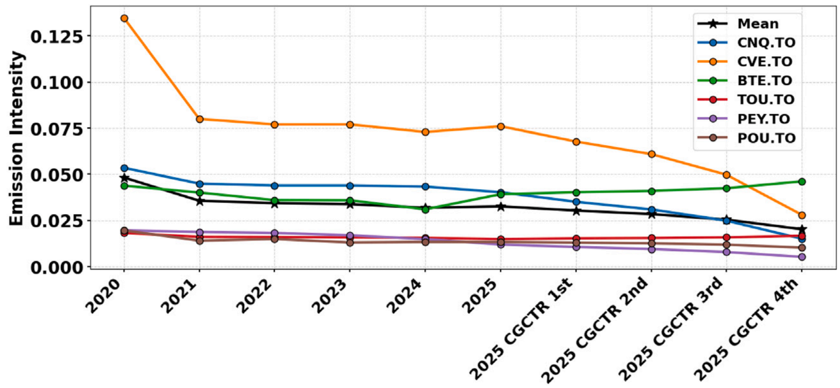

Fig. 6. Each company's emission intensity based on 2020–2023 historical emission data, 2024–2025 predicted emission data, and 2025 CGCTR emission data.

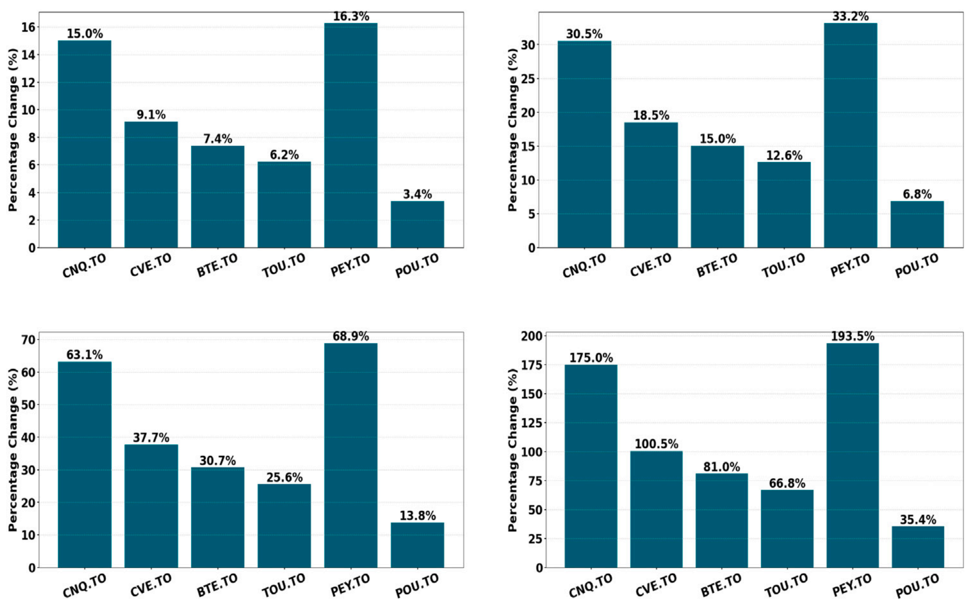

Fig. 7. Estimated 2025 production increase under CGCTR, according to Scenario 1, Scenario 2, Scenario 3, and Scenario 4, respectively.

a conditional and bi-directional carbon pricing framework that promotes long-term economic sustainability and encourages collaborative stakeholder engagement within the energy network.

The sustainability goal of CGCTR is supported by a study conducted by Rodrigues et al. [56] demonstrated that fare-free public transport policies in Brazil resulted in increased employment and decreased emissions, indicating that policies integrating economic and environmental objectives can effectively promote long-term clean energy adoption. Another advancement of CGCTR is its facilitation of cooperative energy investment strategies. The carbon tax rebates under CGCTR are directly linked to collaborative infrastructure and labor force commitments among energy companies, thereby integrating cooperation into the financial framework. This stands in contrast to the emphasis on decentralized governance proposed by Boucher and Pigeon [12], whose coordination model significantly depends on intergovernmental alignment, usually excluding private sector stakeholders during implementation. In contrast, CGCTR promotes inclusive participation, allowing both public and private entities to co-invest in the energy transition.

Methodologically, CGCTR integrates SFA and PSO to guide optimal stakeholder behavior under the policy's cooperative architecture. While SFA and PSO have been independently employed in energy policy research [11,57], CGCTR advances the field by integrating these methodologies within a unified policy framework. This integration facilitates dynamic, emission-based allocation of tax rebates, setting a new precedent in policy-led optimization of energy systems. Moreover, studies by Feng et al. [58] and Rotar [59] highlight the significance of carbon pricing in facilitating environmental-economic transitions across various sectors; however, they fail to address the alignment with the labor market. CGCTR addresses this gap by incorporating labor market strategies into its fiscal framework, thereby enhancing the effectiveness of carbon pricing mechanisms in the region.

