Evolutionary Game Theory Model of the Renewable Energy Market

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Abstract

This study explores the factors that influence consumer choices on whether to invest in renewable energy sources versus fossil fuels, focusing on solar and wind energy. Motivated by the current climate crisis, highlighted by the IPCC's projection of a critical global temperature rise by 2030, and the fluctuating costs of fossil fuels exacerbated by military conflicts, this research underscores the economic and environmental benefits of transitioning to renewable energy. Using an evolutionary game theory approach, we model consumer behavior and tax incentives in the Texan renewable energy market based on the Public Goods game. The model takes into account how varied levels of multiple factors, such as tax rebates and personal environmental concern, impact consumer decisions, assuming a fixed income. Our results show that the level of tax incentives needed to incentivize people to adopt renewable energy varies widely by level of environmental concern. For those with low and medium concern, the evolutionary stable strategy (ESS) becomes wind energy at a 55% and 35% tax incentive, respectively. However, for those with a high level of environmental concern, the ESS is also wind energy but without any tax incentive. These findings imply that government interventions are necessary to encourage people that are not as environmentally conscious to adopt renewable energy sources and limit the climate crisis.

Keywords: renewable energy, consumer behavior, tax incentives, climate change, solar energy, wind energy, fossil fuels, evolutionary game theory

1 Introduction

A 2022 report published by the U.N. Intergovernmental Panel on Climate Change (IPCC) estimates that by 2030, global temperatures will surpass a critical threshold of 2.7°F above pre-industrial levels [1,2]. Scientists predict that surpassing this threshold will induce unprecedented levels of famine, disease, and environmental crises around the globe [1, 2]. A major contributor to this impending crisis is continued reliance on fossil fuels. Fossil fuels are a generic term for a multitude of energy sources such as coal and crude oil [3]. When these energy sources are burnt for energy consumption, they produce greenhouse gas emissions, such as carbon dioxide, that are toxic to both humans and the environment [4] With these all-encompassing negative impacts, climate activists have been calling for a revolution in the energy industry towards large-scale use of renewable energy.

Though fossil fuels were previously known for being cheaper, new global conflicts and societal costs have revealed the expensive reality of nonrenewable energy costs. Cost-wise, fossil fuels are colloquially known as being cheaper than renewable energy sources, which has been changing over the years. Unfortunately, fossil fuels are incredibly sensitive to changing fuel and oil prices, oftentimes rendering it more expensive than renewable energy sources [5]. A prominent example of this was in 2022 with the beginning of Russia's war against Ukraine, where energy prices soared by 14.3% due to the stoppage of energy production from those countries. Here, fossil fuels proved to be quite expensive for governments around the world as they scrambled to subsidize fossil fuel production to cushion consumer expenses [6, 7]. Additionally, climate experts are sounding the alarm that with societal costs, such as air pollution-related deaths and climate-change-related natural disasters, fossil fuels carry a hefty price [8]. These economic and social costs point toward a green future where we move away from fossil and towards renewable energy sources, such as solar and wind.

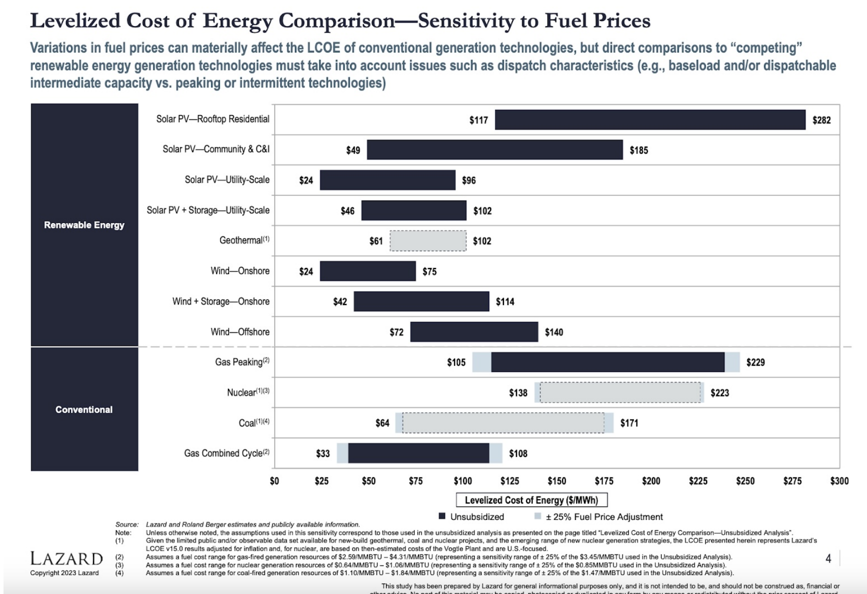


Fig. 1: Price of renewable energy and fossil fuels based on variations in fuel prices
Source: [5]

