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A novel evolutionary game-based low-methane application in three-echelon energy supply chains

Haihui Cheng[a,b], Ali Hamidoğlu[b,*], Liubov Sysoeva[b], Pablo Venegas Garcia[b], Russell Milne[b], Zvonko Burkus[c], Hao Wang[b,*]

[a] School of Mathematics and Statistics, Northeastern University at Qinhuangdao, Qinhuangdao 066004, China

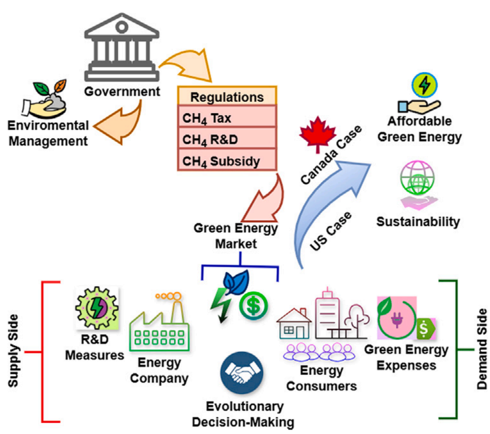
[b] Interdisciplinary Lab for Mathematical Ecology and Epidemiology (ILMEE) & Department of Mathematical and Statistical Sciences, University of Alberta, Edmonton, Alberta, Canada T6G 2G1

[c] Land Policy, Alberta Environment & Protected Areas, Edmonton, Alberta, Canada T5K 2J6

HIGHLIGHTS

- A novel low-methane application (LMA) is proposed in energy supply chains.
- An evolutionary game integrates with LMA for stakeholder cooperation.
- Stakeholder equilibria and social welfare establish affordable energy pricing.
- Case studies in Canada and the U.S. apply LMA to support clean energy transitions.

GRAPHICAL ABSTRACT



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ABSTRACT

Reducing methane emissions across the energy supply chain is critical due to methane's potent short-term global warming potential, which is significantly higher than that of carbon dioxide. The development and deployment of advanced technologies, the implementation of robust regulatory frameworks, and the fostering of collaboration among governments, industry stakeholders, and consumers are important factors in accelerating the transition to a low-methane energy supply chain. This paper proposes a novel evolutionary game framework to create a green and cost-efficient low-methane application in the three-echelon energy supply chain comprising the government, the energy company, and energy consumers. The proposed low-methane application (LMA) integrates with the high-order evolutionary game dynamics, consisting of the replication dynamics of all stakeholders, methane, and social welfare dynamics of the company and consumers. Stable equilibria are achieved through the acceptance of the LMA, which introduces a novel pricing structure aimed at establishing an affordable methane-free market in the supply chain. A Canadian case study demonstrates the robustness of the LMA, which is further reinforced through its integration into the U.S. energy supply chain, showcasing the framework's adaptability and strategic relevance in a major global energy market. Our results suggest that the LMA establishes (1) an ecologically benign and cost-effective energy market for all stakeholders involved; (2) a threshold for affordable energy prices; (3)

* Corresponding authors.
Email addresses: hamidogl@ualberta.ca (A. Hamidoğlu), hao8@ualberta.ca (H. Wang).

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social welfare for both the company and consumers while simultaneously reducing methane emissions within the supply chain; and (4) long-term sustainability for the government by mitigating environmental management costs associated with methane emissions.

1. Introduction

1.1. Motivation and background

Methane and carbon dioxide are recognized as the two primary greenhouse gases that contribute to global warming [1]. Carbon mitigation has been a central focus of climate policies for decades; however, methane, which possesses a global warming potential more than 80 times greater than that of carbon over a 20-year timeframe, remains comparatively neglected [2]. Despite its 12-year atmospheric lifetime, methane reduction is an excellent tool for near-term climate benefits [3]. Recently, governments, energy companies, and consumers have increasingly recognized the urgency of addressing methane emissions, particularly in sectors such as agriculture, waste management, and fossil fuel extraction practices [4]. However, methane-specific policies and mitigation efforts have historically lagged behind those targeting carbon dioxide. For instance, global frameworks like the Paris Agreement often prioritize de-carbonization strategies aimed at reducing carbon emissions, with methane reductions treated as a secondary goal [5]. Similarly, energy companies such as oil sands, despite being major contributors to methane emissions through natural gas production and distribution, have primarily focused on reducing carbon dioxide emissions to meet net-zero targets [6].

The interaction between governments, energy companies, and consumers forms a complex, multi-agent system where each actor's decisions influence the overall equilibrium of the market and its sustainability [7]. This setting is highly relevant in the transition to low-carbon economies, particularly when considering regulatory measures targeting methane emissions [8]. For example, governments may formulate regulations based on policymakers' decisions for the adoption of low-methane applications without discouraging producers, which may result in reduced energy supply or higher prices for consumers [9]. Here, energy companies could decide whether to invest in cleaner technologies, including compliance costs and possible changes in consumer demand [10]. Although energy consumers are not direct participants in regulatory processes, their demand and preferences for cleaner energy affect market outcomes [11]. For example, the social welfare of consumers is partially dependent on the social welfare of oil companies in the region due to the abundance of job opportunities [12]. More precisely, the shift to low-methane applications in the energy supply chain has an immediate impact on social welfare, particularly through employment dynamics such as hiring and firing. While the implementation of these technologies in energy supply chains might establish intricate relationships among stakeholders, the social welfare of consumers would significantly impact labour markets [13]. Implementing low-methane technologies may increase production expenses for energy companies, potentially transferring a portion of these costs to consumers through increased energy prices [14]. As the price rises in energy markets, it reduces their overall welfare, particularly in energy-dependent countries. Conversely, if these companies innovate well, they may ultimately lower operational costs over time, which could improve consumer welfare by offering cleaner energy at a consistent price in the long run [15]. While there may be employment losses in those companies, the transition to low-methane applications has the potential to stimulate job growth in related green sectors [16]. For instance, these companies could provide positions such as environmental monitoring, renewable energy integration, and methane management, requiring employees to create, execute, and sustain innovative technologies aimed at lowering emissions. As a result, retrained workers could benefit from new and stable employment opportunities in industries [17].

Game theory offers a powerful and equitable framework for analyzing stakeholders—such as governments, companies, and consumers—as rational agents seeking to maximize their individual or collective interests. It provides mathematical tools to define the roles and strategic interactions of each participant, enabling the simulation of behaviors that promote shared environmental goals while balancing economic and social considerations [18–22]. Within this domain, evolutionary game theory extends the analysis by capturing how stakeholders adapt their strategies over time. This dynamic modeling approach identifies stable equilibrium strategies for all actors engaged in environmentally sustainable actions [23,24].

Building on this foundation, our study addresses the urgent climate priority of methane emission reduction [25]. While many existing approaches focus narrowly on emission targets or isolated supply chain components, they often overlook the evolving behaviors and interdependencies among key stakeholders [26–28]. To bridge this gap, we propose the Low-Methane Application (LMA)—a dynamic policy framework grounded in eco-evolutionary game theory that captures how government incentives (e.g., subsidies, taxes, and R&D support) influence energy companies' investment in green technologies and consumers' adoption behaviors. Critically, it incorporates feedback mechanisms where stakeholders' strategies are influenced by the social welfare satisfaction level, which is shaped by perceived energy prices and overall methane emissions. Such an approach ensures that LMA is not only theoretically grounded but also behaviorally realistic, capturing the endogenous dynamics of trust, environmental responsiveness, and market participation. By aligning policy levers with adaptive behaviors, LMA supports a stable, cost-effective, and scalable transition toward a low-methane future.

1.2. Literature review

The literature is categorized into four classes and each class is supported by recent references and their relevance to the presented research.

1.2.1. Sustainable efforts for green energy

The transition to sustainable energy systems demands properly produced approaches that balance the interests of governments, businesses, and consumers. Recent studies have examined multiple aspects of this challenge, including renewable energy systems [40], low-carbon practices [30], waste-to-energy policies [32], and carbon pricing mechanisms [36]. Government subsidies alone could provide sustainability in the supply chain. For example, Yang et al. [41] investigate government subsidies in organic agriculture, illustrating how financial assistance reduces obstacles for producers and retailers, thereby promoting sustainable and renewable energy in agricultural practices. However, price deals among stakeholders may lead to disagreements, necessitating more collaboration to achieve robust cooperation in their respective energy markets. In this regard, Kang et al. [35] apply evolutionary game theory to examine investment decisions in manufacturing under cap-and-trade systems, highlighting the need to reduce free-riding behaviors. Amiri et al. [38] also look into time-of-use pricing that isn't just based on government subsidies, but also on energy prices and tax rates for both conventional and renewable energy supply chains. They use the Nash game to show how demand response programs can be used to reduce environmental impacts and maximize energy use. In general, governments sustainable efforts towards green energy not only include subsidies and taxes but also R&D policies. In this context, Chen et al. [42] analyze R&D strategies and subsidy policies for advancing solar cell technologies in the photovoltaic supply chain using game-theoretical models. Recent literature shows that the development of sustainable government strategies for green energy, utilizing government taxes, subsidies, and research and development collectively, receives little attention.

1.2.2. Cost-efficient energy market strategies

Recent studies focus on developing accessible energy markets, particularly those incorporating renewable energy sources [29,37,43,44]. In this context, Hamidoglu & Weber [30] develop a Nash game model to examine how government subsidies and taxes influence the adoption of low-carbon practices among farmers, enterprises, and consumers. The analysis of Brazil's sugarcane supply chain supports the utilization of ethanol as an alternative to gasoline in the region. Moreover, a cooperative Nash game and non-cooperative games are considered by Hamidoğlu et al. [45] to build a clean and cost-effective digital agri-food market involving agricultural enterprises and telecommunication operators under the government subsidy policies within the Internet of Things-based agri-food supply chain. Complementing this, Zhao & You [32] apply a Stackelberg game to waste-to-energy policies in the dairy sector, showing how subsidies and manure disposal fees can drive biomass-based energy generation. Wang et al. [40] expand the cooperative framework to hydrogen energy systems, demonstrating that Nash bargaining can improve renewable energy integration and cost efficiency. On the other hand, Wang et al. [31] examine collaborations in solar photovoltaic and wind power generation and use evolutionary game theory to figure out elements like government subsidies and energy prices that promote stakeholder cooperation towards affordable energy markets.

1.2.3. Social welfare-based energy policies

Recent studies indicate that the social welfare of stakeholders is influenced by various interventions, including penalties, taxes, subsidies and R&D across different energy sectors [46–49]. In the context of governmental green policies, Li et al. [33] examine the effects of green subsidies within a two-echelon supply chain through a Stackelberg model, illustrating that these incentives promote the adoption of environmentally friendly practices among upstream suppliers. Moreover, Manteghi et al. [39] examine pricing models within food supply chains, focusing on greenhouse gas emissions and consumer health implications. Penalties for harmful additives and collaborations among supply chain members can produce both economic and environmental advantages. In addition, Qi et al. [50] develop a tripartite evolutionary game model to investigate strategies for overcoming technological blockades in complex product supply chains. They show that government subsidies play a crucial role in enhancing social welfare among local and foreign suppliers by fostering innovations in technology within these sectors. On the other hand, Li et al. [51] investigate the effects of regulatory policies on renewable and conventional energy power generation companies under feed-in tariff regulations and carbon tax policies. The impact of regulatory policy on the social welfare of these firms is dependent upon the gap between green costs and non-green costs, while the optimal regulatory policy is determined by economic benefits and environmental protection. Last but not least, Yang et al. [52] investigate a multi-energy pricing approach utilizing the Bayesian Stackelberg model, with the objective of improving social welfare and extending optimal outcomes for energy consumers possessing hidden private data. Recent studies show energy strategies focus on social welfare across sectors, but little attention is given to stakeholder welfare in affordable energy markets influenced by government regulations and R&D policies.

