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MODELING PATHWAYS TO THE EMISSION TRADING SYSTEM: POLICY RECOMMENDATIONS FOR THE UAE

Nishant Bhattarai[1], Rahul Rajeevkumar Urs[1], Toufic Mezher[1], and Ahmad Mayyas[1]

[1]Dept. of Management Science and Engineering, Khalifa University, Abu Dhabi, UAE

ABSTRACT

This study leverages a meticulously developed model to explore the profound implications of Emission Trading Systems (ETS) on environmental and economic dimensions in the United Arab Emirates. This model delves into critical parameters, including emission caps and carbon prices, yielding transformative insights into environmental and economic avenues. The results reveal a direct correlation between the stringency of emission caps and emission reduction, particularly impactful in the power generation sector. Conversely, challenges faced by energy-intensive industries prompt discussions on innovative strategies such as alternative fuels and materials. The trading dynamics among participants, portrayed through a randomized auction process, revealed nuanced patterns and highlighted the challenges and opportunities within the emission trading system. This model provides a comprehensive understanding of the complexities inherent in the ETS and can serve as a strategic guide for policymakers and stakeholders, fostering a balanced approach between environmental and economic factors.

1 INTRODUCTION

Although greenhouse gases naturally occur, the significant human contributions from various sectors like industry, transportation, and agricultural byproducts, which are a result of industrialization and evolving development patterns, have had a considerable impact. The history and trend of global greenhouse gas (GHG) emissions paint a sobering picture of humanity's impact on global climate. Since the late 18th century, fossil fuel combustion, deforestation, and industrial processes have released unprecedented levels of GHG into the atmosphere, primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Marcu and Cecchetti 2022). These emissions have resulted in a significant increase in GHG concentrations in the atmosphere, trapping heat and raising global temperatures. In 2018, greenhouse gas (GHG) emissions attained their peak in recorded human history, totaling 58 Gigatons of carbon dioxide equivalent ($GtCO_{2eq}$). The predominant source of emissions during this period was the energy systems sector, contributing 34% (20 $GtCO_{2eq}$), followed by industry at 24% (14 GtCO2eq), AFOLU (Agriculture, Forestry, and Other Land Use) at 21% (12 $GtCO_{2eq}$), transport at 14% (8.3 $GtCO_{2eq}$), and the operation of buildings at 6% (3.3 $GtCO_{2eq}$) (Lamb et al. 2021).

However, by the late twentieth and early twenty-first centuries, a growing awareness of the environmental consequences of GHG emissions led to international efforts such as the Paris Agreement, which aimed to mitigate climate change (Hummieda et al. 2023). While some regions have made progress in renewable energy adoption and emission reductions, global GHG emissions have continued to rise, contributing to the alarming trend of climate change. Urgent and coordinated efforts are now needed to reverse this trend and keep global warming to a manageable level.

Among different solutions proposed to cut emissions, emission trading was proposed and implemented by many countries around the world (Bhattarai et al. 2023). The three main types of carbon pricing mechanisms are cap-and-trade (i.e., emission trading systems (ETS), carbon tax systems, and hybrid systems that combine elements of both (Marcu and Cecchetti 2022). A market-based policy tool that can be used to cut greenhouse gas emissions (GHG) is the emission trading system (ETS). According to the "cap and trade" theory, the government sets a cap on one or more economic sectors, and over time, the cap is lowered. Companies participating in the ETS must hold one permit for each tonne of emissions they emit; these permits can be acquired, purchased, or even traded between companies, providing the state with the opportunity to generate additional revenue that can be utilized in numerous sectors (Bhattarai et al. 2023). As of January 2023, there are 28 ETSs in force. Another eight are under development and expected to be in operation in the next few years. The share of the GHG emission covered by the emission trading system is over 17%, which is triple the amount compared to the year ETS was launched (Marcu and Cecchetti 2022)

Several strong arguments made it necessary to implement emissions trading. First, by offering a financial incentive to do so, it provided a practical means for nations and industries to effectively reduce emissions (Böning et al. 2023). These trading systems also provided much-needed flexibility, allowing emissions reductions to be focused where they were most useful and effective. This was a crucial feature, particularly for developing countries and high-emission industries. Also, these systems promoted international cooperation, encouraging nations to cooperate towards common emission reduction goals because of the global nature of climate change. As companies looked for efficient ways to reduce emissions, the market-based strategy also encouraged innovation, resulting in the development and adoption of cleaner technologies and practices. Emission trading systems also have the potential to spur economic growth by encouraging investment in green technologies and generating jobs in the clean energy industry. They also served as effective compliance mechanisms, providing a clear framework for tracking, disclosing, and verifying emissions, ensuring that nations upheld their commitments under global climate agreements (Aldy 2015; Metcalf and Weisbach 2009).