Therefore, it is imperative that our society invests in alternative energy sources, such as solar and wind energy. By harnessing the natural forces of sunlight and wind, renewable energy sources offer a path towards decarbonization reducing greenhouse gas emissions. The current project seeks to evaluate the factors that contribute to consumers' decisions to invest in renewable energy sources versus those that motivate them to continue to invest in fossil fuels.

The current project will focus on two sources of renewable energy. The first source we will consider is photovoltaic solar technology. In the simplest terms, photovoltaic (PV) technology involves converting sunlight to electricity. This is made possible by taking advantage of the photoelectric effect, as PV cells are constructed utilizing semi-conductor materials [9]. When photons strike a PV cell, the semi-conductor material becomes ionized, causing the photons' electrons to break out of their outer shell [9]. The conductive properties of the PV cell then force the electrons to flow, providing an electrical current [9].

Although PV cells are relatively new technology, they are already experiencing rapid improvements, leading to lower prices. Indeed, the costs associated with the installation and maintenance of PV cells have trended downwards since the early 2000s [10]. In fact, between 2009 and 2017, the costs associated with PV cells fell by close to 60% [10–12]. To put these costs in perspective, the current project will consider the costs associated with the installation and operation of an average PV system. On average, a PV system will consist of an 11 kW solar panel system [12]. In 2024, the average price associated with an 11 kW solar panel system is $22,022 [10]. Although this figure initially seems steep, the US government provides tax credits to incentivize the transition to cleaner, more sustainable energy systems. Relatedly, in 2024, federal tax credits reduce the costs associated with solar panel systems by close to 30% [13]. Further, by utilizing solar panel systems, homeowners can expect to save, on average, between 20,000 and 90,000 dollars in electricity costs over the next 25 years [10]. The current project, however, will consider the costs of solar panel systems in terms of USD/kwH; more specifically, we consider the costs of solar panel systems to be $0.413 per kWh, based on the results of a 2023 Bank of America study, which utilized a levelized full system cost of electricity (LFSCOE) to consider the combined costs of installation and maintenance [14].

The second renewable energy source we will consider is wind farms. The process of switching from fossil fuel-driven systems to wind-driven systems is markedly different than that of transitioning from fossil fuels to solar panel systems. This is because to utilize wind-driven systems, a consumer would have to become invested in a broader community to which energy is delivered from an onshore wind farm. These communities receive energy through a wind turbine located on land (as opposed to offshore turbines, which are more popular in Europe; [15]. Wind itself rotates the turbines' blades, creating kinetic energy that is then harnessed to provide clean, renewable electrical energy. This is made possible by the turbines' hubs, which contain rotating shafts (low and high speeds), generating enormous amounts of force [16]. Once this force is passed to the generator, it is converted into electricity, and an electrical current is produced in the converter [16]. Following this transformation, the energy is passed through the evacuation line, which connects the wind farm to a grid that will provide energy to nearby communities [16].

The costs associated with wind energy have also trended downwards, due to incentives provided by the government and improvements in technology, specifically those related to installation [12]. The current project will consider the 2023 Bank of America report's LFSCOE cost for onshore wind energy systems, which is valued at $0.291 per kWh.