3.3. Policy implications

This part offers policy recommendations for governments and energy companies aiming to implement the CGCTR in their energy networks, based on empirical evidence derived from a comprehensive case study of Canada.

To start with, CGCTR promotes a collaborative energy network by encouraging partnerships among companies through workforce growth and enhanced wages. Simulation results indicate that increased carbon

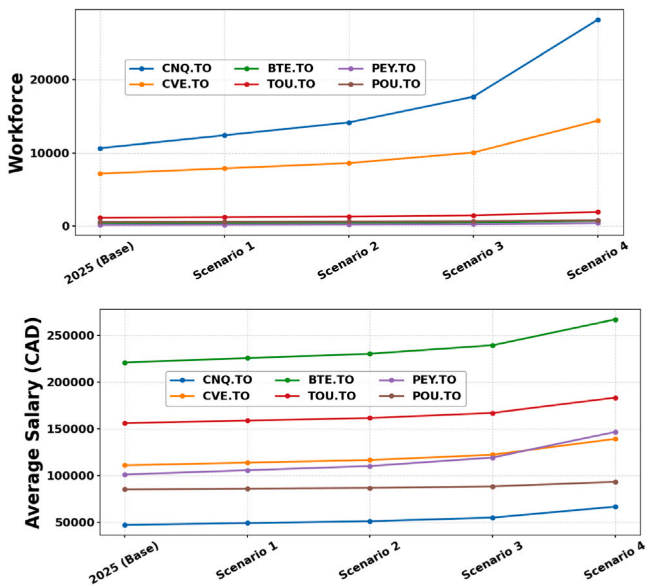

Fig. 8. Assessment of workforce improvements and salary adjustments across four distinct scenarios against the projected 2025 data (without CGCTR).

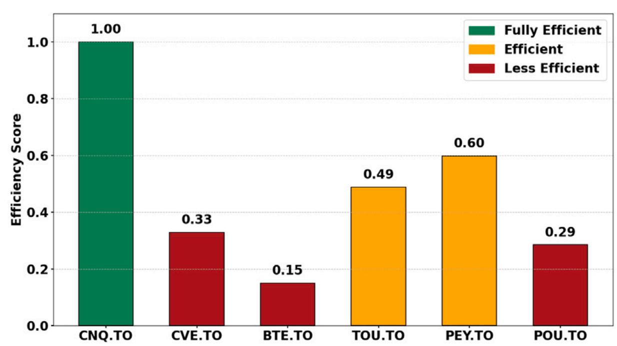

Fig. 9. Efficiency scores of energy companies according to (8) in 2025.

tax rebates under CGCTR improve coalition formation, even among firms experiencing higher emission taxes, aligning with evidence that carbon pricing promotes cooperative strategic behavior [35].

From an economic perspective, CGCTR reallocates carbon tax revenues towards workforce development, thereby improving labor productivity and operational capacity. This reinvestment establishes a feedback loop in which increased emissions initially produce greater tax revenue, which in turn supports additional innovation and human capital development, allowing firms to invest in clean technologies with reduced financial risk [60]. The framework promotes inclusive labor market growth and sustainable energy production, offering a dynamic taxation model that aligns economic resilience with long-term environmental goals [12].

The augmented Cobb–Douglas specification is consistent with how empirical research captures policy–productivity channels. Firm-level wage variation has been used to proxy labor quality and explain productivity gaps, validating wages as a distinct input [61]. Evidence from British Columbia manufacturing plants indicates that carbon taxation operates through efficiency rather than costs, supporting our treatment of policy in the inefficiency term [62]. Cross-country analyses highlight that carbon taxes reshape productivity via reallocation and innovation responses [63], while geographic variation in regulation has been linked to heterogeneous productivity outcomes [64]. Further, environmental taxation in China has been shown to measurably alter total factor productivity [65]. Taken together, these findings reinforce our augmentation: wages are modeled as a quality-sensitive labor input, and environmental policy is incorporated as an efficiency-shifting driver within the SFA framework.

Moreover, the principles of CGCTR, while developed within the Canadian context, are applicable to various regions with differing energy sectors and tax policies. For instance, Switzerland returns two-thirds of the tax revenue from the carbon levy to workers [66]. This approach aligns well with CGCTR's emphasis on reinvesting in the workforce, which aids in job creation and wage increases in the energy sector while also contributing to emission reduction objectives. Another example is Sweden, where emissions were reduced by nearly 29% from 2010 to 2022, and carbon tax revenues have consistently represented about 1.6% of GDP [67]. In this context, the implementation of CGCTR could further enhance progress by reinvesting carbon tax rebates into labor and innovation, thus aligning economic growth with sustainability.