Environmental effectiveness, economic efficiency, market management, revenue management, and stakeholder engagement are the five main criteria used to evaluate ETSs (Bhattarai et al. 2023). The Emissions Trading Systems (ETSs) do not cover 100% of the economy or regulate all greenhouse gases (GHGs). California and Quebec have the most comprehensive ETS, covering 85% of GHG emissions, including the energy intensive transport sector (Bhattarai et al. 2023). The Regional Greenhouse Gas Initiative (RGGI) regulates only CO_2 emissions in the electricity sector of nine participating states, accounting for 20% of the total GHG emissions in the region (Narassimha et al. 2018). Other ETSs like New Zealand, Korea and do not achieve full coverage. The New Zealand ETS excludes biological emissions from agriculture and as a result, reduces the overall GHG coverage by half (Emissions Trading Worldwide, 2022). The European Union's ETS covers approximately 45% of GHG emissions, with national-level carbon taxes in Norway, Sweden and Ireland covering the remaining GHG emissions (Narassimha et al. 2018). Recently, China's national emissions trading scheme (ETS) was established and started to monitor GHG emissions and trade of allowances (Bhattarai et al. 2023).

The UAE, a prominent oil-based economy, has a compelling need for an emission trading system (ETS) for numerous reasons. This necessity arises from various factors unique to the UAE's economy and environmental context. First and foremost, the UAE's heavy reliance on oil exports exposes its economy to the inherent volatility of global oil prices, along with significant emission occurrences. With the implementation of ETS, the UAE can strategically diversify its economy, fostering the growth of the renewable energy and clean technology sectors to reduce its dependence on fossil fuels. Additionally, as a responsible global participant, the UAE's participation in an ETS would demonstrate its commitment to environmental sustainability and align its obligations under international pledges (Böning et al. 2023). Furthermore, revenue generated through ETS, either by auctioning allowances or taxing emissions, can be reinvested in sustainable infrastructure, and clean energy projects, further enhancing the horizons of a diversified economy. transition to a low-carbon economy (Tian et al. 2022). In conclusion, an ETS is an essential step for the UAE, providing both economic stability and environmental responsibility in a changing world.

In the light of the aforementioned challenge posed by insufficient policies to meet international pledges an emission trading system, coupled with a rigorous mathematical model, has been meticulously crafted. This approach aims to address the complexities surrounding emissions by introducing a systematic and quantifiable framework. By integrating mathematical modeling, the system strives to provide a robust foundation for understanding and managing emissions, paving the way for more effective and better policy solutions.

2 METHODOLOGY

Our developed MATLAB script introduces a dynamic and comprehensive model designed to simulate and analyze the implementation of an emission trading system among six entities, representing players in various sectors such as energy, cement, aluminum, and steel, over a three-decade span from 2021 to 2050. The model encapsulates intricate dynamics of carbon emissions by incorporating sensitivity analyses on both emission reduction targets and carbon pricing, providing a versatile framework for assessing different scenarios. In this context, as illustrated in Figure 1, the process begins with the establishment of participants, including the three utility companies in the UAE, namely ADWEA (Abu Dhabi Water and Electricity Authority), DEWA (Dubai Electricity and Water Authority), REWA (Rest of the Emirates Electricity and Water Authority considering combination Sharjah Electricity, and the biggest private industries, namely the cement, aluminum, and steel industries. Their starting emissions and yearly change rates are determined based on historical data and trends. Following this, the government assigns emission caps based on historical data (Hummieda et al. 2023). Throughout the cycle, participants can choose to reduce emissions using green technology or maintain their current levels. Subsequently, emissions are calculated and subtracted from the limit to check compliance. If participants exceed the limit, they can either purchase allowances or face penalties. In the case of multiple participants needing allowances, an auction is conducted, with the highest bidder securing allowances. Ultimately, profits are computed and contribute to government funds, and the cycle repeats.