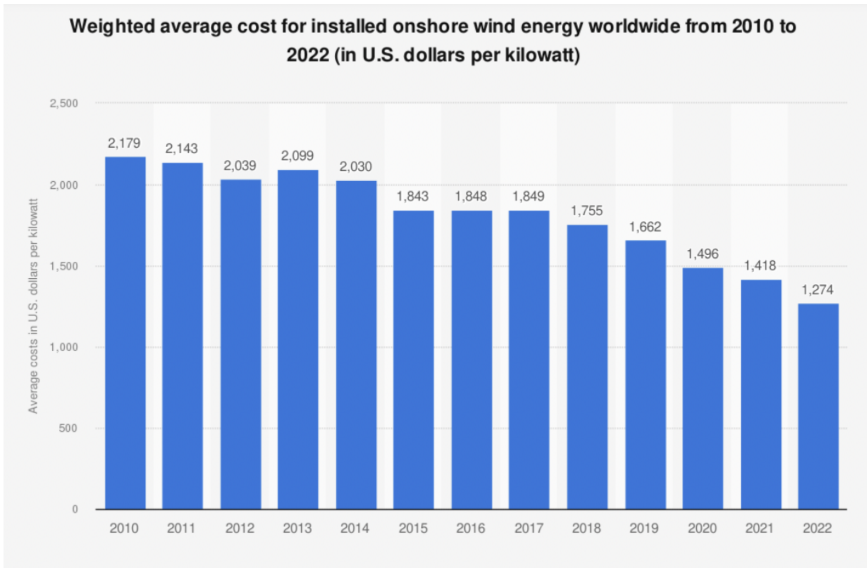


Fig. 2: The average global cost of onshore wind farms has trended downwards over the past decade. Source: [17]

It is important to note that the 2023 Bank of America report considers the LFSCOE of solar panels and onshore wind systems in Texas. The state of Texas is of particular interest to the current project as well as broader investigations into the dynamics of renewable energy consumption. This is largely due to the Texas climate being particularly well suited for both photovoltaic solar panels and onshore wind systems [18]. Further, the LFSCOE of both systems is lower in Texas compared to the national average [18]. By 2022, Texas generated more electricity from photovoltaic solar panels and onshore wind systems than any other US state [18]. In the context of the current project, we are interested in the factors driving Texans to switch to these renewable energy systems, and how this model can be mapped onto other regions.

1.1 Significance Statement

Understanding consumer choices in regard to renewable energy is critical in moving towards a greener future. Despite monetary incentives and scientific findings in supporting the implementation of renewable energy, only 13.1% of the United States' energy comes from renewable energy [19]. This is concerning as climate change remains a major concern, with scientists warning of irreparable damage to the multiple of Earth's ecosystems and agricultural industry. Interestingly, 67% of American adults support the US prioritizing the development of alternative energy sources to address the climate crisis [20]. By exploring how consumers allocate their energy budget, we provide new insights into how governments can adjust their tax incentives to encourage citizens to use renewable energy.

2 Model & Method

This project employs a game theory approach to model the interactions between key players in the renewable energy market. The objective is to understand how consumers allocate their energy budget among solar, wind, and fossil fuel energy to maximize their payoff, which depends on energy costs, tax incentives, and environmental impact. We also aim to understand how government incentives can help make renewable energy sources compete with non-renewable energy sources. The project is modeled as a Public Goods Game, where consumer choices contribute to or deplete a common environmental resource.

2.1 Construction of the Payoff Matrix

The construction of the payoff matrix involves the use of various data and analytical tools. Relevant economic data includes information on the costs associated with each energy source, such as installation, maintenance, and operational costs that contribute to the overall LFSCOE. Policy data provide details on tax incentives for renewable energy sources and penalties or taxed associated for renewable energy sources and penalties or taxes associated with fossil fuel consumption. Environmental data quantify the harm to the environment induced by each energy source, measured in CO_2 emissions. Game theory software such as Dynamo(Mathematica) was used to simulate and analyze the strategic interactions between consumers and find out which strategy is the evolutionary stable (ESS).

The participants in this game theory model are consumers who choose between different energy sources. The energy sources considered are solar energy, wind energy, and fossil fuel energy. Consumers are modeled as rational agents who aim to maximize their utility by selecting the energy source that provides the best payoff, considering both economic and environmental factors. Additionally, the government acts as a "ghost player," indirectly influencing the decisions of consumers through tax rebate incentives and penalties.

2.1.1 Variables

Key variables in the model include the cost of solar energy (C_S), the cost of wind energy (C_W), the cost of fossil fuel energy (C_F), the environmental impact of solar energy in CO2 emissions (E_S), the environmental impact of fossil fuel energy in CO2 emissions (E_F), the environmental impact of fossil fuel energy in CO_2 emissions (E_F), the tax incentive for renewable energy (T), and the environmental impact multiplier (I). The tax incentives are assumed to take the form of a percentage rebate for solar and wind energy and a percentage tax on fossil fuel energy. These incentives are calculated as a single uniform value for all energy sources. Consumers are assumed to have the same fixed budget to spend on energy, and the environmental impact is calculated based on the average amount of CO_2 emitted by an energy source. The environmental impact multiplier is a factor used in the payoff calculation to quantify the effect of CO_2 emissions on consumer decision-making. Essentially, it represents the weight or significance that consumers place on the environmental harm caused by the energy sources they choose to utilize. In the context of payoff calculation, a higher I increases the penalty associated with the environmental impact of the chosen energy sources.