Finally, the effectiveness of carbon tax regimes is enhanced when fiscal tools are tailored to local economic and institutional contexts, a strength that CGCTR provides through its revenue recycling and stakeholder-centered design [10].

4. Conclusions

The implementation of CGCTR stands for a crucial advancement in Canada's shift towards a sustainable and inclusive energy economy. CGCTR reallocates carbon tax revenues towards workforce development and wage enhancement, ultimately facilitating investments in clean energy. This approach establishes a dual-purpose mechanism that promotes economic growth alongside environmental stewardship. In contrast to conventional carbon pricing models, CGCTR designates firms, especially those engaging in sector-wide collaboration, as direct recipients of carbon tax rebates attributable to their hiring of new employees. This strategic shift fosters a sustainable production environment within the context of the government's low-tax policy and encourages inter-firm collaboration. Hence, the adoption of CGCTR by firms highlights its practical viability and its function in long-term investment decisions. In the end, CGCTR enhances regional economic resilience, contributing to an increase in wage-based GDP and advancing a broader social welfare agenda.

Despite these promising results, specific limitations remain. First, the model's dependence on cooperative behavior requires a fundamental level of trust and transparency among firms, which may not consistently exist in highly competitive or volatile markets. Second, the possibility for firms to alter reported emissions in order to maximize government rebates. To mitigate the risk of manipulation, policy design must incorporate safeguards such as third-party verification, carbon account monitoring and strict penalties, including exclusion from the CGCTR program. Third, CGCTR framework does not properly address regional disparities in labor market conditions and infrastructure readiness, potentially impacting equitable policy outcomes. Finally, a further limitation of the CGCTR framework is its dependence on static assumptions throughout the transition period (2024–2025), notably the stability of workforce size and salaries. This simplification enhances tractability but may neglect dynamic market responses. Moreover, the incorporation of machine learning regression to impute missing values may introduce estimation bias and risks.

Future research may expand CGCTR framework beyond Canada to evaluate its transferability and scalability in various national or regional energy networks. The application of CGCTR in countries with diverse energy mixes, regulatory frameworks, and carbon pricing mechanisms will yield important insights regarding its adaptability and

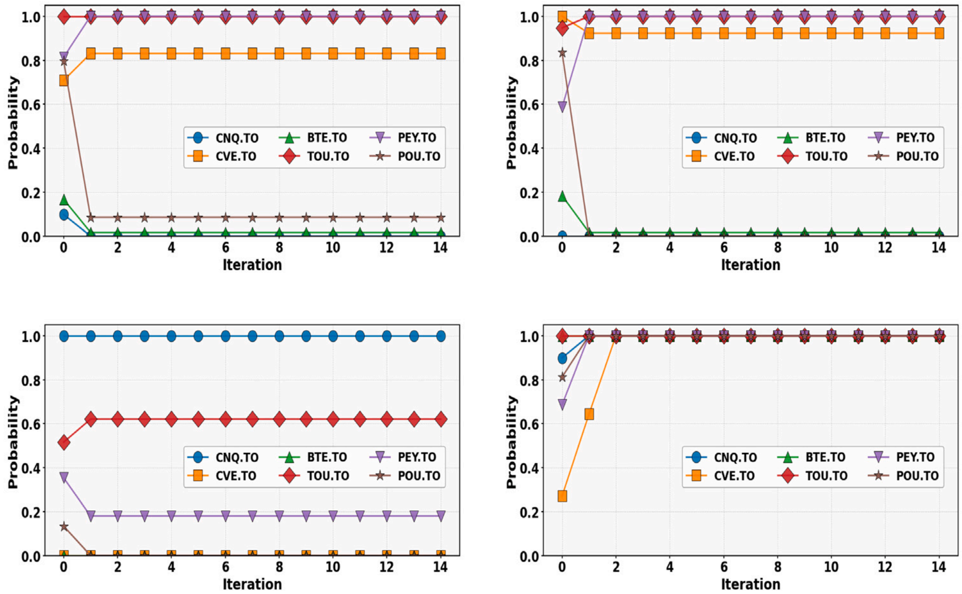

Fig. 10. Simulations of PSO for collective acceptance probabilities of companies regarding CGCTR in Scenario 1, Scenario 2, Scenario 3, and Scenario 4, respectively.