Through a meticulous simulation, the script captures the evolution of carbon emissions, accounting for factors influencing emission levels, and conducts sophisticated carbon trading mechanisms to balance excesses and allowances among the players. The script aims to evaluate the economic consequences of simulated trades, including penalties incurred due to excess emissions, economic gains from carbon trading, and final profits. With an emphasis on transparency and flexibility, this model serves as a valuable tool for policymakers and stakeholders seeking insights into the complex interplay between emission reduction strategies and economic considerations in a carbon-constrained environment.

The primary goal is to reduce carbon emissions over time and minimize penalties by allowing players to trade carbon allowances. Exhibit 1 shows a breakdown of the main parts and objectives of the scripts.

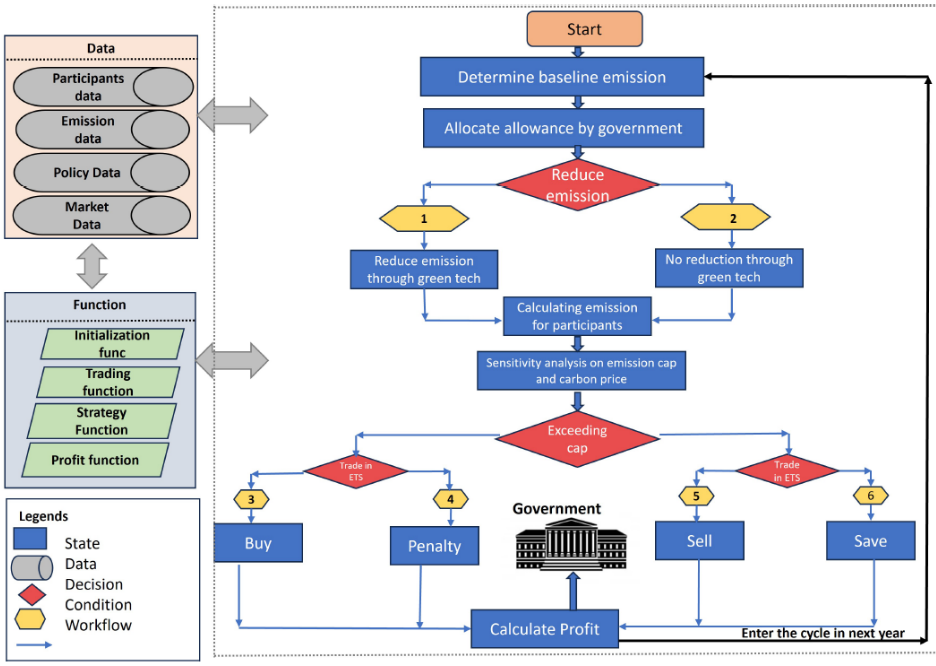


Figure 1: Methodology framework of proposed ETS.

Exhibit 1. Steps of the Energy Trading System Model

1. ***Initialization***: The script initializes various parameters such as the number of players (*n*), the current and target years, player names, initial carbon emissions (*baset_co2e*), and factors affecting emissions over time (*increasefactor, reductionfactor*).
2. ***Sensitivity Analysis***: The script conducts sensitivity analysis by varying parameters related to the interest rates, carbon emissions (*co2ecap*) and carbon prices (*carbonprice*).
The impact of different sensitivity values on carbon emissions and economic outcomes is evaluated where the carbon cap's sensitivity is set \$20, \$40 and \$60, and the carbon cap's value is set to [0.85; 0.90; 0.95; 0.975; 1.0] times the baseline emission. This assessment aligns with the most recent
3. ***Carbon Emission Simulation***: The script models the progression of carbon emissions for each player throughout the projection period by applying annual reduction.
4. ***Carbon Trading Simulation***: The script mimics a carbon trading game among players over time, working to balance carbon excess and allowances. Auctions decide the highest bidder from those with extra allowances and players in need. Player's trade, borrow allowances, and cut down excess emissions in this interactive process.
5. ***Results and Analysis***: The script stores and displays the results of the sensitivity analysis for both carbon emissions and carbon prices. It calculates and displays the total penalty incurred by players due to excess emissions. Economic outcomes, including revenue from selling allowances and final profit, are calculated and displayed.
6. ***Winners Matrix***: The script tracks the winners of each auction, indicating which player successfully traded allowances. It also allows for the exploration of different scenarios and their impacts on carbon reduction and economic outcomes.