2.1.2 Payoff Calculation Reasoning

Consumer payoff is inversely proportional to the cost tax applied, minus the combined environmental impact of energy sources used by both players. The environmental impact is multiplied by an "environmental impact multiplier" (I), which simulates the level to which CO_2 emissions affect decision-making. When the cost increases, the payoff decreases proportionally, and vice versa, For instance, if we assume that consumers have a budget of \$100 and the cost of an energy source is \$5 per unit with a 20% tax rebate, the price is effectively \$4, allowing consumers to purchase 25 units of energy with their budget. If the price doubles to \$10, the effective price after the tax rebate is \$8, and the energy utility gained by the consumer is 12.5 units. The combined environmental impact of all energy sources being used is then subtracted from this number to get the net payoff.

The generalized equation for Player i against Player j when Player i plays Solar or Wind energy,

$$\text{Payoff}_i = \frac{1}{C_i(1-T)} - I \cdot (E_i + E_j) \tag{1}$$

or Fossil Fuels

$$\text{Payoff}_i = \frac{1}{C_i(1+T)} - I \cdot (E_i + E_j) \tag{2}$$

2.1.3 Procedures

The procedures for constructing the payoff matrix involve several steps. First, the players and strategies are defined. The main players in the game are the consumers, and the possible strategies include choosing solar energy, wind energy, or fossil fuel energy. Next, payoffs are assigned to each strategy combination. Economic data is gathered to estimate the costs ($_S$, C_W, C_F) and benefits of each energy source, including upfront costs, ongoing expenses, and savings from tax incentives (T). Policy data is collected to determine the impact of tax incentives (T). Policy data is collected to determine the impact of tax incentives and penalties on the payoffs. Environmental data is used to quantify the negative externality (environmental harm in CO_2 emissions, E_S, E_W, $_F$) associated with each energy source. The generalized equations are then applied to calculate the overall payoff for each strategy combination. The payoff for consumers is a function of cost saving, tax incentives, and the penalty for environmental harm.

The payoff matrix is constructed by creating a matrix where rows represent the different energy sources consumers can choose (solar, wind, fossil fuel) and columns represent the strategies chosen by the other player (Player j). The matrix is filled in with the corresponding payoff for each energy source, considering the combined effect of costs, tax incentives, and environmental impact. Table. The payoff matrix is as follows:

Player 1 / Player 2	**Solar (S)**	**Wind (W)**	**Fossil Fuel (F)**
Solar (S)	$\frac{1}{C_S(1-T)} - 2E_S I$	$\frac{1}{C_S(1-T)} - I(E_S + E_W)$	$\frac{1}{C_S(1-T)} - I(E_S + E_F)$
Wind (W)	$\frac{1}{C_W(1-T)} - I(E_S + E_W)$	$\frac{1}{C_W(1-T)} - 2E_W I$	$\frac{1}{C_W(1-T)} - I(E_W + E_F)$
Fossil Fuel (F)	$\frac{1}{C_F(1+T)} - I(E_S + E_F)$	$\frac{1}{C_F(1+T)} - I(E_W + E_F)$	$\frac{1}{C_F(1+T)} - 2E_F I$

Table 1: Payoff Matrix for the Consumer Energy Choice Game

2.2 Model Description & Implementation

We used Texas as a case study as a case study to explore how different tax incentives and environmental impact multipliers affect consumer choices between solar, wind, and fossil fuel energy sources. The selection of Texas was based on its diverse energy landscape significant renewable energy investments, and ongoing policy discussions around energy costs and environmental impact. This case study allowed us to apply real-world data to our theoretical model, providing a practical context for our analysis

Based on data from Texas, US, the following variables were used to model the payoff matrix. LFSCOE values are defined in USD per kWh. For solar energy, the cost was \$0.413 per kWh, for wind energy, it was \$0.291 per kWh, and for fossil fuels, the average cost was \$0.065 per kWh, considering coal and natural gas [14].