1.2.4. Low-carbon oriented energy markets

Recent studies indicate that government subsidy policies and collaborations among key stakeholders regarding carbon pricing and low-carbon investments enhance the acceptance of low-carbon practices within energy supply chains [53–55]. In this context, Wen et al. [36] encompass China's thermal power sector, determining strategies like subsidies and carbon pricing that can effectively eliminate carbon lock-in by using evolutionary game theory. Additionally, Li et al. [56] examine the impact of inter-firm cooperation on carbon emission reduction in a supply chain involving a manufacturer and a retailer that exhibit differing levels of environmental innovation efficiencies. The study indicates that collaboration, especially via environmental innovation cartels, contributes to technological advancement, decreases product emission intensity, lowers wholesale prices, and increases sales. However, the results suggest that the government's excessive elevation of carbon tax rates could negatively impact the environmental outcomes of such collaboration. This is consistent with the findings of Lv et al. [34], who assess carbon taxes in China's propylene production sector, determining optimal tax rates that balance emissions reduction and market stability. Furthermore, emission reduction may enhance consumer preference for low-carbon consumption. This observation is partially demonstrated by Yang et al. [57], who analyze the effectiveness of different energy efficiency and emission reduction programs in China's pursuit of carbon peaking and carbon neutrality. On the other hand, Xia et al. [58] reveal that government regulations and costs of reducing emissions determine the equilibrium state, and effective external constraint mechanisms are needed to maximize benefits. Those studies highlight carbon emission reduction through tax strategies, subsidies, and regulations, but lack focus on developing effective, environmentally friendly, and cost-efficient methane policies to mitigate climate change in the supply chain.

Table 1 provides a gap analysis utilizing game theory applications to improve efficiency and sustainable energy practices across diverse supply chain frameworks, considering various policies such as tax, subsidy, methane, and carbon regulations.

Table 1
Model comparison with reviewed literature regarding the integration of different energy practices within various supply chain frameworks using game theoretical aspects, taking into account the influence of different regulatory schemes.

Authors	Evolutionary	Cooperative	Case study	Tax policy	Subsidy policy	Methane policy	Affordable market	Social welfare	Sustainability
Yan et al. [29]	✘	✔	✔	✘	✘	✘	✘	✘	✘
Hamidoğlu & Weber [30]	✘	✔	✔	✔	✔	✘	✔	✘	✘
Wang et al. [31]	✔	✔	✔	✘	✔	✘	✘	✘	✘
Zhao & You [32]	✘	✘	✔	✘	✔	✔	✘	✘	✘
Li et al. [33]	✘	✔	✘	✔	✔	✘	✘	✔	✘
Lv et al. [34]	✘	✘	✔	✔	✘	✔	✘	✘	✘
Kang et al. [35]	✔	✔	✘	✘	✘	✘	✘	✘	✔
Wen et al. [36]	✔	✔	✔	✘	✔	✘	✘	✘	✘
Ding et al. [37]	✔	✔	✘	✘	✔	✘	✔	✘	✘
Amiri et al. [38]	✘	✘	✘	✔	✔	✘	✔	✔	✔
Manteghi et al. [39]	✘	✔	✘	✔	✔	✘	✘	✔	✔
Wan et al. [40]	✘	✔	✔	✘	✘	✔	✔	✔	✘
Yang et al. [41]	✔	✔	✘	✘	✔	✘	✘	✔	✔
This paper	✔	✔	✔	✔	✔	✔	✔	✔	✔

1.3. Research gap

The review of the literature highlights three significant research gaps that require focus:

- *Environmental governance for sustainability*: Previous studies on government sustainability policies have not considered the impact of direct environmental management on non-green energy in supply chains. In the LMA, government involvement reduces expenses and promotes long-term sustainability initiatives, such as tree planting, rather than promoting cap-and-trade systems [35].
- *Affordable methane-free energy*: Research on cost-effective green pricing strategies for energy stakeholders often overlooks methane emissions in sectors like carbon [34], hydrogen [40], wind [31], and biomass [32]. The LMA aims to establish an affordable price reflecting methane emissions and social welfare concerns, promoting stakeholder cooperation and reducing supply chain methane emissions.
- *Social welfare-based methane reduction*: This study provides a new perspective on social welfare dynamics, combining economic surpluses, government surpluses, and environmental surpluses for supply chain members. It highlights the impact of methane emissions on environmental benefits and helps reduce regional emissions.
- *Behaviorally robust, evolutionarily stable policy deployment*: While prior studies incorporate methane into macroeconomic or market-based models, they largely overlook the behavioral evolution and strategic co-adaptation of decentralized stakeholders [59–61]. In contrast, the LMA framework introduces a dynamic eco-evolutionary game approach that links government policies, industry behavior, and consumer choices through replicator dynamics and methane feedback loops, enabling behaviorally robust and evolutionarily stable policy outcomes.

1.4. Paper contribution

The following is a list of the paper's primary contributions:

- *A novel low-methane application (LMA):* The study introduces a new framework, LMA, for energy supply chains, involving government, the energy company, and consumers, aiming to encourage methane-free energy markets, improve social welfare, and enhance green pricing.
- *Game theory based affordable green pricing:* This study establishes an evolutionary game-based LMA framework that models stakeholders' stable strategies through eco-evolutionary dynamics, incorporating social welfare and methane emissions. It introduces affordable green pricing, derived from equilibrium outcomes, to foster cooperative, cost-effective, and environmentally sustainable energy transitions.
- *The LMA integration into energy supply chains:* The study integrates the LMA framework into Canada and the United States' energy supply chains, demonstrating its practical adaptability and strategic relevance. The LMA facilitates methane-conscious decision-making among key stakeholders, offering a scalable policy tool for promoting low-emission transitions in regionally diverse energy systems.

1.5. Organization

The rest of this paper is organized as follows: Section 2 describes the complete system of the LMA within the energy supply chain, consisting of the government, energy company, and energy consumers. Section 3 presents the evolutionary game consisting of three distinct dynamical models and formulates two research problems. Section 4 presents results and discussions of the study, including sensitivity analyses and case studies. In the end, Section 5 concludes the study with further observations and suggestions for future research.

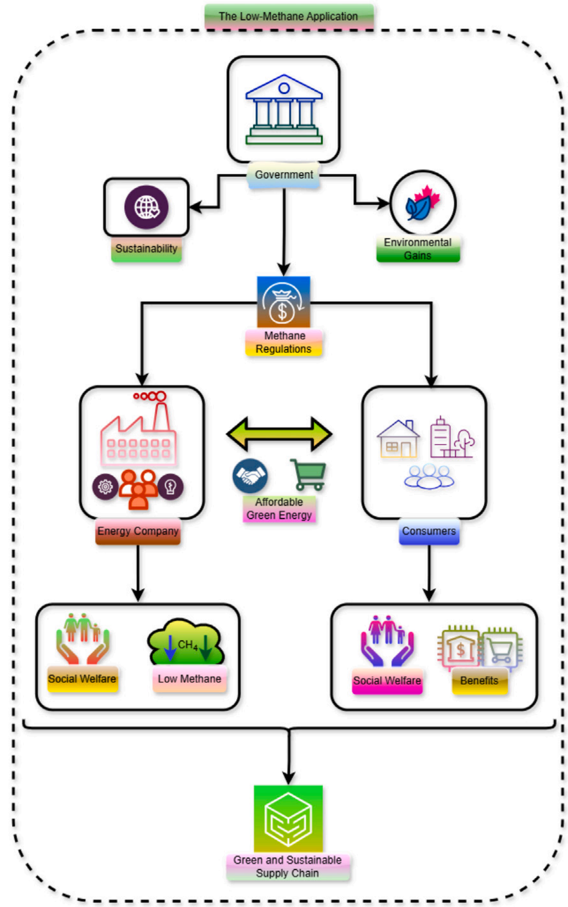


Fig. 1. The flowchart of the LMA in the energy supply chain.

2. System description

This section presents the system description of the LMA which integrates the government, the energy company, and consumers in the energy supply chain, influenced by government methane policy and stakeholder cooperation. In this setting, all stakeholder parameters are considered based on their annual energy transactions and policies.

Throughout the paper, we define green energy under the LMA as methane-free energy produced without environmental harm from methane-related emissions, whereas non-green energy refers to conventional energy priced without the adoption of LMA-driven methane mitigation efforts in the energy market. In this context, we define the satisfactory rate as the ratio of green energy costs under the LMA compared to those without the LMA, thereby quantifying consumers' green satisfaction in relation to energy pricing. The complete framework of the LMA is presented in Fig. 1.

2.1. Government

The government regulates the green market within the LMA by establishing R&D investments (R) for both itself and the energy company to implement low methane policies in its operations. These investments may cover research and development of green technologies, the deployment of methane-control technologies, and the purchase of methane-control equipment by corporations. Additionally, the government provides subsidies (S) to both the company and consumers to foster a cooperative relationship based on an affordable energy price, enabling consumers to access green energy. In the absence of the LMA, the government collects fines and methane related taxes from the energy company (denoted as F_e).

Table 2
Parameters of the government in the low-methane application (LMA).

Parameters	Descriptions
S	Amount of subsidies under the LMA
R	Amount of R&D under the LMA
F_e	Amount of methane related tax for the company without the LMA
E_g	Environmental benefits under the LMA
M_g	Costs for environmental management without the LMA

Table 3
Methane impact parameters for all stakeholders.

Parameters	Descriptions
γ_1	Impact of methane on environmental benefits of the government
γ_2	Impact of methane on the environmental benefits of the energy company
γ_3	Impact of methane on environmental benefits to consumers
γ_4	Impact of methane on the cost of environmental remediation
β	Decay rate of methane

When the LMA is embraced by the government, there are indirect environmental benefits (denoted as E_g), such as improved air quality, the promotion of methane-control technologies, improved public healthcare, and sustainability. On the other hand, the government absence from the LMA creates costs related to environmental management (denoted as M_g), and as methane levels increase, so do the costs of managing environmental damage. Given that the LMA aims to limit methane emissions in the region, the environmental benefits would at least offset the costs associated with damages addressed by environmental management. Hence, we have

$$E_g \geq M_g. \tag{1}$$

The government intends to plant trees to offset emissions and then evaluate the planting expenses to estimate environmental management expenditures without the LMA. Table 2 demonstrates the parameters of the government both with and without the LMA.

Table 3 presents the effects of methane on the environmental benefits for each stakeholder, along with its implications for governmental environmental management aimed at mitigating damage. Here, we assume that the government pays the most interest in reducing the methane emission, followed by the company and lastly consumers. Namely, we have the following relation:

$$\gamma_1 \geq \gamma_2 \geq \gamma_3. \tag{2}$$

2.2. Energy company

The energy company that pursues the LMA strategy receives direct benefits from government subsidies. By reducing methane emissions, the company enhances its brand image and demonstrates corporate social responsibility, which boosts consumer and investor trust, ultimately leading to increased energy sales and higher investments. Furthermore, negotiations with consumers to establish an affordable energy price, along with the capture and conversion of methane into valuable energy products, yield environmental benefits (represented as E_e) for the energy company.

Upon receiving a portion of government R&D investment, the company is responsible for the costs (denoted as R_e) associated with the development and implementation of new technologies, as well as the purchase of necessary equipment for methane control, dependent upon the acceptance of the LMA. Meanwhile, the company not adopting the LMA strategy is subject to government-imposed fines and taxes, called methane-related taxes (F_e), and it would face the absence of the government subsidy and R&D policy. The government evaluates the methane-related tax based on the company's methane emissions in the absence of the LMA adoption.

Table 4
Parameters of the energy company in the low-methane application (LMA).

Parameters	Descriptions
R_e	R&D costs under the LMA
E_e	Environmental benefits under the LMA
w_e	Social welfare rate under the LMA
λ_e	Subsidy rate under the LMA

Table 5
Parameters of consumers in the low-methane application (LMA).

Parameters	Descriptions
C_{c1}	Cost of green energy under the LMA
C_{c2}	Cost of non-green energy without the LMA
w_c	Social welfare rate under the LMA
E_c	Environmental benefits under the LMA
λ_c	Subsidy rate under the LMA

Table 4 presents the parameters of the LMA for the energy company. The government subsidies (S) are allocated according to the subsidy rate (λ_e) for the energy company, resulting in an amount of $\lambda_e S$ in subsidies for the company when the LMA is accepted. Finally, the company establishes a social welfare rate, denoted as w_e, which is dependent upon the economic benefits and the level of methane emissions derived from the LMA. This rate is directly affected by consumer satisfaction with green pricing and the levels of methane emissions.