The model illuminates the potential effectiveness of a carbon trading system. Through dynamic simulations and sensitivity analyses, it reveals strategic pathways for players to balance emissions and allowances. The results underscore adaptability and collaboration as crucial elements in achieving sustainable reductions. This insight contributes to discussions on policy implications and the broader impact of such systems on both the environment and the economy. Further, the adaptability of the model to different scenarios makes it a versatile tool, offering insights into the intricate interplay between environmental targets and economic considerations.

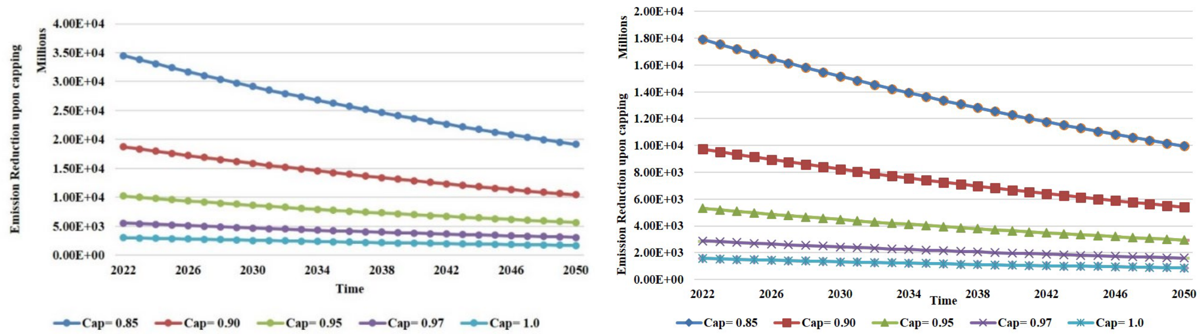
In the given code, player selection involves the initialization of various parameters and the definition of player characteristics. The variable *n* represents the number of players, and (*playernames*) is a cell array containing the names of the players. The players are associated with their initial CO_2 emission values, stored in the vector (basetco2e). These values are subject to modification over time through factors such as an increase factor (*increasefactor*) and a reduction factor (*reductionfactor*). The objective is to assess the impact of the emission trading system on the key sectors, namely power generation and high-intensity industries like cement, aluminum, and steel, in terms of both environmental and economic advantages. The methodology involves a multi-step process to model and analyze the players' CO_2 emissions over time. The code initializes matrices to store results and uses a nested loop structure to iterate through sensitivity values for CO_2 emission caps (*co2ecap*) and carbon prices (*carbonprice*). The main loop calculates and updates the excess and allowance matrices, simulating a trading mechanism to minimize emissions. The winner's matrix keeps track of successful auctions, and the results are displayed for both CO_2 emission caps and carbon prices. Finally, economic metrics such as total penalty, economics, and final profit are computed based on the simulated trading outcomes, see Exhibit A1 in the appendix for detailed Matlab code. In this script, designed within the framework of self-language model capabilities, a simulation is executed to analyze the effects of carbon emission caps and prices on a group of players over a specified time period on emission reduction and economic gains. The players, each associated with baseline carbon emissions, engage in a dynamic trading system influenced by bid dynamics. The program iteratively assesses variations in emission caps and prices, capturing the resultant outcomes in matrices. Through this simulated process, the script aims to provide insights into how environmental and economic factors influence carbon trading dynamics among the involved entities. Subsequently, with the help of the obtained results it has allowed us to provide relevant policy recommendations for the implementation of the emission trading system in UAE.

3 RESULTS AND DISCUSSION

Emission reduction achieved with ETS implication for power generation participants module is used to simulate and check sensitivity analyses for the model, particularly focusing on the cap's impact on emission reduction over time, noteworthy insights emerged. The results indicate a clear correlation between the stringency of the emission cap and the degree of emission reduction achieved. In Figure 2, emission reduction is observed when the cap becomes increasingly stringent. Notably, the years with a 15% reduction cap exhibit the most significant change in emission reduction. As the cap decreases to 10%, 5%, and 3%, a gradual decrease in the emission reduction is evident. This consistent trend is observed across all power generation participants, including ADWEA and DEWA.