The CO_2 output for each energy source was also measured in grams per kWh. Solar energy had an average output of 44.5 grams per kWh, wind energy had 11.5 grams per kWh, and fossil fuels had an average output of 655 grams per kWh. These values were averaged from different types of solar (Solar PV - utility and Solar PV - roof) and wind (Wind offshore and Wind onshore) energy sources [21].

The tax incentive (T) variables were set at 0.0, 0.3, and 0.5, while the environmental impact multiplier (I) ranged from 0.005 to 0.02, specifically 0.005, 0.01, and 0.02. We tested these input variables using the payoff matrix model and obtained the following results.

	Solar	Wind	Fossil Fuels
Solar	1.9763	2.1413	-1.0762z
Wind	3.1564	3.3214	0.1039
Fossil Fuels	11.8871	12.0521	8.8346

Table 2: Tax Incentive: 0.0, Environmental Impact Multiplier: 0.005

	Solar	Wind	Fossil Fuels
Solar	1.5313	1.8613	-4.5737
Wind	2.8764	3.2064	-3.2286
Fossil Fuels	8.3896	8.7196	2.2846

Table 3: Tax Incentive: 0.0, Environmental Impact Multiplier: 0.01

	Solar	Wind	Fossil Fuels
Solar	0.6413	1.3013	-11.5687
Wind	2.3164	2.9764	-9.8936
Fossil Fuels	1.3946	2.0546	-10.8154

Table 4: Tax Incentive: 0.0, Environmental Impact Multiplier: 0.02

	Solar	Wind	Fossil Fuels
Solar	3.0140	3.1790	-0.0385
Wind	4.6292	4.7942	1.5767
Fossil Fuels	8.3368	8.5018	5.2843

Table 5: Tax Incentive: 0.3, Environmental Impact Multiplier: 0.005

	Solar	Wind	Fossil Fuels
Solar	2.5690	2.8990	-35360
Wind	4.3492	4.6792	-1.7558
Fossil Fuels	4.8393	5.1693	-1.2657

Table 6: Tax Incentive: 0.3, Environmental Impact Multiplier: 0.01

	Solar	Wind	Fossil Fuels
Solar	1.6790	2.3390	-10.5310
Wind	3.7892	4.4492	-8.4208
Fossil Fuels	-2.1557	-1.4957	-14.3657

Table 7: Tax Incentive: 0.3, Environmental Impact Multiplier: 0.02

	Solar	Wind	Fossil Fuels
Solar	4.3976	4.5626	1.3451
Wind	6.5929	6.7579	3.5404
Fossil Fuels	6.7589	6.9239	3.7064

Table 8: Tax Incentive: 0.5, Environmental Impact Multiplier: 0.005

	Solar	Wind	Fossil Fuels
Solar	3.9526	4.2826	-2.1524
Wind	6.3129	6.6429	0.2079
Fossil Fuels	3.2614	3.5914	-2.8436

Table 9: Tax Incentive: 0.5, Environmental Impact Multiplier: 0.01

	Solar	Wind	Fossil Fuels
Solar	3.0626	3.7226	-9.1474
Wind	5.7529	6.4129	-6.4571
Fossil Fuels	-3.7336	-3.0736	-15.9436

Table 10: Tax Incentive: 0.5, Environmental Impact Multiplier: 0.02

2.2.1 Analysis

In examining the payoff matrices for various tax incentives and environmental impact multipliers, we observe distinct trends in consumer preferences towards energy sources.

The data presented includes payoff matrices for different combinations of tax incentives and environmental impact multipliers across three energy sources: Solar, Wind, and Fossil Fuels. These results are analyzed using the S2 dynamics approach and visualized through ternary plots to provide a comprehensive understanding of the competitive dynamics among these energy sources.