2.3. Consumers

In the LMA, consumers incur the expense of acquiring green energy, represented as C_{c1}, which exceeds the cost C_{c2} associated with the absence of the LMA. Consumer energy expenditures are considered a singular unit cost, directly influenced by the population size of consumers within the supply chain. Given the constant state of the consumer population, it is acceptable to compare unit energy prices with and without the LMA in the supply chain. Moreover, consumers' energy market is influenced through the government's subsidy policy, which provides subsidies at a rate of λ_c. The social welfare of consumers is reliant upon the unit green price and methane concentration. Consequently, an increase in their social welfare rate w_c indicates an increased emphasis on these two subjects. Methane concentrations in the environment significantly affect the magnitude of environmental benefits (denoted as E_c) experienced by consumers. More specifically, the government reduces methane-related tax for the consumers in case of using the LMA, which is considered as E_c, total amount of methane cuts provided to the consumers.

Table 5 illustrates the parameters of the LMA for energy consumers. Since the government subsidy is distributed among the company and consumers, we have

$$\lambda_e + \lambda_c = 1. \tag{3}$$

2.4. Affordable pricing

In this section, we provide the method to set an affordable price based on decisions of stakeholders and social welfare of the company and consumers based on the energy market. First of all, we define the satisfaction rate of the cooperation between the company and consumers as

$$\mu := \frac{C_{c2}}{C_{c1}(\mu)}, \tag{4}$$

where $C_{c1}(\mu)$ represents the green energy costs for consumers under the LMA. Let $P_{c1}(\mu)$ represent the unit green energy price with a satisfactory rate μ under the LMA.

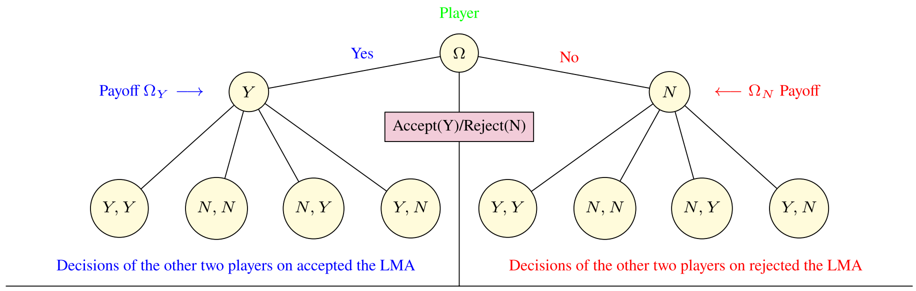


Fig. 2. Player's payoff diagram based on the acceptance and rejection of the LMA.

In this framework, the collaboration between the company and consumers in establishing a market price becomes more affordable as μ approaches 1. This approach aims to define a threshold for the satisfactory rate, say, $\hat{\mu}$, ensuring that the decisions made by all stakeholders exceed fifty percent for the acceptance of the LMA. Additionally, we aim to ensure that the social welfare of the company and consumers rises above fifty percent under this pricing strategy. In this setting, $\hat{\mu}$ satisfies

$$\mu < \hat{\mu} < 1. \tag{5}$$

We have the following definition, which describes the affordable market in the supply chain.

Definition 1. The price of green energy $P_{c1}(\mu_a)$ is called affordable if

$$\mu_a \in [\hat{\mu}, 1). \tag{6}$$

3. Problem formulation

This section formulates the LMA integration within the novel evolutionary game. In this game, the government has two strategies: to adopt the LMA with probability x or to reject it with probability $1 - x$. The company has two strategic options: to execute the LMA with probability y or opting to ignore it with probability $1 - y$. Finally, consumers have two strategies: to accept the LMA with probability z or to reject it with probability $1 - z$.

Fig. 2 shows a diagram for determining the payoff of an arbitrary player in the game. Here, we consider the expected payoff functions of the government, the company and consumers as f, g, and h, respectively. We illustrate f_Y, g_Y, and h_Y as the payoffs for the acceptance of the LMA for the government, the company, and the consumers, respectively. In contrast, we define f_N, g_N, and h_N as the payoffs associated with the rejection of the LMA for the government, the company, and consumers, respectively. Here, we see that the player with the expected payoff function $\Omega \in \{f, g, h\}$ includes the payoff associated with the acceptance of the LMA (Ω_Y) and the payoff linked to the rejection of the LMA (Ω_N).

Now, we are ready to build payoffs of each stakeholder based on the LMA. In this regard, we construct the possible costs associated with each player's decision to accept or reject the LMA based on parameters presented in Tables 2–5. More precisely, each player has two options: to accept or reject the LMA, resulting in eight possible scenarios as shown in Table 6.

Based on the payoffs in Table 6, we find out each player's payoff and expected decision in the game. Firstly, we derive the payoff function of the government in case of the acceptance of the LMA as

$$\begin{aligned} f_Y &= \left(\frac{\gamma_1}{1+m}E_g - S - R\right) yz + \left(\frac{\gamma_1}{1+m}E_g - \lambda_e S - R\right) y(1-z) \\ &+ \left(F_e + \frac{\gamma_1}{1+m}E_g - \lambda_c S - R\right)(1-y)z \\ &+ \left(\frac{\gamma_1}{1+m}E_g + F_e - R\right)(1-y)(1-z) \\ &= \frac{\gamma_1}{1+m}E_g - R + F_e(1-y) - Syz - \lambda_e S y(1-z) - \lambda_c S(1-y)z, \end{aligned}$$

where the government receives $\frac{\gamma_1}{1+m}E_g$ in environmental benefits, allocates R for research and development support, and collects methane related tax F_e when the LMA is not accepted by at least one of stakeholders It distributes a subsidy amount S to stakeholders who accept the LMA at rates λ_e and λ_c for the company and consumers, respectively. Additionally, it collects a methane-related tax F_e when at least one stakeholder does not accept the LMA.

The payoff function of the government in case of the rejection of the LMA is

$$\begin{aligned} f_N &= -\gamma_4 m M_g yz - \gamma_4 m M_g y(1-z) - \gamma_4 m M_g (1-y)z \\ &\quad - \gamma_4 m M_g (1-y)(1-z) \\ &= -\gamma_4 m M_g, \end{aligned}$$

where the government allocates $\gamma_4 m M_g$ to mitigate the damage resulting from methane emissions.

Secondly, we calculate the payoff function of the company in case of the acceptance of the LMA as

$$\begin{aligned} g_Y &= \left(\lambda_e S + \frac{\gamma_2}{1+m}E_e - R_e + w w_e\right) xz \\ &+ \left(\lambda_e S + \frac{\gamma_2}{1+m}E_e - R_e + w w_e\right) x(1-z) \\ &+ \left(\frac{\gamma_2}{1+m}E_e - R_e + w w_e\right)(1-x)z \\ &+ \left(\frac{\gamma_2}{1+m}E_e - R_e + w w_e\right)(1-x)(1-z) \\ &= \lambda_e S x + \frac{\gamma_2}{1+m}E_e - R_e + w w_e, \end{aligned}$$

where the company obtains a government subsidy of $\lambda_e S$ upon government approval of the LMA, realizes $\frac{\gamma_2}{1+m}E_e$ in environmental benefits, and achieves $w w_e$ in social welfare, while incurring an expenditure of R_e for research and development purposes.

The payoff function of the company when the LMA is rejected, is as follows

$$g_N = -F_e xz - F_e x(1-z) = -F_e x,$$

where the company receives methane-related tax F_e upon government approval of the LMA.

Finally, we derive the payoff function of consumers upon acceptance of the LMA as follows.

$$\begin{aligned} h_Y &= \left(\lambda_c S + \frac{\gamma_3}{1+m}E_c - C_{c1} + w w_c\right) xy \\ &+ \left(\lambda_c S + \frac{\gamma_3}{1+m}E_c - C_{c1} + w w_c\right) x(1-y) \\ &+ \left(\frac{\gamma_3}{1+m}E_c - C_{c1} + w w_c\right)(1-x)y \\ &+ \left(\frac{\gamma_3}{1+m}E_c - C_{c1} + w w_c\right)(1-x)(1-y) \\ &= \lambda_c S x + \frac{\gamma_3}{1+m}E_c - C_{c1} + w w_c, \end{aligned}$$

Table 6
Payoffs of each stakeholder under the LMA and without the LMA (WLMA).

Strategic combinations	Payoffs		
	Government	Energy company	Consumer
$\{LMA, LMA, LMA\}$	$\frac{\gamma_1}{1+m}E_g - S - R$	$\lambda_e S + \frac{\gamma_2}{1+m}E_e - R_e + ww_e$	$\lambda_c S + \frac{\gamma_3}{1+m}E_c - C_{c1} + ww_c$
$\{LMA, LMA, WLMA\}$	$\frac{\gamma_1}{1+m}E_g - \lambda_e S - R$	$\lambda_e S + \frac{\gamma_2}{1+m}E_e - R_e + ww_e$	$-C_{c2}$
$\{LMA, WLMA, LMA\}$	$F_e + \frac{\gamma_1}{1+m}E_g - \lambda_c S - R$	$-F_e$	$\lambda_c S + \frac{\gamma 3}{1+m}E_c - C_{c1} + ww_c$
$\{LMA, WLMA, WLMA\}$	$\frac{\gamma_1}{1+m}E_g + F_e - R$	$-F_e$	$-C_{c2}$
$\{WLMA, LMA, LMA\}$	$-\gamma_4 m M_g$	$\frac{\gamma_2}{1+m}E_e - R_e + ww_e$	$\frac{\gamma_3}{1+m}E_c - C_{c1} + ww_c$
$\{WLMA, LMA, WLMA\}$	$-\gamma_4 m M_g$	$\frac{\gamma_2}{1+m}E_e - R_e + ww_e$	$-C_{c2}$
$\{WLMA, WLMA, LMA\}$	$-\gamma_4 m M_g$	0	$\frac{\gamma_3}{1+m}E_c - C_{c1} + ww_c$
$\{WLMA, WLMA, WLMA\}$	$-\gamma_4 m M_g$	0	$-C_{c2}$

where consumers receive a government subsidy of $\lambda_c S$ following government approval of the LMA, realize $\frac{\gamma_3}{1+m}E_e$ in environmental benefits, and attain ww_c in social welfare, while paying a cost of C_{c1} for green energy under the LMA.

Conversely, the payoff function of consumers is as follows when the LMA is rejected.

$$h_N = -C_{c2}xy - C_{c2}x(1-y) - C_{c2}(1-x)y - C_{c2}(1-x)(1-y) = -C_{c2},$$

where they pay C_{c2} for non-green energy.

Then, the expected payoff of the government, energy company, and consumer are

$$f = xf_Y + (1-x)f_N,$$
$$g = yg_Y + (1-y)g_N,$$
$$h = zh_Y + (1-z)h_N,$$

which provides the replication dynamics as

$$\begin{cases} \frac{dx}{dT} = x(f_Y - f), \\ \frac{dy}{dT} = y(g_Y - g), \\ \frac{dz}{dT} = z(h_Y - h), \end{cases} \tag{7}$$

where T is evolution time.

Now, we construct the dynamics of methane emissions (M) which integrate with the replication dynamics (7) as follows:

$$\frac{dM}{dT} = \alpha_1(1-y) + \alpha_2(1-z) - \beta M, \tag{8}$$

where α_1 and α_2 denote the rate of methane emissions from the energy company and consumers not adopting the LMA strategy, respectively, and β is the decay rate of methane. Normalizing Eq. (8) by $m = \frac{M\beta}{\alpha_1+\alpha_2}$ yields

$$\frac{dm}{dT} = \beta\left(1 - \frac{\alpha_1}{\alpha_1+\alpha_2}y - \frac{\alpha_2}{\alpha_1+\alpha_2}z - m\right), \tag{9}$$

where $m \in [0,1]$ is defined as a standardized measure of the abundance of methane. $m = 1$ indicates that methane is abundant. while $m = 0$ indicates that methane is poor.

Moreover, we propose the following social welfare dynamics (W) of the supply chain under the LMA, which quantifies the social welfare accrued over time. which integrates with replication dynamics (7) as follows:

$$\frac{dW}{dT} = yw_e + zw_c - \gamma_c W, \tag{10}$$

where γ_c illustrates the social dissatisfaction rates of collaboration of the company and consumers under the LMA, respectively defined as

$$\gamma_c = (1-\mu)m.$$

Normalising Eq. (10) by $w = \frac{W\gamma_c}{w_c + w_e}$, we obtain

$$\frac{dw}{dT} = \gamma_c\left(\frac{w_e y + w_c z}{w_e + w_c} - w\right), \tag{11}$$

where w denotes the social welfare index, which measures the level of social welfare. $w = 1$ indicates a high level of social welfare. $w = 0$ indicates a low level of social welfare.