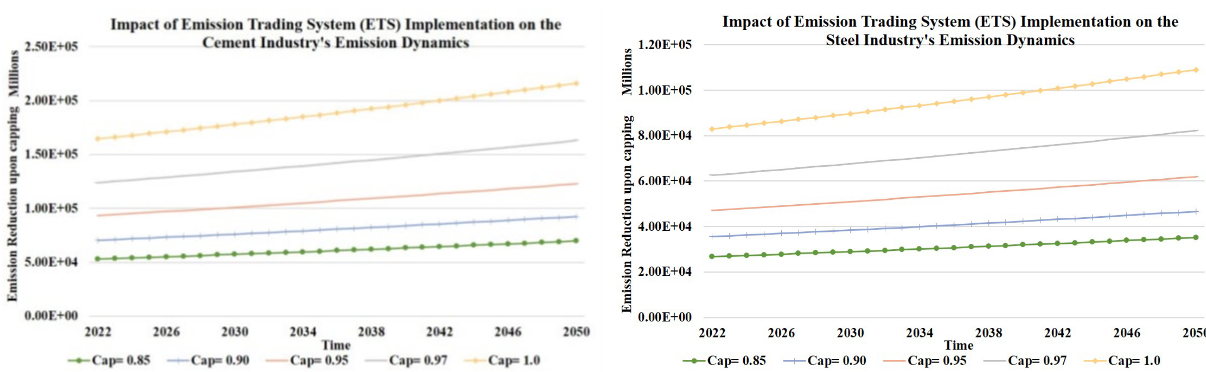
After simulations and sensitivity analyses for the model were conducted, with a specific emphasis on the impact of the cap on emission changes over time, notable contrasting outcomes overcame, especially when comparing high-intensive industries to power generation. Upon conducting the simulation, it became apparent that despite the implementation of the emission trading system (ETS), heavy industries, such as those involved in the production of cement, aluminum, and steel, were unable to achieve emission reductions as illustrated in Figure 3. This was attributed to the substantial demand for the materials they manufactured. Given that these products significantly contribute to industrial development and economic gains in countries, their demand continued to rise even with the ETS in place, making it challenging for them to achieve emission reductions. Meeting net-zero targets in these industries would necessitate future efficient decarbonization efforts. Nevertheless, the implementation of ETS did lead to reduced emissions compared to business-as-usual (BAU) conditions. Also, provided an opportunity to generate revenue through allowance trading, which could be invested in greener technologies to reduce overall emissions. Some of the measures which are concurred by different studies for the decarbonization in the heavy industry is further explained below. For the cement industry, one of the most energy-intensive sectors, potential solutions for emissions reduction include switching to less carbon-intensive fuels like biomass, natural gas, and waste-derived fuels, using dry kilns instead of wet ones, repairing kiln leaks, and capturing CO_2 through carbon capture and storage. Additionally, producing cement from calcium oxide, adopting grinding technology, preheating the kiln, processing wastes in kilns, and utilizing grinding media and mill liners are suggested measures (Khondaker et al. 2016). In the steel industry, carbon capture and storage are viable options, especially when carbon is used as a reductant (Gielen et al. 2019).

An ultra-low carbon alternative involves completely replacing carbon with hydrogen as a reductant, potentially eliminating greenhouse gas emissions from iron-making processes. This technology is under development in the European Union (EU), Sweden, Germany, Japan, and Austria (Rechberger et al. 2020). The International Aluminum Institute outlined pathways for the decarbonization of the aluminum industry, focusing on electricity decarbonization, direct emissions reduction, and recycling/resource efficiency to decrease the primary aluminum need by 20% (International Aluminium Institute 2021).

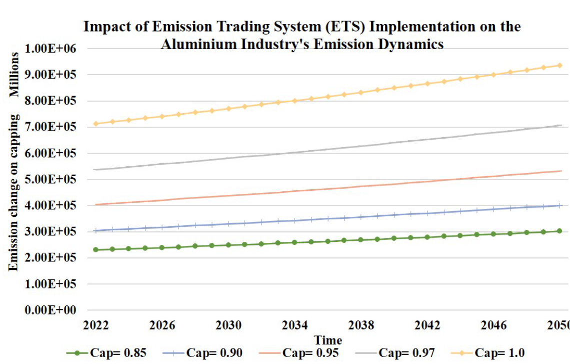


(a) **(b)**

Figure 2: ETS implementation in: (a) ADWEA emission reduction, and (b) DEWA emission reduction.