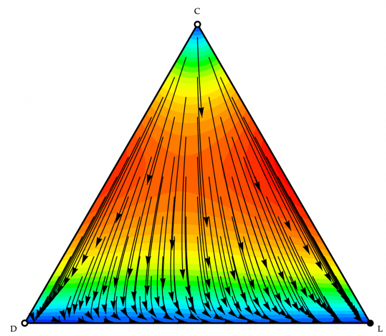
To better analyze the results, we categorized the results into three groups based on the level of environmental impact concern. Low concern scenarios include a tax incentive range of 0.05 to 0.055 and an environmental impact multiplier of 0.005. Medium concern scenarios involve tax incentives of 0.03 to 0.035 and an environmental impact multiplier of 0.01. High concern scenarios are characterized by a tax incentive of 0.0 and an environmental impact multiplier of 0.02. The result of each category is analyzed using the S2 dynamics approach and visualize through ternary plots to provide a comprehensive understanding of the competitive dynamics among these energy sources.

In low concern scenarios with a tax incentive of 0.05 and an environmental impact multiplier of 0.005, Wind energy shows a higher payoff compared to Solar, indicating a competitive advantage. However, Fossil Fuels have a slightly higher payoff, making it the dominant strategy. When the tax incentive is increased to 0.055 with the same environmental impact multiplier, different trends are observed. Wind energy outperforms Fossil Fuel, while Fossil Fuel still outperforms Solar but both are significantly outperformed by Wind energy.

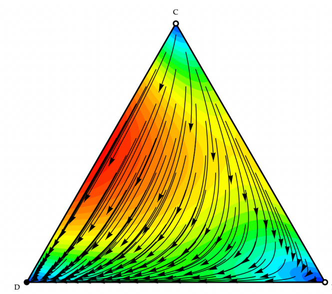
In medium concern scenarios with a tax incentive of 0.03 and an environmental impact multiplier of 0.01, Wind shows a competitive edge over Solar. However, Fossil Fuels remain the dominant strategy overall, with payoffs significantly higher than those of Solar and Wind. When the tax incentive is increased to 0.035, Wind energy becomes the dominant strategy while Solar energy starts to become competitive with Fossil Fuel.

High concern scenarios with a tax incentive of 0.0 and an environmental impact multiplier of 0.02 show that Solar and Wind are almost equally competitive, with payoffs relatively close to each other. The gap between Solar and Fossil Fuels payoffs has decreased significantly. The renewable energy sources become more dominant with Wind still leading but Fossil Fuel quickly loses it advantage.

2.2.2 Low



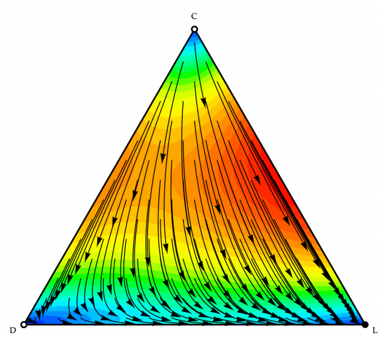
(a) T: 0.6, I: 0.03



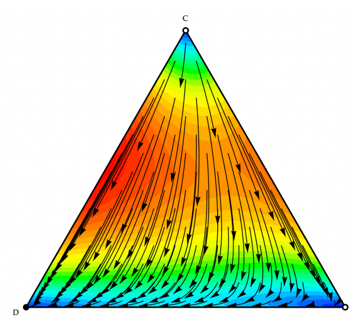
(b) T: 0.7, I: 0.01

Fig. 3: Ternary Plot: Top Vertex(Solar), Left Vertex(Wind), Right Vertex(Fossil Fuels)

2.2.3 Medium



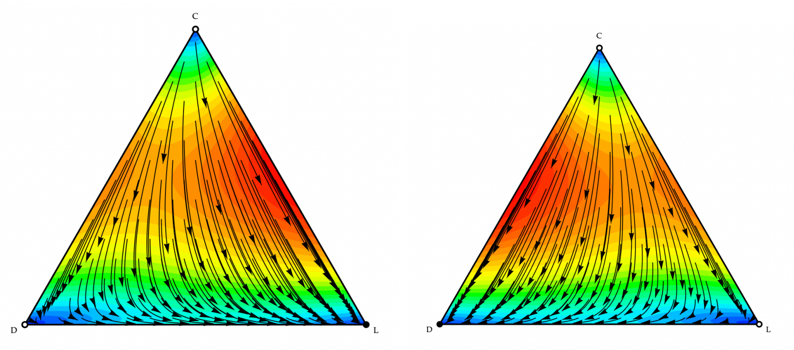
(a) T: 0.6, I: 0.03



(b) T: 0.7, I: 0.01

Fig. 4: Ternary Plot: Top Vertex(Solar), Left Vertex(Wind), Right Vertex(Fossil Fuels)