Combining all Eqs. (7), (9) and (11), we obtain the following eco-evolutionary game system

$$\begin{cases} \epsilon_1\epsilon_2\frac{dx}{dT} = x(f_Y - f), \\ \epsilon_1\epsilon_2\frac{dy}{dT} = y(g_Y - g), \\ \epsilon_1\epsilon_2\frac{dz}{dT} = z(h_Y - h), \\ \epsilon_2\frac{dm}{dT} = \beta\left(1 - \frac{\alpha_1}{\alpha_1+\alpha_2}y - \frac{\alpha_2}{\alpha_1+\alpha_2}z - m\right), \\ \epsilon_1\frac{dw}{dT} = \gamma_c\left(\frac{w_e y + w_c z}{w_e + w_c} - w\right), \end{cases} \tag{12}$$

where ϵ_1 (ϵ_2) is the relative timescale used to represent the relative evolutionary speed of methane (social welfare) and strategies. $\epsilon_1 < 1$ $(\epsilon_1 > 1)$ indicates methane evolves slower (faster) than strategies. $\epsilon_2 < 1$ $(\epsilon_2 > 1)$ indicates social welfare evolves slower (faster) than strategies [62–64]. Re-scaling the time via $t = \frac{T}{\epsilon_1\epsilon_2}$, then Eq. (12) is rewritten as the following high-dimensional high-order eco-evolutionary game system with methane and social welfare feedback

$$\begin{cases} \frac{dx}{dt} = x(f_Y - f), \\ \frac{dy}{dt} = y(g_Y - g), \\ \frac{dz}{dt} = z(h_Y - h), \\ \frac{dm}{dt} = \epsilon_1\beta\left(1 - \frac{\alpha_1}{\alpha_1+\alpha_2}y - \frac{\alpha_2}{\alpha_1+\alpha_2}z - m\right), \\ \frac{dw}{dt} = \epsilon_2\gamma_c\left(\frac{w_e y + w_c z}{w_e + w_c} - w\right). \end{cases} \tag{13}$$

Based on eco-evolutionary game system (13), the following two problems are formulated.

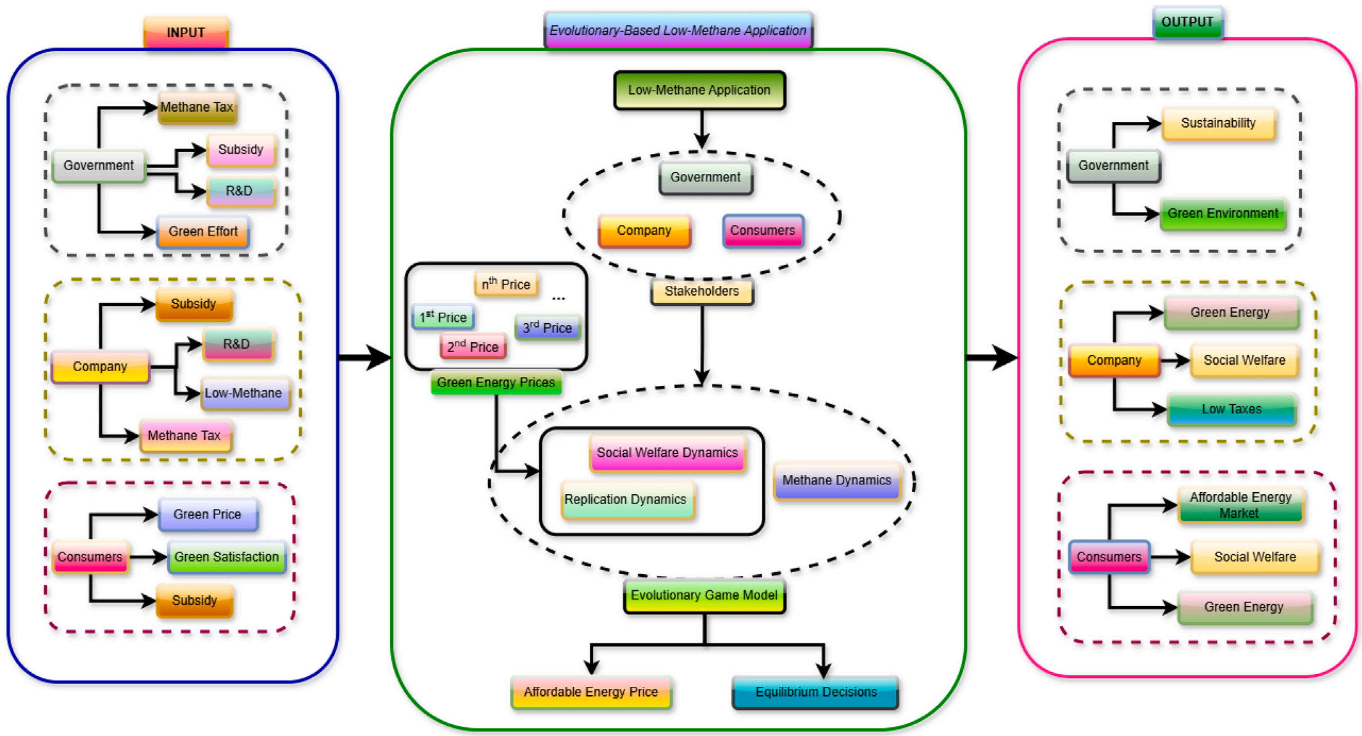


Fig. 3. The flowchart for the methodology of the evolutionary game-based LMA.

Table 7
A sample data for the government, the company and consumers based on the LMA.

Government		Company		Consumers	
Parameter	Value	Parameter	Value	Parameter	Value
S	1×10^7	R_e	2×10^7	C_{c1}	2.89×10^9
R	2×10^7	E_e	2×10^7	C_{c2}	2.8×10^9
F_e	2×10^7	w_e	0.3	w_c	0.5
E_g	5×10^7	λ_e	0.7	E_c	4×10^7
M_g	5×10^7	γ_2	0.5	λ_c	0.3
γ_4	0.6	α_1	0.9	α_2	0.1
γ_1	0.7			γ_3	0.2
β	0.1				

Problem 1. Determine stable equilibria of the eco-evolutionary game dynamics (13).

Problem 2. Estimate a threshold $\hat{\mu}$ as described in (5) and determine an affordable pricing based on the stable equilibria of replication dynamics and social welfare, (x_e, y_e, z_e, w_e), satisfying

$$x_e > 0.5, \quad y_e > 0.5, \quad z_e > 0.5, \quad and \quad w_e > 0.5.$$

In the following section, we investigate the Problem 1 and perform numerical simulations to derive the equilibria of the game both in non-real case and real case scenarios. To address Problem 2, once the equilibrium decisions of all individuals are established, $\hat{\mu}$ can be estimated through a sensitivity analysis on varying green energy costs C_{c1}, dependent upon the level of approval of the LMA by all stakeholders.

Fig. 3 illustrates each phase of the evolutionary game-based LMA and an organized framework for the research formulation.

4. Results and discussions

4.1. Sensitivity analyses

In this section, we generate a sample data set for each stakeholder's parameters based on the assumptions and rules of the game from the energy supply chain's LMA architecture. Table 7 shows the sample data for the government, the company and consumers in this setting.

Based on data shown in Table 7, the company receives more government subsidies than consumers all sum to 1 according to (3). Moreover, impact of methane for each player is ordered according to (2). Here, we derive that

$$\mu = \frac{2.8 \times 10^9}{2.89 \times 10^9} \approx 0.968.$$

In the sensitivity analysis of energy prices, we construct a threshold, $\hat{\mu}$, based on the satisfaction rate of the consumers presented in (4) to create an affordable green energy price, $P_{c1}(\mu_a)$ with μ_a satisfying (6).

4.1.1. Government subsidy

In this section, we consider the following five scenarios based on government subsidy when the LMA is applicable within the supply chain:

$$S = 5 \times 10^6; S = 8 \times 10^6; S = 1.1 \times 10^7; S = 1.3 \times 10^7; S = 1.5 \times 10^7.$$

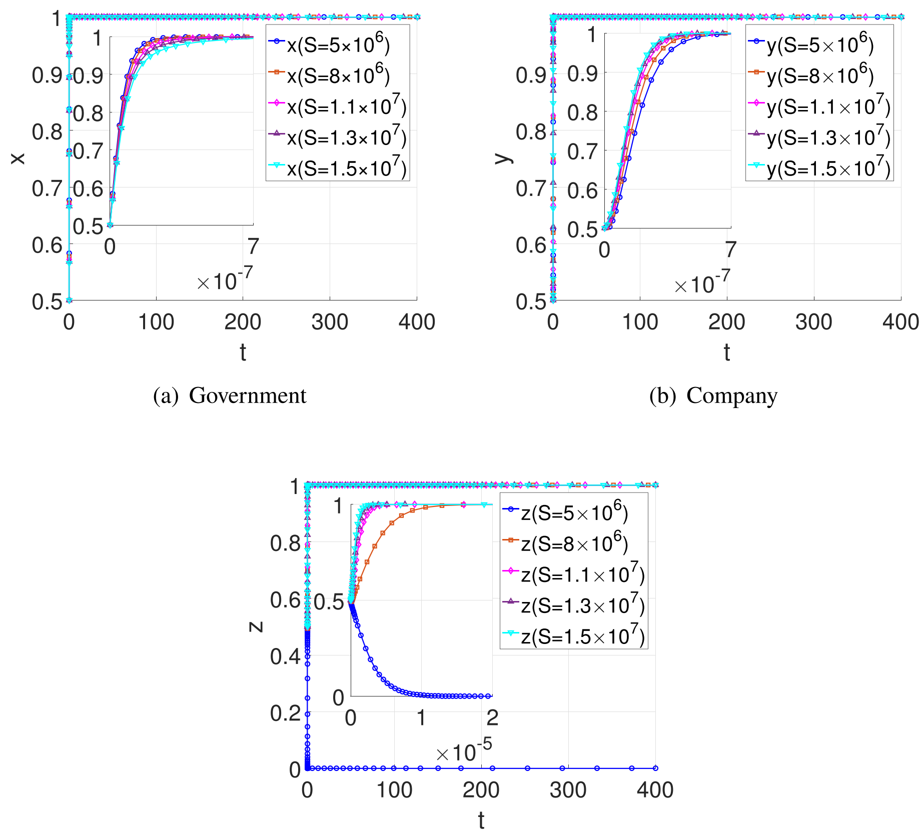
Fig. 4 shows that increased government subsidies hinder the adoption of the LMA, leading to a slower evolutionary process. The likelihood of an energy company adopting LMA increases with subsidies, indicating a faster decision-making process. Conversely, reduced subsidies for consumers decrease their preference for green energy, ultimately leading to no green energy.

4.1.2. Methane-related tax

In this part, we investigate the following five different scenarios based on methane-related tax when the LMA is not applicable in the supply chain:

$$F_e = 1 \times 10^7; F_e = 1.5 \times 10^7; F_e = 2.1 \times 10^7; F_e = 2.5 \times 10^7; F_e = 3 \times 10^7.$$

Fig. 5 illustrates that an increase in the methane-related tax leads to improved government revenue, thereby encouraging the adoption of



(a) Government　(b) Company

(c) Consumers

Fig. 4. Evolutionary decisions regarding the LMA on various government subsidies.

the LMA by the government. A higher tax on the energy company similarly accelerates the transition to the LMA. The methane-related tax affects the decision-making dynamics of the government, energy company, and consumers; however, it does not change the final evolutionary outcome.

4.1.3. *Allocation of subsidies*

In this section, we consider five subsidy allocation strategies for the energy company and consumers provided by the government. More precisely, we consider cases when

$$\lambda_e = 0.4; \lambda_e = 0.5; \lambda_e = 0.6; \lambda_e = 0.8; \lambda_e = 0.9.$$

Fig. 6 demonstrates that government subsidies to energy companies and consumers do not affect the adoption of the LMA strategy by all stakeholders. However, the rate of subsidies influences the pace at which the company evolves to adopt the LMA strategy, with higher subsidies accelerating this process.

4.1.4. *Energy price*

In this part, we conduct sensitivity analysis on green energy prices under the LMA.

In this regard, the following energy prices will be considered:

$$C_{c1} = 2.81\times10^9; C_{c1} = 2.83\times10^9; C_{c1} = 2.85\times10^9; C_{c1} = 2.95\times10^9; C_{c1} = 3\times10^9.$$

Fig. 7 illustrates that a reduction in green energy costs substantially enhances consumer willingness to adopt the LMA, thereby contributing to effective methane mitigation. In contrast, elevated costs discourage adoption, leading to a deterioration in the social welfare index and a corresponding rise in methane abundance.