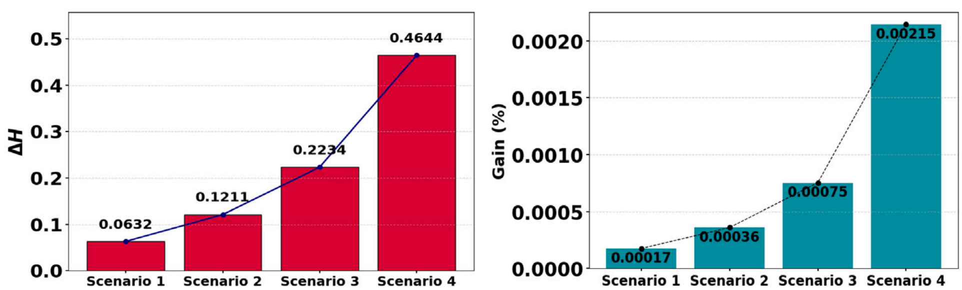

Fig. 11. CGCTR gains in social welfare and wage-based GDP across four distinct scenarios.

global significance. Furthermore, a significant methodological improvement would entail the inclusion of research and development (R&D) as a defined input in the SFA production function. Incorporating R&D would enable the extended CGCTR model to account for innovation-driven productivity improvements in addition to conventional factors such as carbon tax intensity, workforce size, and salary structures.

CRediT authorship contribution statement

Ali Hamidoğlu: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yuhao Wang:** Writing – review & editing, Writing – original draft, Software, Resources, Data curation. **Hao Wang:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Funding acquisition, Conceptualization.

Statement of use of Artificial Intelligence

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Hao Wang reports financial support was provided by Natural Sciences and Engineering Research Council of Canada. Ali Hamidoğlu reports financial support was provided by Natural Sciences and Engineering Research Council of Canada. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Case study data

See Tables A.1–A.5.

Table A.1
Energy production (P), carbon emission (CE), workforce (W) and average salary (S) of upstream energy production companies (2020).

Company	P (Bbl)	CE (tCO_2e)	W (#)	S ($ CAD/year)
Canadian Natural Resources	424,860,000[a]	22,730,000[b]	9993[c]	39,127[d]
Cenovus Energy	172,185,100[e]	23,200,000[f]	2413[g]	121,011[h]
Baytex Energy	29,120,065[i]	1,278,000[j]	206[k]	166,350[l]
Tourmaline Oil	113,368,270[m]	2,067,000[n]	604[o]	105,783[m]
Peyto Exploration	29,045,605[q]	571,000[p]	52[p]	129,404[q]
Paramount Resources	24,944,100[r]	490,000[s]	493[s]	66,734[r]

[a] According to Canadian Natural Resource annual report 2020 (multiplied by 365 for annual production) [68].
[b] According to Canadian Natural Resource stewardship report 2020 [69].
[c] According to the Employee Count section from the website Macrotrends [70].
[d] According to Canadian Natural Resource annual report 2020 [68].
[e] According to Cenovus reports 2020 fourth-quarter and full-year results (multiplied by 365 for annual production) [71].
[f] According to Cenovus ESG report 2020 [72].
[g] According to Cenovus annual information form 2020 [73].
[h] According to Cenovus consolidated financial statement 2020 (unaudited) [74].
[i] According to Baytex annual report 2021 (multiplied by 365 for annual production) [75].
[j] According to Baytex TCFD report 2022 [76].
[k] According to Baytex annual information form 2020 [77].
[l] According to Baytex annual report 2020 [78].
[m] According to Tourmaline management's discussion and analysis and consolidated financial statements for the years ended 2021 and 2020 (multiplied by 365 for annual production) [79].
[n] According to the performance data section from Tourmaline official website, Corporate Responsibility [80].
[o] According to Tourmaline annual information report 2020 [81].
[p] According to Peyto ESG report in 2022 [82].
[q] According to Peyto annual report 2020 (multiplied by 365 for annual production) [83].
[r] According to Paramount annual result 2020 (multiplied by 365 for annual production) [84].
[s] According to Paramount ESG report 2023 [85].

Table A.2
Energy production (P), carbon emission (CE), workforce (W) and average salary (S) of upstream energy production companies (2021).

Company	P (Bbl)	CE (tCO_2e)	W (#)	S ($ CAD/year)
Canadian Natural Resources	450,775,000[a]	20,284,875[b]	9735[c]	37,596[d]
Cenovus Energy	288,715,000[e]	23,100,000[f]	5938[g]	142,977[h]
Baytex Energy	29,256,940[i]	1,174,000[j]	208[k]	196,173[i]
Tourmaline Oil	161,006,975[l]	2,599,000[n]	688[m]	126,134[l]
Peyto Exploration	33,215,000[p]	624,000[o]	55[q]	112,200[r]
Paramount Resources	29,930,000[s]	420,877[t]	487[u]	85,421[s]