(a) **(b)**



(c)

Figure 3: ETS implementation in three industries in the UAE: (a) cement, (b) steel, and (c) aluminum.

Trading of allowances amongst players in MATLAB model is designed to simulate and analyze the trading of carbon emission allowances among six players representing participants in distinct industries. As previously mentioned, the initial carbon emission levels (*baset_co2e*) for each player undergo annual adjustments, determined by specified increase and reduction factors, which are established using historical trends and projections from recent journal papers, governmental reports, and international reports (e.g. Hummieda et al. 2023, UAE.gov. 2024). The simulation incorporates sensitivity analyses for two critical parameters: the cap on carbon emissions and carbon prices. These sensitivity analyses explore different scenarios to understand how variations in these parameters influence the outcomes of the ETS.

The trading mechanism within the model operates through a randomized auction process. In each simulated year, players with excess emissions (*negative_excess*) participate in auctions to acquire allowances from players with available allowances (*positive_allowance*). The auction process involves players submitting random bids, and the highest bidder secures the right to sell their allowances to players in deficit. This process repeats until players with negative excess emissions are no longer in deficit. The model also tracks several matrices, including excess emissions, allowances, borrowed amounts, winners of each auction, and economic factors. Economic factors include penalties for exceeding emissions, economic gains from allowance trading, and final profits. The penalties reflect the financial consequences of surpassing emission caps, while economic gains arise from successful allowance trading. As illustrated in Figure 4, each bar serves as a visual representation of the total allowances transacted by players within a given year. The upper section, situated above the zero level, signifies allowances sold, while the lower half, positioned below the zero level, denotes allowances purchased. Notably, power generation companies demonstrate a consistent trend of selling allowances, attributed to their relatively seamless transition to greener technologies. Conversely, high-intensive industries face challenges in selling allowances due to the intricacies of adopting environmentally friendly practices while meeting demand. Nevertheless, there were instances where high-intensive industries found opportunities to engage in allowance trading among themselves when the allocated allowances fell short. A noteworthy outcome from the simulation reveals the complexity faced by the cement industry in reducing carbon emissions, primarily stemming from the by-products of carbon dioxide and the heating process involved in cement production. Consequently, the cement industry emerges as a major purchaser of allowances, closely followed by the aluminum and steel industries. In terms of allowance sales, ADWEA takes the forefront, leveraging its expansive green electricity generation specifically from solar capacity. DEWA follows suit, with REWA occasionally participating in allowance sales. This subtle analysis of allowance transactions sheds light on the distinct patterns observed among various industries, emphasizing the challenges and opportunities inhereted in the evolving landscape of emission allowance trading.

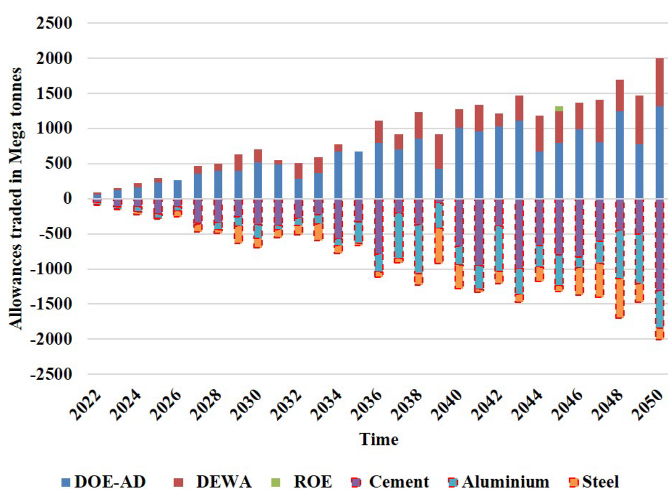


Figure 4: Trading of emission allowances over time.