In addition, consumers disagree on green energy costs: $C_{c1} = 3 \times 10^9$ and $C_{c1} = 2.95 \times 10^9$, but agree on green energy costs: $C_{c1} = 2.81 \times 10^9$, $C_{c1} = 2.83 \times 10^9$, and $C_{c1} = 2.85 \times 10^9$ over time. Here, we find our threshold as

$$\hat{\mu} = \frac{2.8 \times 10^9}{2.85 \times 10^9} \approx 0.982,$$

and we say any green energy price $P_{c1}(\mu_a)$ with satisfactory rate μ_a satisfying

$$\mu_a \in [0.982, 1),$$

is affordable. In this case, we have three affordable green prices associated with green energy costs, $C_{c1} = 2.81 \times 10^9$, $C_{c1} = 2.83 \times 10^9$ and $C_{c1} = 2.85 \times 10^9$.

4.1.5. *Interplay of different parameters*

In this section, we enhance the sensitivity analysis by examining the potential interactions between key policy factors, focusing on the combined effects of multiple parameters on system behavior. Figs. 8–11 illustrate the interplay between two simultaneously varied parameters and their joint effects on the evolutionary dynamics of governments, energy companies, and consumers.

Regarding the government, across all scenarios, variations in methane-related taxes, government subsidies, subsidy rates, and green energy costs do not alter its steadfast commitment to pursuing the LMA strategy.

Regarding the energy company, as illustrated in Fig. 8(b), the energy company's strategic decisions are influenced by the relationship between methane-related tax and subsidy rate. Low subsidy rates and methane-related taxes discourage LMA adoption. Increases in either

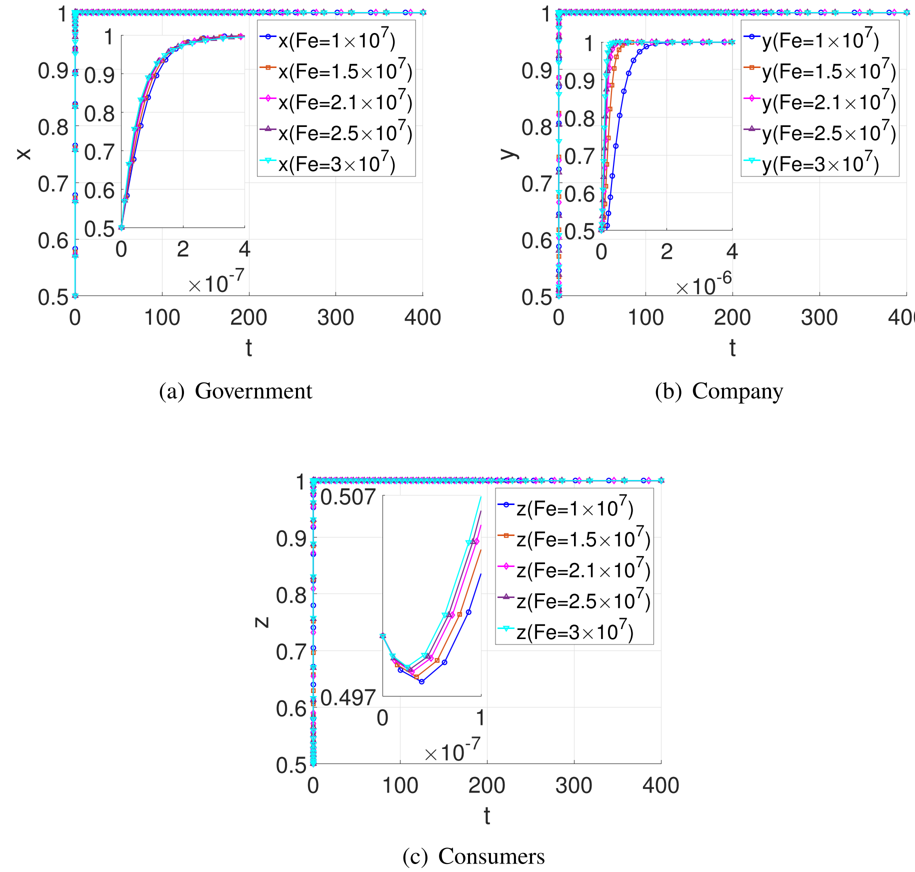


Fig. 5. Evolutionary decisions regarding the LMA on various methane-related taxes.

methane-related tax or subsidy rate improve the cost-benefit structure, encouraging LMA adoption.

Regarding consumers, as shown in Fig. 9(c), their strategic behavior is jointly shaped by government subsidies and green energy costs. Low subsidy levels impose a substantial financial burden, thereby discouraging adoption of the LMA strategy. Increasing subsidies alleviates this burden and, in turn, incentivizes adoption. Conversely, high green energy costs exacerbate financial strain, reducing consumers' willingness to adopt green energy (see Figs. 10(c) and 11(c)). When green energy costs are moderate, higher subsidies further relieve financial pressure, thereby motivating consumers to adopt the LMA strategy (see Fig. 10(c)).

4.2. Case study

The Canadian province of Alberta is the center of the oil and gas business. As a result, it is driving both economic and energy growth in the area [65]. It is important to make the energy supply chain greener because oil mining in Alberta produces a lot of greenhouse gases [66]. In the case study, the government refers to the Alberta government in Canada, the energy company is Cenovus Energy Inc., a major oil corporation operating in Alberta, and the consumers are the residents of Alberta who purchase oil from Cenovus. According to Cenovus's annual report for 2023, its total production in Alberta in 2023 was 593.4 thousand barrels per day [67], whereas the overall oil production in Alberta in 2023 was 6.7 million barrels per day [68]. Thus, Cenovus makes up around 9 percent of total oil production in Alberta. We use this factor of 0.09 to scale parameters for consumers based on the overall Alberta level.

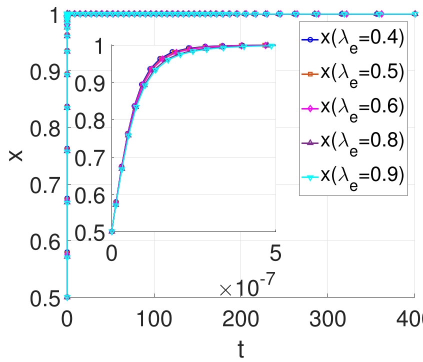
To calculate the cost of energy without the LMA, we use 77.62 Canadian dollars (CAD) per barrel as the average cost of WTI per barrel for 2023 [68] multiplied by daily liquid oil consumption in Alberta, which is 2450×10^3 barrels/day [69], multiplied by 365, and scaled with a 9 % factor.

We assume that the environmental benefits under the LMA for consumers are equivalent to 10 % of the total carbon tax charge for Albertians, given that methane emissions are only a fraction of the total greenhouse gas emissions. Carbon tax charge rates for Alberta in 2023 were 0.1431 CAD per litre of gasoline [70], while the average gasoline price in Alberta was 1.3434 CAD per litre [71], which gives a ratio of 0.1065, which we apply to the cost of energy without the LMA to obtain the total fuel charge, which is then scaled by 0.1 to calculate environmental benefits under the LMA for consumers.

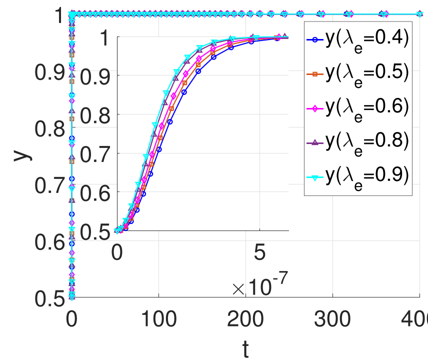
To calculate subsidy rate under the LMA for consumers we use a ratio of environmental benefits for consumers to the sum of that and total amount of methane-related tax for Cenovus. The resulting parameters for consumers are shown in Table 8.

In Cenovus's annual report for 2023 [67], it is stated that they will spend 94 million CAD in 5 years for research and development. Therefore, we calculate the R_e parameter by dividing this amount by the number of years. As the carbon tax in Alberta was 65 CAD per tonne of CO_2-equivalent in 2023, and Cenovus reported 0.4 MtCO2e [72], we estimated Cenovus methane related tax for this year as 26 million CAD.

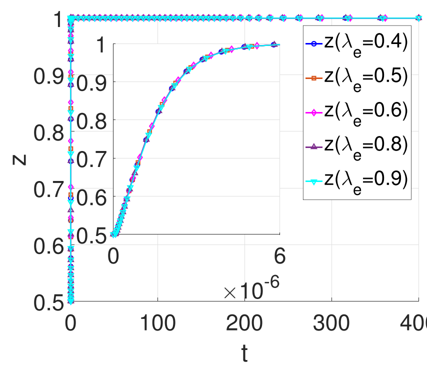
Based on the green policy of the LMA, we assume that green energy prices will rise by 2 CAD per barrel, resulting in the growth of the cost of energy, which provides environmental benefits for the company in the future. The price of a green barrel increases by roughly 2.6 % according to [68], resulting in an energy cost of approximately 6.411 billion



(a) Government



(b) Company



(c) Consumers

Fig. 6. Effects of λ_e on the evolution of stakeholders regarding the LMA.

CAD under the LMA, as indicated in Table 8. The subsidy rate under LMA for Cenovus is calculated based on λ_c and formula 3. The resulting parameters for the company are shown in Table 9.

Emissions Reduction Alberta (ERA) is the Climate Change and Emissions Management Corporation, receiving funding from the Government of Alberta. ERA announced funding committing 34.5 million CAD for late-stage projects and 22.5 million CAD for early-stage projects [73]. We use these amounts as the government subsidies and research and development costs, respectively.

To estimate environmental management costs without the LMA, we convert methane emissions into CO_2-equivalent units, determine the area of planted forest required to offset these emissions, and afterwards calculate the associated planting costs. According to [74], one hectare of forest, on average, absorbs 2.98 tonnes of CO_2-equivalent per year. Planting one tree costs about 5 CAD, and one hectare might contain 800–5000 trees [75], which results in a cost of 4000–25,000. We use 14,500 CAD per hectare as the average cost of planted trees. Based on (1), we assume that environmental benefits under the LMA are equal to environmental management costs without the LMA. The resulting parameters for the government are shown in Table 9.

The methane lifespan in the atmosphere is about a decade [76]. Thus, we assume methane decay rate β to be equal to 0.1. Based on sensitivity analyses conducted on Section 4, we architecture the rest of parameters based on all stakeholders positive evolutionary decisions towards the LMA. Here, we assume that $\gamma_1 = 0.9$, $\gamma_2 = 0.7$, $\gamma_3 = 0.5$ (2), $\gamma_4 = 0.9$, $\alpha_1 = 0.9$, $\alpha_2 = 0.1$, $w_e = 1$ and $w_c = 1$. Last assumptions are due to paying more attention to the social welfare of Cenovus and energy consumers.