[a] According to Canadian Natural Resource annual report in 2024 (multiplied by 365 for annual production) [86].
[b] According to Canadian Natural Resource ESG highlight report in 2022, the number is approximated according to the GHG emissions management graph provided [87].
[c] According to the Employee Count section from the website Macrotrends [70].
[d] According to Canadian Natural Resource fourth quarter and year end report 2022 [88].
[e] According to Cenovus reports 2022 fourth-quarter and full-year results (multiplied by 365 for annual production) [89].
[f] According to Cenovus ESG report 2022 [90].
[g] According to Cenovus annual information form 2021 [91].
[h] According to Cenovus consolidated financial statement 2022 (unaudited) [92].
[i] According to Baytex annual report 2021 (multiplied by 365 for annual production) [75].
[j] According to Baytex TCFD report 2022 [76].
[k] According to Baytex annual information form 2021 [93].
[l] According to Tourmaline management's discussion and analysis and consolidated financial statements for the years ended 2021 and 2020 (multiplied by 365 for annual production) [79].
[m] According to Tourmaline annual information form in 2021 [94].
[n] According to the performance data section from Tourmaline official website, Corporate Responsibility [80].
[o] According to Peyto ESG report in 2022 [82].
[p] According to Peyto Q4 and annual report 2022 (multiplied by 365 for annual production) [95].
[q] According to Peyto annual information form in 2021 [96].
[r] According to Peyto annual report in 2021 [97].
[s] According to Paramount annual result 2021 (multiplied by 365 for annual production) [98].
[t] According to Paramount ESG report 2024 [99].
[u] According to Paramount ESG report 2023 [85].

Table A.3
Energy production (P), carbon emission (CE), workforce (W) and average salary (S) of upstream energy production companies (2022).

Company	P (Bbl)	CE (tCO_2e)	W (#)	S ($ CAD/year)
Canadian Natural Resources	467,565,000[a]	20,572,860[b]	10,035[c]	41,355[d]
Cenovus Energy	286,963,000[e]	22,100,000[f]	5998[g]	144,215[h]
Baytex Energy	30,295,000[i]	1,091,000[j]	222[k]	226,441[l]
Tourmaline Oil	182,803,680[m]	2,933,000[n]	758[o]	136,377[m]
Peyto Exploration	37,595,000[p]	686,000[q]	103[r]	51,000[p]
Paramount Resources	32,365,280[t]	483,762[s]	523[u]	81,644[v]

[a] According to Canadian Natural Resource annual report 2024 (multiplied by 365 for annual production) [86].
[b] According to Canadian Natural Resource ESG highlight report in 2022, the number is approximated according to the GHG emissions management graph provided [87].
[c] According to the Employee Count section from the website Macrotrends [70].
[d] According to Canadian Natural Resource fourth quarter and year end report 2022 [88].
[e] According to Cenovus reports 2022 fourth-quarter and full-year results (multiplied by 365 for annual production) [89].
[f] According to Cenovus ESG report 2022 [90].
[g] According to Cenovus annual information form 2022 [100].
[h] According to Cenovus consolidated financial statement 2022 (unaudited) [92].
[i] According to Baytex annual report 2023 (multiplied by 365 for annual production) [101].
[j] According to Baytex TCFD report 2022 [76].
[k] According to Baytex annual information form 2022 [102].
[l] According to Baytex annual report 2022 [103].
[m] According to Tourmaline management's discussion and analysis and consolidated financial statements for the years ended 2022 and 2023 (multiplied by 365 for annual production) [104].
[n] According to the performance data section from Tourmaline official website, Corporate Responsibility [80].
[o] According to Tourmaline annual information report 2022 [105].
[p] According to Peyto Q4 and annual report 2022 (multiplied by 365 for annual production) [95].
[q] According to Peyto ESG report in 2023 [106].
[r] Due to the unavailability of data, this number is approximated by taking average of the number of employees in 2021 and 2022.
[s] According to Paramount ESG report 2024 [99].
[t] According to Paramount annual result 2023 (multiplied by 365 for annual production) [107].
[u] According to Paramount ESG report 2023 [85].
[v] According to Paramount annual result 2022 [108].

Table A.4
Energy production (P), carbon emission (CE), workforce (W) and average salary (S) of upstream energy production companies (2023).

Company	P (Bbl)	CE (tCO_2e)	W (#)	S ($ CAD/year)
Canadian Natural Resources	486,180,000[a]	21,391,920[b]	10,272[c]	44,003[d]
Cenovus Energy	284,225,500[e]	21,900,000[b]	6925[f]	99,350[g]
Baytex Energy	44,530,000[h]	1,600,000[b]	367[i]	190,161[h]
Tourmaline Oil	189,800,000[k]	3,000,000[b]	1025[j]	125,098[k]
Peyto Exploration	38,306,020[l]	651,000[m]	151[n]	70,126[o]
Paramount Resources	35,183,445[p]	460,416[q]	574[r]	86,063[p]