Auction and allocation of permits among participants module projects the outcomes of allowance auctions won by participants in the emission trading model. Among the players, the steel industry consistently emerged as a dominant force in securing auction victories, accumulating a total of 45 wins over the simulation period. Following closely, the aluminum industry also demonstrated robust performance, securing a total of 45 wins as well. The Cement industry participants secured a noteworthy total of 39 auction victories. A significant consideration was made in the model that, despite winning more auctions, the steel and aluminum industry was surpassed by the cement and aluminum sector in terms of the number of allowances obtained. This discrepancy was attributed to the greater challenge faced by cement industries in reducing emissions compared to the other two sectors and their requirement for more allowances to meet the cap. Notably, the participants from ADWEA, DEWA, and REWA did not register any auction wins during the simulated period, indicating a unique dynamic in their involvement or strategic choices in implementation of the greener electricity generation. The randomness and mechanisms behind auction victories were intricately developed into the MATLAB model, where players engaged in competitive bidding processes. This randomness was reflected in the fluctuating numbers of auction wins among industries, illustrating the diverse challenges and opportunities each sector faced in the emission trading landscape. The steel and aluminum industries, with their consistent victories, suggested effective strategies or advantageous positions in the trading dynamics.

Projected revenue generated from allowance trading. For this part, allocation of auction victories among participants shows that aluminum and steel industries share 35% each, leaving 30% to the cement industry. The model, incorporating sensitivity analyses for carbon prices at $20, $40, and $60, reveals the financial outcomes for each player from 2022 to 2050. ADWEA emerges as a consistent leader, securing substantial revenue over the years, contributing significantly to the total revenue across the 33-year simulation. DEWA also demonstrates a noteworthy financial performance, while ROE, although registering revenue, exhibits a comparatively lower economic impact. The varying carbon prices likely play a pivotal role in shaping revenue trends, influencing the profitability of allowance trading for each player. These results underscore the financial complexities and opportunities inherent in emission trading, with carbon pricing acting as a critical factor in determining the economic success of participating industries. The cumulative revenue data further emphasizes the economic potential of the emission trading system over the simulation period. A remarkable prospect lies in the potential to generate a substantial sum of $1,599 billion over a period of 33 years through the effective implementation of the ETS. This represents a unique and significant financial opportunity derived from the strategic application of emission trading policies and practices. The data analysis not only provides insights into the financial contributions of each player but also highlights the significant role of carbon pricing policies in shaping the economic landscape of emission trading. This understanding is crucial for policymakers and industry stakeholders aiming to optimize revenue generation, foster sustainable practices, effectively mitigate carbon emissions, and even in utilization in increasing competitiveness.

Projected revenue generation from penalty module estimaetes the penalties that should be paid by participants for exceeding emission caps valuable to the consequences of non-compliance within the emission trading model. The penalties for non-compliance were determined by benchmarking against the non-compliance penalty in the EU-ETS (phase 1) (Hu et al. 2015). Figure 5 provides a visual representation of the penalties imposed on high-intensive industries, showcasing the financial burden they had to endure to adhere to regulations and navigate their market demand and profitability. Over the simulated years, the cement, aluminum, and steel industries collectively incurred substantial penalties, amounting to a total of $176.9 million. This significant sum highlighted the financial repercussions faced by industries that failed to align with emission reduction targets set by governing bodies. This amount raised by the government can be in numerous avenues whether to invest in greener technology or in supporting vulnerable communities. It was found that the penalties escalated over time, reflecting the increasing severity of emissions non-compliance which was a result of the instance where the industry had to meet the cap and were not able to cover with the allowance trading. Such panalities were proven to be an effective motivation to reduce emissions by industrial producers and energy-intensive industries (Narassimha et al. 2018; Emissions Trading Worldwide, 2022).