Fig. 12 illustrates that both the government and the company accept the LMA, regardless of green energy prices, as the government demonstrates a more rapid evolution toward it. On the other hand, consumers only accept the LMA when the green price is the lowest among others, rejecting other prices. Here, we find our threshold as

$$\hat{\mu} = \frac{6250}{6300} \approx 0.992,$$

and we say any green or methane-free energy price $P_{c1}(\mu_a)$ with satisfactory rate μ_a satisfying

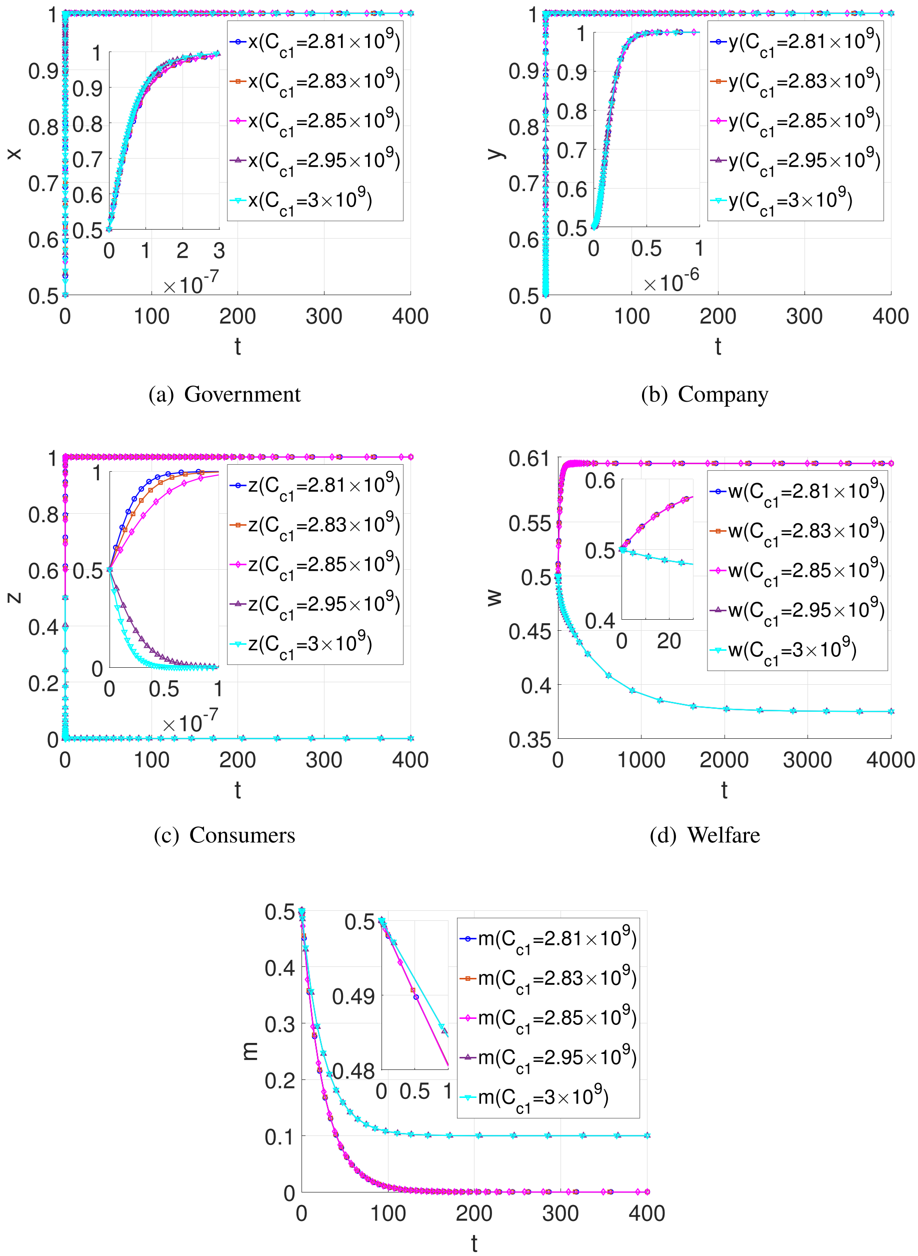
$$\mu_a \in [0.992, 1),$$

is affordable. In case of $\mu_a = 0.992$, we find our affordable green energy price as $P_{c1}(\mu_a) = 78.24$ CAD per barrel, which is 1.38 CAD less than the normal green energy proposed initially for the LMA, and it is 0.62 CAD more expensive than the original non-green energy when the LMA is not embraced.

Fig. 13 indicates that the evolutionary-based LMA, with an energy price of $P_{c1} = 78.24$ CAD per barrel, is accepted by all stakeholders, resulting in a social welfare level of approximately 51.5 percent. This price makes the energy supply chain more accessible, environmentally friendly, and robust, ensuring a high social welfare.

4.3. LMA and beyond

In this section, in addition to the integration of the LMA framework into the Alberta energy supply chain, we extend our case study analysis to the United States (U.S.). Specifically, we examine the dynamics involving ExxonMobil, the largest oil company in the U.S. as identified in its 2024 annual report, alongside the U.S. government and American consumers, to explore the applicability of LMA in fostering an affordable green energy market.

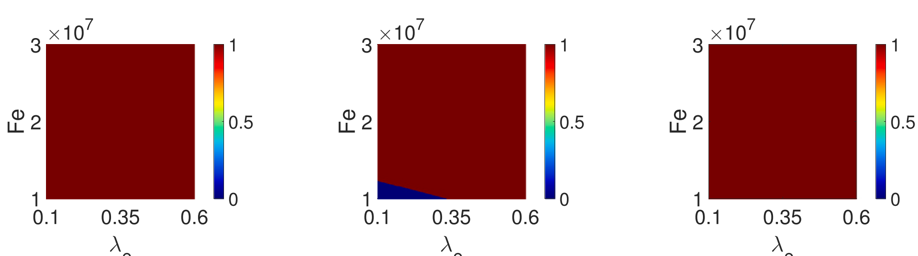


(a) Government (b) Company

(c) Consumers (d) Welfare

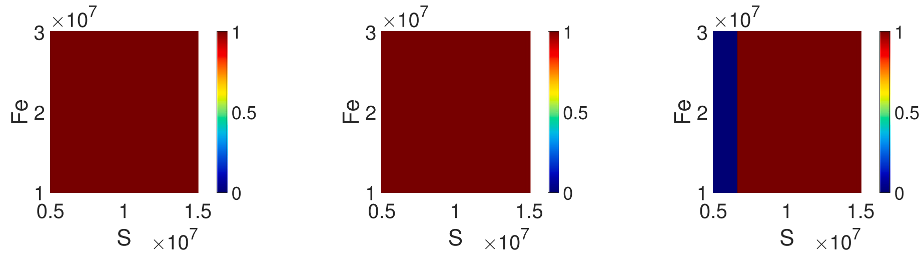
(e) Methane

Fig. 7. Effects of C_{c1} on the evolution of stakeholders regarding the LMA.



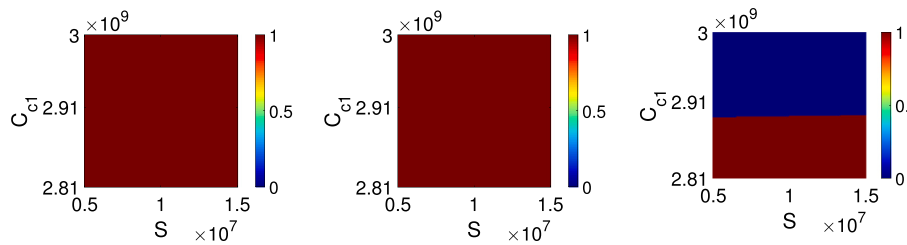
(a) Government (b) Company (c) Consumers

Fig. 8. Effects of subsidy rate (λ_e) and methane-related tax (Fe) on LMA adoption.



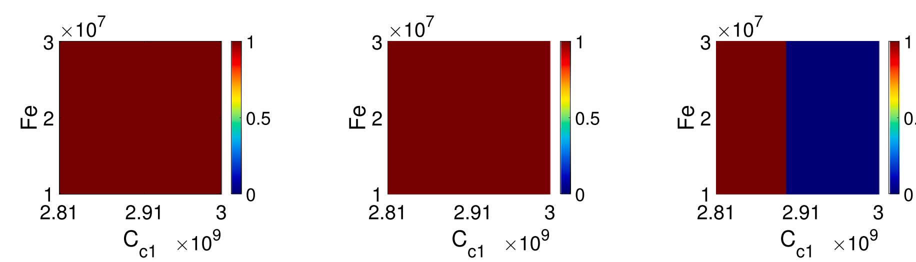
(a) Government (b) Company (c) Consumers

Fig. 9. Effects of government subsidy (S) and methane-related tax (Fe) on LMA adoption.



(a) Government (b) Company (c) Consumers

Fig. 10. Effects of government subsidy (S) and green energy cost (C_{c1}) on LMA adoption.



(a) Government (b) Company (c) Consumers

Fig. 11. Effects of green energy cost (C_{c1}) and methane-related tax (Fe) on LMA adoption.

Table 8
Parameters of consumers in Alberta, Canada for 2023.

Value	Unit	Parameter	Description
6.25[a]	bil. CAD	C_{c2}	Cost of non-green energy without the LMA
6.411	bil. CAD	C_{c1}	Cost of green energy under the LMA
66.56	mil. CAD	E_c	Environmental benefits under the LMA
0.72		λ_c	Subsidy rate under the LMA

[a] According to U.S. Energy Information Administration [69].

Table 9
Parameters of Cenovus oil sand company for 2023.

Value	Unit	Parameter	Description
18.8[a]	mil. CAD	R_e	R&D costs
0.4[b]	MtCO2e		Total Methane emissions
0.28		λ_e	Subsidy rate under the LMA
161	mil. CAD	E_e	Environmental benefits under the LMA

[a] According to Cenovus annual report for 2023 [67].
[b] According to Upstream Petroleum Industry Emissions Report to Alberta Energy Regulator for 2023 [72].

A detailed case study analysis is provided in Appendix. In this regard, consumers parameter values are given in Table A1, those for ExxonMobil are presented in Table A2, and the values corresponding to the U.S. government are summarized in Table A.3.

Fig. 14 illustrates that both the government and the company accept the LMA, regardless of green energy prices, as the government demonstrates a more rapid evolution toward it. On the other hand, consumers accept the LMA only when the green cost $C_{c1} \leq 665$, rejecting any price above this threshold, as shown in Fig. 15.

Here, we find our threshold as

$$\hat{\mu} = \frac{658}{665} \approx 0.989,$$

and we say any green or methane-free energy price $P_{c1}(\mu_a)$ with satisfactory rate μ_a satisfying

$$\mu_a \in [0.989, 1),$$

is affordable. In case of $\mu_a = 0.989$, we find our affordable green energy price as $P_{c1}(\mu_a) = 77.41$ USD per barrel, which is 1.19 USD less than the

Table 10
Government parameters for 2023.

Value	Unit	Parameter	Description
34.5[a]	mil. CAD	S	Amount of subsidies
22.5[b]	mil. CAD	R	Amount of R&D
26[c]	mil. CAD	F_e	Amount of methane-related tax
2.7	bil. CAD	M_g	Costs for environmental management

[a] Based on Government of Alberta's Technology Innovation and Emissions Reduction (TIER) fund [73].
[b] According to Competition 2 of Hydrogen Centre of Excellence [73].
[c] According to Cenovus annual report for 2023 [67].

normal green energy proposed initially for the LMA, and it is 0.81 USD more expensive than the original non-green energy when the LMA is not embraced.

4.4. Comparative analysis

The Low Methane Application (LMA) framework advances methane-abatement modeling by treating collaboration, policy, behavior, and affordability as one coupled system. Whereas strands of the literature move toward multi-actor integration, the typical pattern is still fragmented: some streams fold in market design and consumer response but keep the public sector largely exogenous, while others model cooperation inside the supply chain without the consumer or a truly adaptive state [60,77–79]. LMA positions the government–industry–consumer triangle as central to strategy formation, enabling the coevolution of policy signals, firm decisions, and household adoption rather than their future integration.