[a] According to Canadian Natural Resource annual report 2024 (multiplied by 365 for annual production) [86].
[b] Due to the unavailability of data, the number is approximated by taking the ratio of production and emission in 2022, and multiplying the ratio with the production in 2023.
[c] According to the Employee Count section from the website Macrotrends [70].
[d] According to Canadian Natural Resource fourth quarter and year end report 2024 [109].
[e] According to Cenovus reports 2024 fourth-quarter and full-year results (multiplied by 365 for annual production) [110].
[f] According to Cenovus annual information form in 2023 [111].
[g] According to Cenovus consolidated financial statement 2024 (unaudited) [112].
[h] According to Baytex annual report 2023 (multiplied by 365 for annual production) [101].
[i] According to Baytex annual information form 2023 [113].
[j] According to Tourmaline annual information 2023 [114].
[k] According to Tourmaline management's discussion and analysis and consolidated financial statements for the years ended 2022 and 2023 (multiplied by 365 for annual production) [104].
[l] According to Peyto annual report 2024 (multiplied by 365 for annual production) [115].
[m] According to Peyto ESG data in 2023 [106].
[n] According to Peyto modern slavery report 2023 [116].
[o] According to Peyto Management's Discussion and Analysis in 2024 [117].
[p] According to Paramount annual result in 2023 (multiplied by 365 for annual production) [107].
[q] According to Paramount ESG report in 2024 [99].
[r] According to Paramount annual information form in 2023 [118].

Table A.5
Energy production (P), carbon emission (CE), workforce (W) and average salary (S) of upstream energy production companies (2024).

Company	P (Bbl)	CE (tCO_2e)	W (#)	S ($ CAD/year)
Canadian Natural Resources	497,495,000[a]	21,574,450[b]	10,640[c]	47,274[d]
Cenovus Energy	29,0978,000[e]	21,214,777[b]	7150[f]	111,049[g]
Baytex Energy	55,859,600[h]	1,732,696[b]	370[i]	220,935[j]
Tourmaline Oil	211,398,145[k]	3,290,739[b]	1130[l]	156,100[k]
Peyto Exploration	45,698,730[m]	681,119[b]	140[n]	101,129[o]
Paramount Resources	35,948,850[p]	480,392[b]	566[q]	85,159[p]

[a] According to CNRL annual report in 2024 (multiplied by 365 for annual production) [86].
[b] Due to the unavailability of data, we use production and emission data from 2020 to 2023 as true data to predict 2024 emission data by using ridge regression.
[c] According to the Employee Count section from the website Macrotrends [70].
[d] According to Canadian Natural Resource fourth quarter and year end report 2024 [109].
[e] According to Cenovus reports 2024 fourth-quarter and full-year results (multiplied by 365 for annual production) [110].
[f] According to Cenovus annual information form 2024 [119].
[g] According to Cenovus consolidated financial statement 2024 (unaudited) [112].
[h] According to Baytex year end press release in 2024 (multiplied by 365 for annual production) [120].
[i] According to Baytex annual information form 2024 [121].
[j] According to Baytex annual report 2024 [122].
[k] According to Tourmaline management's discussion and analysis and consolidated financial statements for the years ended 2023 and 2024 (multiplied by 365 for annual production) [123].
[l] According to Tourmaline annual information form in 2024 [124].
[m] According to Peyto annual report in 2024 (multiplied by 365 for annual production) [115].
[n] According to Peyto annual information report 2024 [125].
[o] According to Peyto Management's Discussion and Analysis in 2024 [117].
[p] According to Paramount annual result in 2024 (multiplied by 365 for annual production) [126].
[q] According to Paramount annual information form in 2024 [127].

Appendix B. Inefficiency sensitivity data

See Fig. B.1.