2.2.4 High



(a) T: 0.6, I: 0.03 (b) T: 0.7, I: 0.01

Fig. 5: Ternary Plot: Top Vertex(Solar), Left Vertex(Wind), Right Vertex(Fossil Fuels)

The ternary plots provide a visual representation of the dynamics of strategy adoption under different scenarios. For low concern scenarios (tax incentive of 0.05 and environmental impact multiplier of 0.005), the plot indicates a clear preference towards Fossil Fuels, with trajectories pointing towards the Fossil Fuels. However with a increase in tax incentive the preference becomes Wind energy. In medium concern scenarios (tax incentive of 0.03 and environmental impact multiplier of 0.01), the dynamics show increased competition between Solar and Wind energy with Fossil Fuel still dominant but with a slight increase in Tax incentive, we the shift towards the sustainable choices, specifically Wind Energy. High concern scenarios (tax incentive of 0.0 and environmental impact multiplier of 0.02) reveal a swift and high preference towards Wind energy, indicating the importance of favorable tax policies for sustainable energy.

Using the S2 dynamics approach, which compares sub-matrices of each strategy against another, we can observe how payoffs evolve. Solar energy shows improvement in payoffs as tax incentives increase, particularly under all environmental impact concern scenarios. Wind energy becomes more competitive with higher environmental impact multipliers, indicating its sensitivity to environmental policies. Fossil Fuels show the highest payoffs in low concerns with low tax incentive, but its dominance heavily reduces under high environmental impact concerns with higher tax incentives across all groups.

The analysis highlights the importance of tax incentives and environmental impact multipliers in shaping energy strategy payoffs. While Fossil Fuels initially remained dominant in some scenarios, their advantage diminishes as environmental concerns increase. Solar and Wind energy sources show potential for competitiveness under higher environmental impact multipliers and appropriate tax incentives. The ternary plots and S2 dynamics provide valuable insights into the interplay between different strategies, suggesting that balanced policies can lead to more sustainable energy choices.

Conclusion

While comprehending the evolving dynamics between fossil fuels and wind energy, there is a unique relationship in regard to tax incentives and external concern scenarios. Particularly when tax incentives shift from 30% to 35%, and similarly from 50% to 55%, the ternary plots illustrate a shift between fossil fuels and wind as a dominating Evolutionary Stable Strategy (ESS). Moreover, in cases with high concern and a tax rate of 0%, wind energy outperforms the other energy sources indicating the interaction where wind emerges as an ESS. When considering the stability of these interactions, we can see that the nodal points of both strategies signify an unstable equilibrium shifting from fossil fuels to wind energy.

Based on these implications, it can also be stated that wind energy acting as an ESS at low tax incentives and high concern, signifies a dominant and sustainable position within the energy market. It is with this benefit that we can see how a major transition to wind energy could lead to a significant reduction in greenhouse gas emissions and other beneficial long term implications. Additionally, due to the fact that the costs associated with wind energy have also trended downwards, due to incentives provided by the government, wind acting as an ESS is anticipated because it also aids in mitigating effects of climate change by generating clean energy and not releasing any carbon emissions [12]. This in turn potentially keeps us within the 1.5°C threshold till the year 2030 as it is essential that CO_2 emissions are reduced by at least 43% before 2030, according to the IPCC [1, 2]. While wind energy reduces potential effects of climate change, to expand our scope of analysis for future studies, we could include additional renewable energy sources such as hydroelectric, geothermal, and biomass to provide a more comprehensive view of the renewable energy market.

Overall, our project highlights the critical importance of understanding consumer behavior and the role of government incentives in shaping energy market dynamics, especially in an era where policymakers are focused on transitioning to cleaner energy sources. Additionally, our research explored the minimum level of government intervention required to persuade individuals with varying degrees of environmental concern to adopt renewable energy systems. In future studies, it may be reliable to examine regional variations in consumer preferences and government incentives to understand localized trends and impacts while also identifying the most influential factors driving the adoption of renewable energy sources. By delving into the intricacies of consumers' energy allocation, however, we unveiled profound insights that empower governments to refine their tax incentives, fostering a shift towards renewable energy adoption among citizens. In essence, these renewable resources like wind will have profound and far-reaching implications, driving the global energy market towards a more sustainable, secure, and prosperous future.

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