A central comparative advantage of LMA lies in its treatment of government. Evidence across policy and governance studies shows that taxes, subsidies, and price mechanisms can raise compliance and shape competitiveness, yet these instruments are commonly specified as static, top-down levers [61,80,81]. LMA instead models the state as

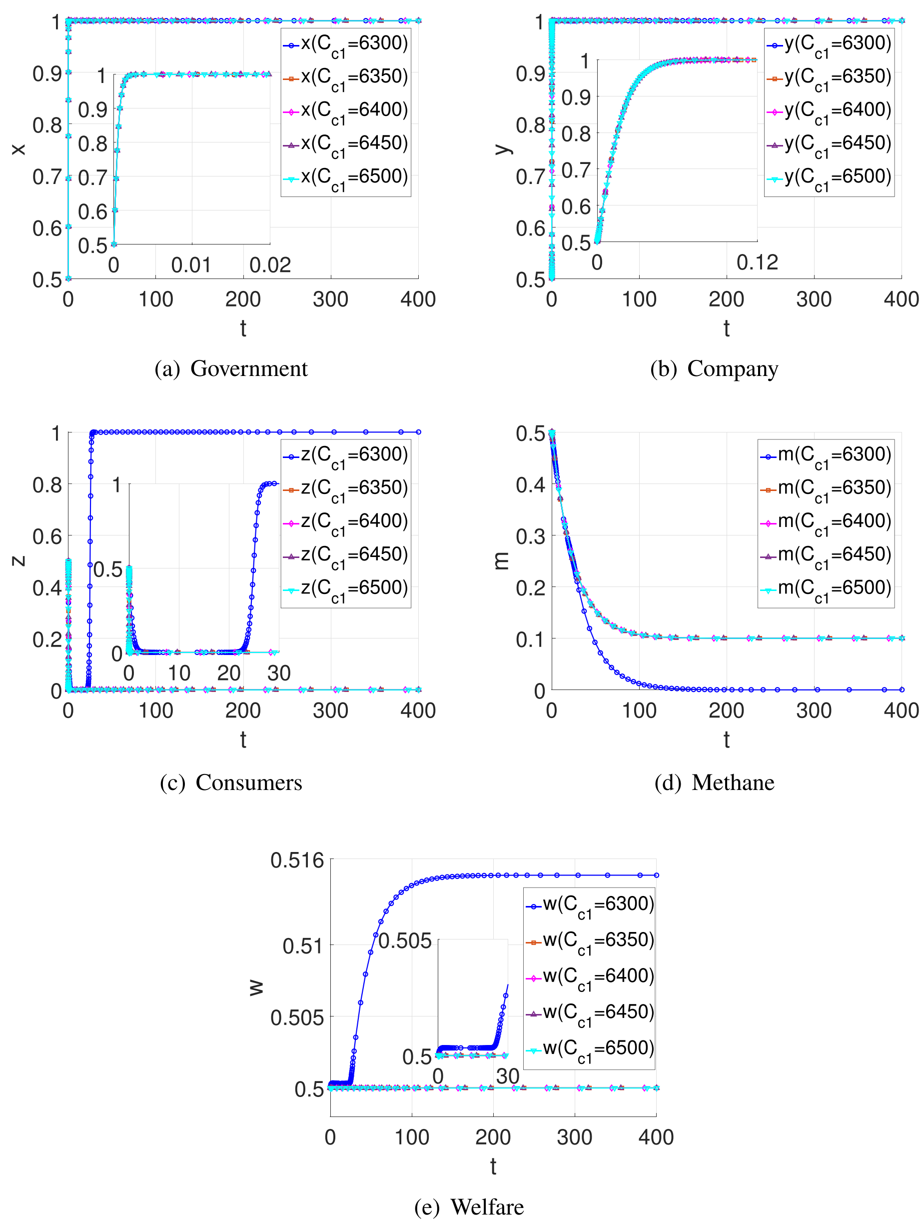


Fig. 12. Effects of C_{c1} on the evolution of the government, the energy company, consumers, and welfare indices based on realistic data.

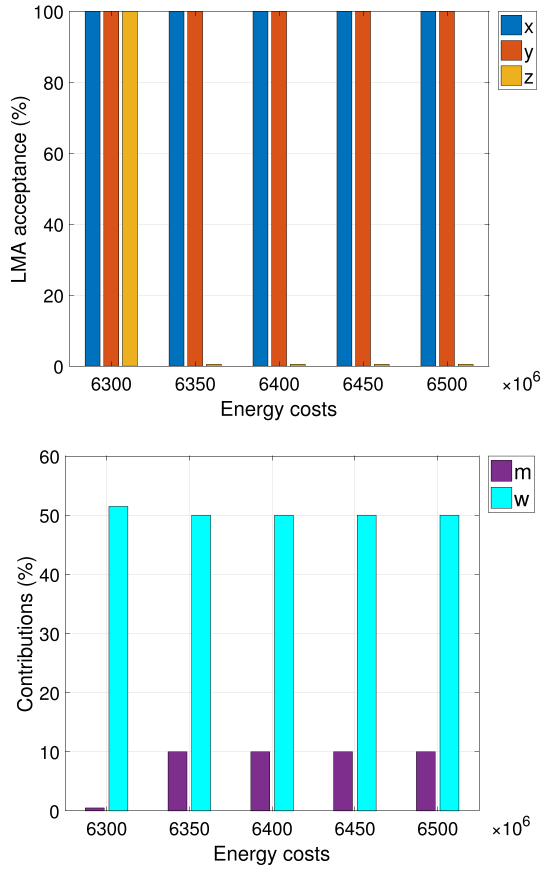


Fig. 13. Effects of energy prices on the evolutionary outcomes of the government, the energy company, consumers, and welfare indices based on realistic data.

a strategic transformer of the game, adjusting penalties, rewards, and adoption thresholds in response to observed behavior, market phases, and environmental efforts. The result is not a one-off calibration of parameters but a feedback-driven policy engine that steers the system toward welfare-enhancing equilibria while remaining sensitive to real-time signals that conventional designs leave outside the model boundary.

On the behavioral side, LMA departs from static or purely simulation-based representations by embedding eco-evolutionary adoption dynamics. Work emphasizing payoffs without explicit evolutionary propagation offers valuable comparative statics yet leaves the transmission of strategies under-specified [59,77,80]. In contrast, evolutionary game approaches provide mechanisms for how strategies spread, stabilize, or collapse, typically within firm networks or supply chains [78,79,82]. LMA aligns with the evolutionary tradition while extending it: the replicator and reinforcement logic is directly linked to environmental and economic performance, allowing externalities such as emission levels and welfare benchmarks to influence the incentives governing propagation, rather than being treated as mere final-stage metrics.

Affordability serves as a distinguishing factor for LMA. Consumer-side costs have been recognized in various strands of market design and trade literature, encompassing concepts such as pricing-penalty uplift and competitive emissions arrangements [60,61]. What remains uncommon is an explicit affordability threshold linked to price elasticity and participation gates. LMA integrates these features into the adoption logic, rendering uptake dependent on socially realistic pricing conditions, thus safeguarding the political sustainability of low-methane transitions, an aspect that models treating cost and environmental performance as distinct objectives find challenging to address.

Finally, LMA translates macro-level imperatives into deployable rules. Integrated environmental economy analyses have clarified the necessity for targeted strategies regarding methane by quantifying its upcoming impact and associated system-wide costs [26]. LMA carries that rationale from abstraction to practice by wiring methane-specific goals into an operational policy architecture that interacts with supply-chain behavior and household response. In comparative perspective, this closes the gap between models that diagnose the need for methane focus and frameworks that can actually orchestrate change across public, private, and consumer domains.

Taken together, Fig. 16 shows that LMA's triadic collaboration, adaptive governance, evolutionary adoption, and affordability constraints act as mutually reinforcing elements rather than the isolated parts often found in recent literature. By tying behavior to emissions and welfare while enabling adaptive policy, the framework offers a clearer pathway from principle to implementation than static or single-actor approaches.

4.5. Policy implications

This section provides practical and managerial insights for government entities and supply chain participants to implement the suggested evolutionary-based low-methane application in their markets, backed by data from case studies in Canada and the U.S. and sensitivity analysis.

The Low-Methane Application (LMA) demonstrates that affordability and environmental integrity can go hand in hand. Our simulations show that when methane abatement is monetized and reinvested through the supply chain, consumer prices remain stable—or even slightly lower—compared to conventional energy prices (e.g., 78.24 CAD vs. 79.62 CAD in Canada; 77.41 USD per barrel in the U.S., about 1.19 USD below the benchmark). This finding aligns with the International Energy Agency's latest evidence that a significant share of methane abatement is available at no net cost [83]. Regional studies, such as recent work in Malaysia, further confirm that more than half of upstream methane can be abated without raising costs, showing that affordability thresholds can bind without sacrificing climate performance [84]. Importantly, the price impacts of methane charges are modest compared to normal commodity market fluctuations, which is consistent with the U.S. 2024 analysis of the environmental charge [85].

Where LMA adds policy value is in how it turns detection and repair into enforceable economics. Advances in sensor networks, satellite monitoring, and hybrid inventories mean that invisible methane losses can be measured and managed with growing accuracy [86]. Evidence from Alberta and Saskatchewan shows that improved monitoring, combined with regulation, has already driven substantial declines in emissions without cutting production [87]. Applied to a government tree-planting program under LMA, the approach is straightforward yet effective: prioritize planting on dry, well-drained soils that naturally capture methane, while avoiding boggy areas prone to emissions [88]. The revenue from verified carbon credits can then be reinvested to reduce household energy bills and support small operators, making the program self-financing without increasing costs.

From a consumer perspective, the question of "who pays" is central. In liberalized markets, environmental costs often pass through to end users, sometimes at high rates [89]. LMA tackles this by tying pass-through rules to evolutionary dynamics, ensuring that captured-gas revenues lower bills when affordability constraints bind. In regulated markets, where the cost of lost gas has traditionally been passed on to consumers, LMA's government program offers financial incentives to green energy users based on captured methane savings, aligning with empirical evidence regarding regulated gas distributors' capacity to pass leak costs to customers [90].

Governance is equally critical. LMA treats the state not as a passive tax collector but as a strategic actor. Canada's methane reduction pathway toward a 75 % cut by 2030 already illustrates how environmental

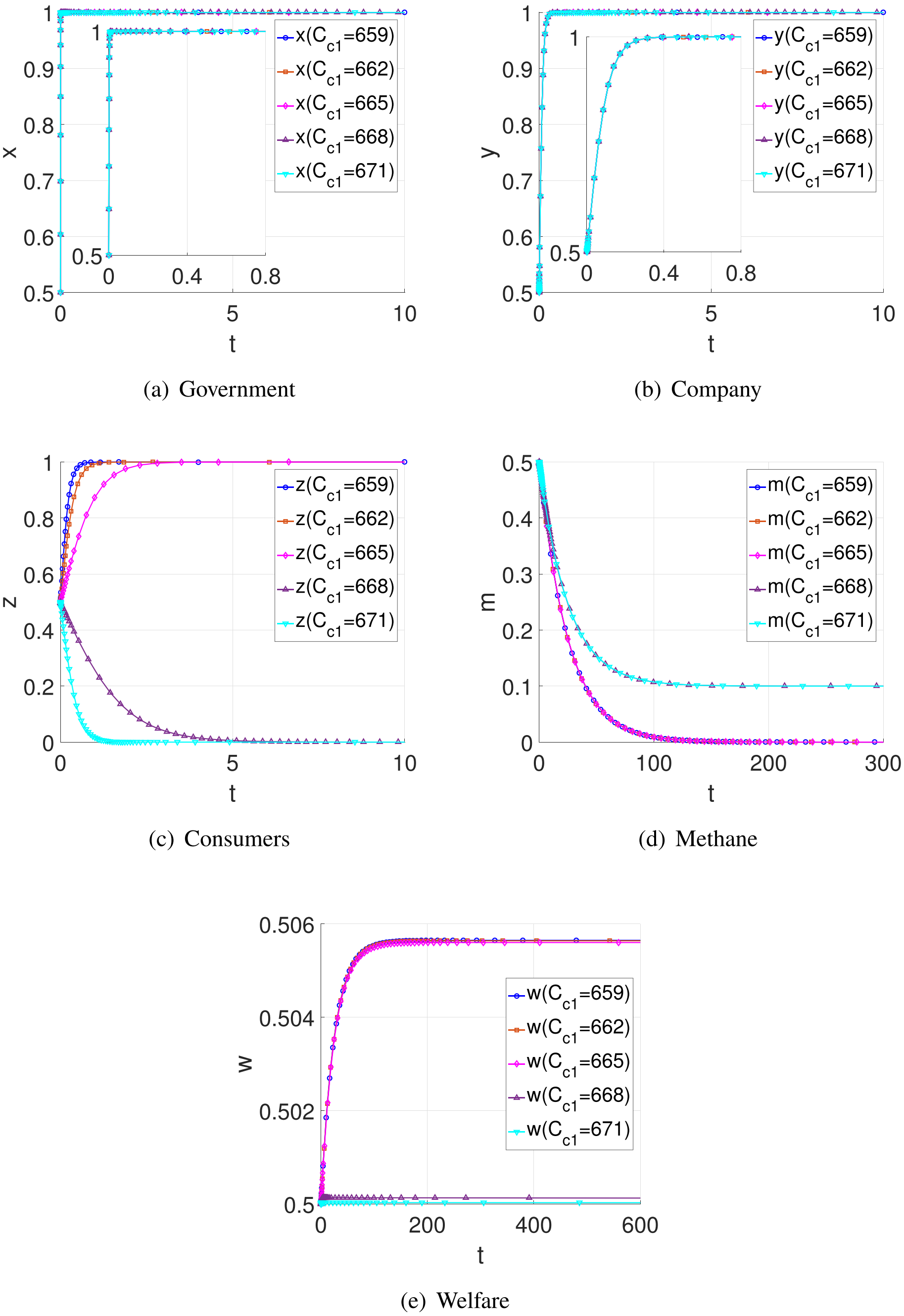


Fig. 14. Effects of C_{c1} on the evolution of the government, the energy company, consumers, and welfare indices based on realistic data.

efforts, performance targets, and fiscal tools can be coordinated, mechanisms that LMA embeds within its controller logic [91]. In the U.S., environmental efforts regarding new methane standards provide similar scaffolding, though recent repeal attempts highlight the need for LMA to remain adaptable to shifting politics [92]. By recycling fiscal gains, estimated at over 2.7 billion CAD in our scenarios, into targeted subsidies and R&D, LMA also prevents small operators from being stranded in the low-methane transition.