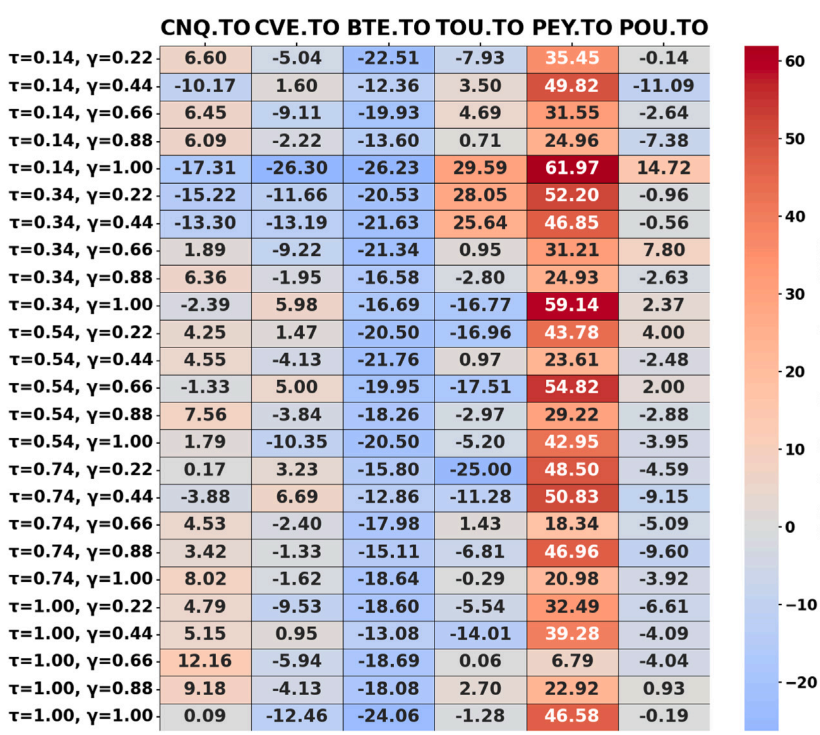

Fig. B.1. Sensitivity analysis of estimated 2025 production levels with respect to policy-induced changes in the inefficiency term, relative to 2024 baselines.

Appendix C. Estimated production levels

See Fig. C.1.

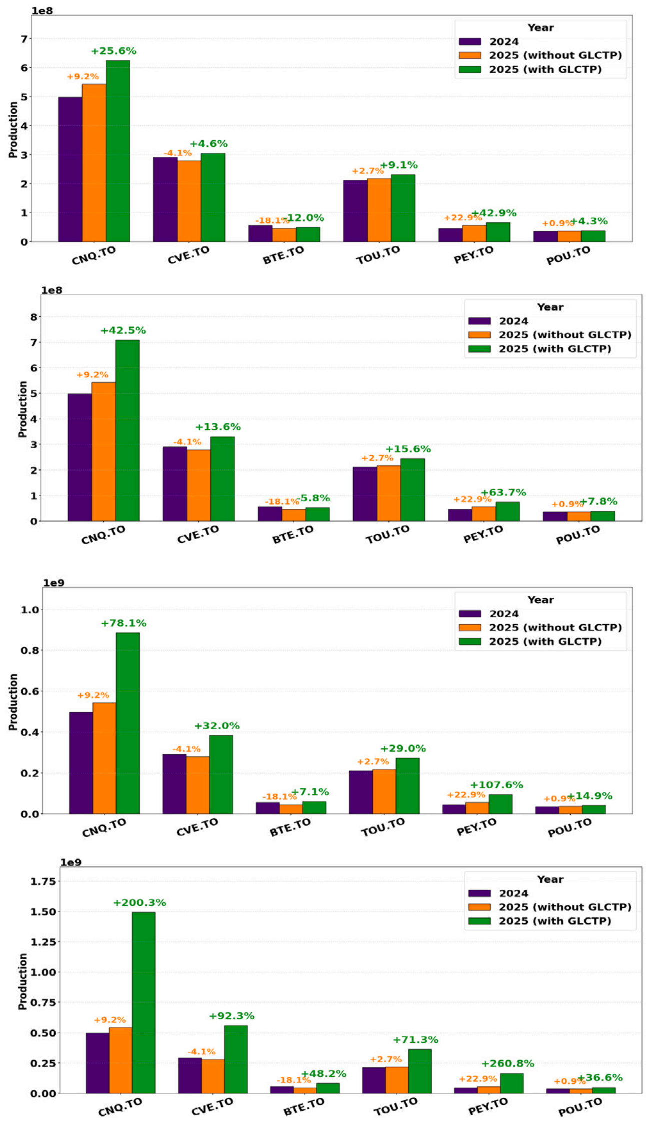

Fig. C.1. Companies' 2025 output levels with and without CGCTR compared to 2024 data from Scenario 1, Scenario 2, Scenario 3, and Scenario 4, respectively.

Table E.1
Firm-level emission intensity and the mean from 2020 to 2025, which includes historical observations, model-based estimates, and projections under CGCTR policy scenarios.

Year/Scenario	Mean	CNQ.TO	CVE.TO	BTE.TO	TOU.TO	PEY.TO	POU.TO
2020 (Actual)	0.04828	0.05350	0.13474	0.04389	0.01823	0.01966	0.01964
2021 (Actual)	0.03569	0.04500	0.08001	0.04013	0.01614	0.01879	0.01406
2022 (Actual)	0.03438	0.04400	0.07701	0.03601	0.01604	0.01825	0.01495
2023 (Actual)	0.03381	0.04400	0.07705	0.03593	0.01581	0.01699	0.01309
2024 (Estimated)	0.03185	0.04337	0.07291	0.03102	0.01557	0.01490	0.01336
2025 (Estimated)	0.03264	0.04031	0.07606	0.03921	0.01493	0.01196	0.01335
2025 (CGCTR 1st)	0.03036	0.03510	0.06777	0.04032	0.01533	0.01063	0.01301
2025 (CGCTR 2nd)	0.02843	0.03097	0.06096	0.04103	0.01551	0.00952	0.01261
2025 (CGCTR 3rd)	0.02546	0.02489	0.04976	0.04247	0.01585	0.00789	0.01189
2025 (CGCTR 4th)	0.02026	0.01512	0.02802	0.04622	0.01672	0.00524	0.01026

Appendix D. Cooperative game flow

See Fig. D.1.

Appendix E. Emission intensity data

See Table E.1.

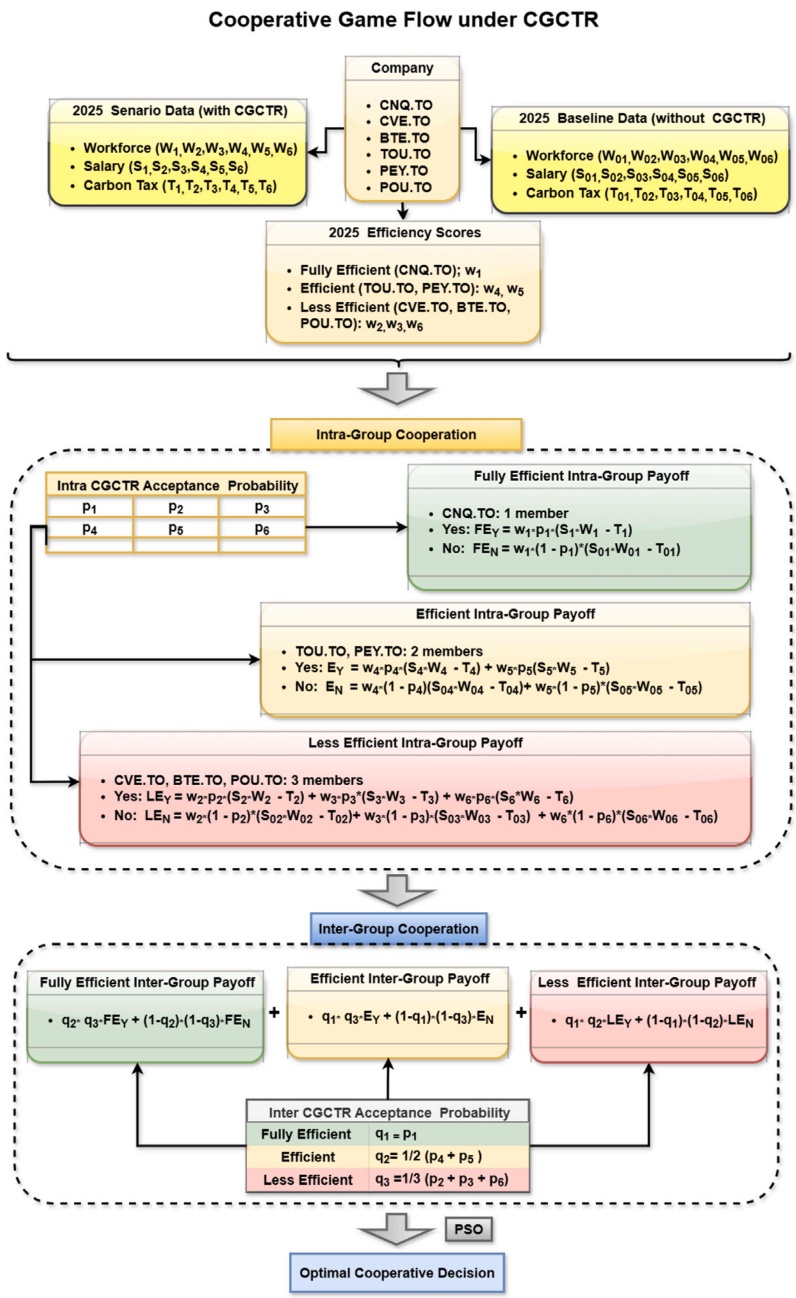

Fig. D.1. Proposed cooperative game flow under CGCTR in the Canadian case.

Data availability

The data for the case study in the paper was obtained from Companies' official websites:

- https://www.cnrl.com for Canadian Natural Resources,
- https://www.cenovus.com for Cenovus Energy,
- https://www.baytexenergy.com for Baytex Energy Crop,
- https://www.tourmalineoil.com for Tourmaline Oil,
- https://www.peyto.com for Peyto Exploration & Development,
- https://www.paramountres.com for Paramount Resources Ltd.

Moreover, a few of the data points were acquired from Macrotrends at the website https://www.macrotrends.net. All these datasets are public.

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