Finally, realism about market dynamics matters. The analytical framework of the LMA suggests a unique, globally stable equilibria; however, this assumption overlooks empirically observed characteristics of energy markets, including the presence of multiple locally stable equilibria, lock-in dynamics, and significant path dependence [93]. In these circumstances, it cannot be assumed that there will be autonomous convergence to a low-methane outcome. Purposeful, early-stage, and precisely targeted interventions, such as intensive leak detection and repair, accelerated equipment turnover, and time-limited financial support, are generally necessary to alter the system's trajectory towards a low-emissions basin of attraction [94]. In the LMA framework, the single-equilibrium representation should be viewed as a tool for tractability rather than a predictive assertion, given that behavioral and environmental feedback can stabilize both high- and low-emission regimes [95]. The policy implication involves creating instruments that address coordination failures and lock-in effects, intentionally guiding the system towards a low-methane equilibrium. Then, support should be gradually reduced and adjusted once this state is achieved to maintain adaptability and prevent excessive intervention.

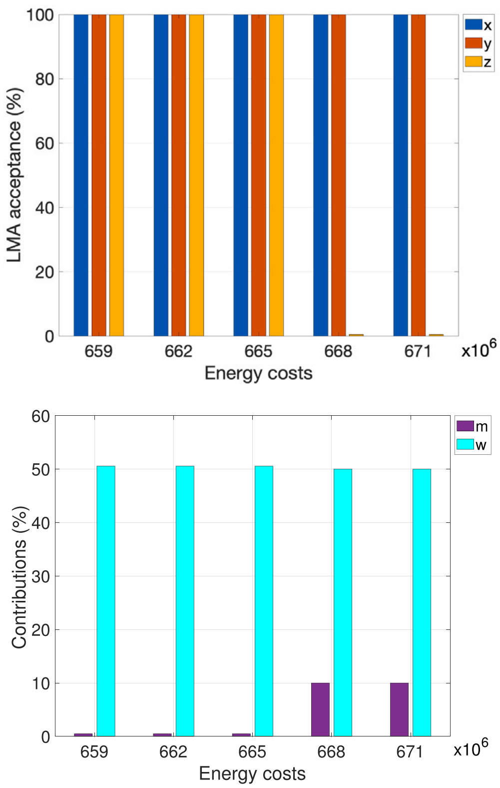


Fig. 15. Effects of energy prices on the evolutionary outcomes of the government, the energy company, consumers, and welfare indices based on realistic data.

	This Study	Aleshina et al. (2024)	Guo et al. (2023)	Olczak et al. (2023)	Li et al. (2021)	Wang et al. (2024)	Bera & Giri (2023)	Acosta et al. (2023)	Azar et al. (2023)	Zhao et al. (2023)	Piria & Görlach (2024)
LMEC	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗
GLEM	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
EEAE	✓	✗	✓	✗	✗	✓	✓	✗	✗	✗	✗
WGTE	✓	✓	✗	✗	✓	✗	✓	✓	✓	✓	✓
AEPT	✓	✗	✗	✓	✗	✗	✗	✓	✗	✓	✗

Fig. 16. Comparative analysis of LMA with recent studies based on its five achievements: Low-Methane Energy Collaboration (LMEC), Government-led Emission Management (GLEM), Eco-Evolutionary Adoption Equilibria (EEAE), Welfare Gains Through Emission (WGTE) and Affordable Energy Price Threshold (AEPT).

In summary, LMA provides a mechanism for reducing methane emissions while maintaining affordable prices, increasing welfare gains, and expanding fiscal capacity. Evidence from Canada and U.S. indicates that this is not only achievable but is already in progress when monitoring, regulation, and affordability safeguards operate collaboratively.

5. Conclusions

The study explores the integration of the LMA into the energy supply chain, proposing a green pricing framework to enhance market robustness and accessibility.

5.1. Main outcomes

The main outcomes of this study are presented as follows:

- A novel evolutionary-based low-methane application provides significant motivation for the government, the energy company, and consumers to establish environmentally friendly and cost-effective energy collaboration within the supply chain.
- The government prioritizes the LMA to mitigate environmental management costs associated with methane emissions. This approach aims to transform damages into increased subsidies and research and development for supply chain participants, thereby promoting long-term sustainability.
- The proposed high-order eco-evolutionary game dynamics establish stable equilibria for the acceptance of the LMA among all stakeholders within the supply chain.
- It is feasible to enhance social welfare for both the company and consumers while simultaneously reducing methane emissions under the LMA.
- The LMA establishes a cost-effective, approved methane-free energy market within the region, as stated by the game framework.

5.2. Limitations

While the construction of a sustainable and clean energy supply chain offers significant advantages, it also has several limitations and challenges that might restrict its extensive implementation. One notable limitation of this work is that it involves three key candidates: the government, the company, and consumers. In general, the energy supply chain involves multiple energy companies. Nevertheless, this limitation could be addressed by building a common cooperation on energy price and energy parameters of those companies, including subsidy, R&D, and benefits, possibly resulting in a greater number of parameters in the LMA. Once energy companies achieve a common agreement, they can participate in the LMA as a single entity under this engagement. Moreover, the integration of the LMA into the supply chain may encounter limitations due to external market forces such as macroeconomic conditions, political stability, and global events. Fortunately, this study operates under the assumption that the government consistently maintains its research and green policies—tax, subsidy, and R&D—for supply chain members, regardless of any potential adverse effects in the region.

5.3. Future works

Our future agenda involves investigating evolutionary game theory frameworks within a broadened energy supply chain comprising multiple governments. Unlike having multiple companies in a region, different governments link their regulatory policies to those of their respective energy companies and consumers, with the aim of fostering sustainability in the development of green and cost-efficient energy markets. These directions need additional illustration and improvement in our future studies.

While our current framework assumes real-time perception of environmental changes, future work could extend the model to account for delayed stakeholder responses. One promising direction is to incorporate lagged perception functions or adaptive expectations, which would allow stakeholders to update their strategies based on imperfect or delayed environmental information. Another approach is to model information diffusion mechanisms, where awareness spreads gradually through the network of stakeholders. Such extensions would allow exploration of how perception delays affect the stability of cooperative equilibria, the persistence of free-riding behavior, and the effectiveness of policy instruments such as taxes, subsidies, or information campaigns.

CRediT authorship contribution statement

Haihui Cheng: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ali Hamidoğlu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Liubov Sysoeva:** Writing – review & editing, Writing – original draft, Validation, Methodology, Data curation, Conceptualization. **Pablo Venegas Garcia:** Writing – original draft, Conceptualization. **Russell Milne:** Writing – original draft, Funding acquisition. **Zvonko Burkus:** Writing – original draft, Validation. **Hao Wang:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Funding acquisition.

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. Liubov Sysoeva reports financial support was provided by Natural Sciences and Engineering Research Council of Canada. Russell Milne 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. U.S. case study

This section examines a U.S. case study centered on the implementation of the LMA framework in ExxonMobil's operations, the largest oil corporation in the nation, to assess the framework's relevance in facilitating low-methane energy transitions within the American energy sector. The annual report for 2024 of ExxonMobil states U.S. production of 862 thousand barrels per day [96], while the total oil production in the U.S. in 2024 was 13.2 million barrels per day [97]. Thus, ExxonMobil makes up around 6.5 percent of total oil production in the U.S. Here, we use this factor of 0.065 to scale parameters for consumers from the overall U.S. level.

To calculate the cost of energy without LMA, we use 76.6 USD per barrel as the average cost of WTI per barrel for 2024 [98] multiplied by daily liquid oil consumption in U.S., which is 362 thousand barrels per day [99], multiplied by 365, and scaled with 6.5 % factor. Moreover, we assume the environmental benefits under LMA to be equal to 10 percent of the total U.S. federal excise tax on gasoline as we consider a whole country, and methane emissions are just a part of the GHG emissions.

The United States federal excise tax on gasoline in 2024 was 18.4 cents per gallon of gasoline [100], while the average gasoline price in the U.S. in 2024 was 3.304 USD per gallon [101], which gives a ratio of 0.056 that we apply to the cost of energy without LMA to obtain the total excise tax, which is then scaled by 0.1 to calculate environmental benefits under LMA for consumers. To calculate the subsidy rate under LMA for consumers, we use a ratio of environmental benefits for consumers to the sum of that and the total amount of methane-related tax for ExxonMobil. The resulting parameters for consumers are shown in Table A1.

In its annual report for 2024, ExxonMobil stated 987 million USD in research and development costs and reported methane emissions as 0.03 metric tons of methane per 100 metric tons of production [96]. In this study, we consider a focused allocation of 6 million USD within the reported R&D expenditure, specifically directed toward methane emission reduction technologies. Based on methane emissions, ExxonMobil's U.S. production, and the Biden administration's proposed methane fee of 900 USD per metric ton for 2024, we calculated ExxonMobil's total methane-related tax to be 13.29 million USD.

In addition, we assume that the green energy price under the LMA will rise by 2 USD per barrel, resulting in the growth of the cost of energy, which we will denote as environmental benefits for the company. The subsidy rate under LMA for ExxonMobil is calculated based on λ_c and formula 3. The resulting parameters for the company are shown in Table A2.

The Global Carbon Capture and Storage Institute's 2024 report [102] indicates that 10 billion USD has been allocated (or is under negotiation) to facilitate carbon management and clean hydrogen hubs, with 4 operational Direct Air Capture projects and 16 in different phases of development.

Based on ExxonMobil's 6.5 % share of U.S. oil production and a 10 billion USD carbon management fund reported by the Global Carbon Capture and Storage Institute [102], we allocate 650 million USD to ExxonMobil's emission efforts—10 million USD for subsidies and 640 million USD for R&D as shown in Table A.3.

To estimate the environmental management costs without LMA, we convert ExxonMobil's methane emissions into CO_2-equivalent units using the methane global warming potential over a 100-year period (28) as a scaling factor. Afterwards, we translate this into the area of planted forest, similar to the Alberta case. The resulting parameters for the government are shown in Table A.3.

Table A1
Parameters for consumers in the U.S. for 2024.

Value	Unit	Parameter	Description
658[a]	mil. USD	C_{c2}	Cost of non-energy without LMA
675	mil. USD	C_{c1}	Cost of green energy under the LMA
3.7	mil. USD	E_c	Environmental benefits under LMA
0.72		λ_c	Subsidy rate under LMA

[a] According to the U.S. Energy Information Administration [97].

Table A2
Parameters for ExxonMobil for 2024.

Value	Unit	Parameter	Description
6	mil. USD	R_e	R&D costs
0.28		λ_e	Subsidy rate under LMA
17.18	mil. USD	E_e	Environmental benefits under LMA

Table A.3
Parameters for the U.S. government for 2024.

Value	Unit	Parameter	Description
10[a]	mil. USD	S	Amount of subsidies
640[a]	mil. USD	R	Amount of R&D
13.29[b]	mil. USD	F_e	Amount of methane-related tax for companies
1	bil. USD	M_g	Costs of environmental management without LMA

[a] According to Global Carbon Management Foundation [102].
[b] According to ExxonMobil annual report for 2024 [96].

Data availability

Data for the case study in the paper were obtained from the annual financial reports of Cenovus Oil Sand Company, Emissions Reduction Alberta, and Tree Canada. Further data on the tax percentage and subsidy rate for energy in Alberta were sourced from the Alberta provincial government. All these datasets are public. Similarly, data related to the U.S. case study—including oil production, pricing, consumption, taxation, and corporate financials—were obtained from publicly accessible government and industry sources such as the U.S. Energy Information Administration, the U.S. Department of Transportation, and ExxonMobil's corporate reports.

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