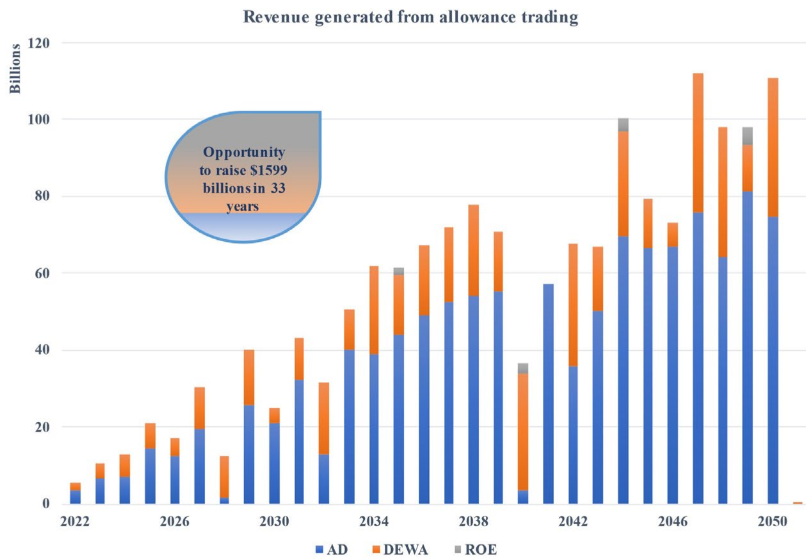


Figure 5: Revenue generated from allowances traded.

The results of this model were validated using smilar studies, mainly our previous work (Hummieda et al. 2023). In this study we considered several scenarios, business as usual, optimistic and pessimistic scenarios for emissions in the UAE until 2050. In that study we focused on power production and energy-intensive industries (Aluminum, Steel and Cement). Simulation-based System Dynamics methodology was used to model these sectors and industries to model emissions produced up to 2050. The System Dynamics model is validated to reflect the real-world state of the system using the emissions inventory projections as reference modes. We also studied nineteen different mitigation policies across the selected sectors, and 4 policy scenarios were simulated.

4 RECOMMENDATIONS

- Enhanced Enforcement and Compliance Mechanisms: Strengthen enforcement mechanisms to ensure industry compliance with emission caps. Develop robust monitoring systems and consider implementing penalties that escalate over time for persistent non-compliance (Narassimha et al. 2018).
- Promotion of Circular Economy Practices: Encourage industries to adopt circular economy practices, emphasizing the importance of resource efficiency and waste reduction.
- Green Technology Subsidies: Introduce subsidies specifically for the adoption of green technologies. Financial incentives for investments in renewable energy, carbon capture and storage, and energy-efficient technologies can accelerate the transition to a low-carbon economy. ETS was among the best systems that boosted invetments in the renewable energy systems in the Eurepan Union countries (Rabe, 2019; Hu et al. 2015).
- Inclusive Stakeholder Engagement: Foster inclusive stakeholder engagement by involving representatives from various industries, environmental organizations, and local communities in policy discussions. This inclusive approach ensures that diverse perspectives are considered, leading to more effective and equitable emission trading policies.
- Dynamic Adjustment of Carbon Prices: this was considered in the sensitivity analysis. Consider implementing a mechanism for dynamic adjustment of carbon prices based on market conditions,

technological advancements, and global economic trends. A responsive pricing system can better align with the economic realities faced by industries, encouraging continuous participation in emission trading.

5 CONCLUSIONS

In conclusion, the meticulously developed MATLAB model has unveiled profound insights into the far-reaching implications of Emission Trading Systems (ETS) on both the environmental and economic facets of carbon emissions trading within the UAE. The model's simulations and sensitivity analyses, particularly focused on emission caps and carbon prices, have yielded transformative findings. The results illuminated a striking correlation between the stringency of emission caps and the magnitude of emission reduction, particularly evident in power generation participants. A 15% reduction cap emerged as the most impactful, underscoring the vital role of stringent caps in driving substantial emissions reductions within the trading system. Conversely, high-intensive industries faced challenges in curtailing emissions due to escalating demand for their products, prompting discussions on innovative strategies such as adopting less carbon-intensive fuels and exploring alternative materials. The trading dynamics among players simulated through a randomized auction process uncovered distinct patterns. Power generation entities consistently sold allowances, while high-intensive industries grappled with challenges in sales but engaged in some internal trading. The model demonstrated the complicated details of auction victories, illuminating the various opportunities and challenges that face every industry in the emission trading landscape. Furthermore, the revenue projections provided valuable insights into the economic intricacies of the ETS. The cumulative revenue data projected a substantial sum of $1,599 billion over 33 years, underscoring the economic potential of the ETS.

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AUTHOR BIOGRAPHIES

NISHNAT BHATTARAI is a graduate student in the Department of Management Science and Engineering at Khalifa University. His research interests lie in energy modeling and analysis, and carbon taxation and trading systems. His email is 100061993@ku.ac.ae.

RAHUL RAJEEVKUMA URS is a graduate student in the Department of Management Science and Engineering at Khalifa University. His research interests lie in techno-economic analysis for clean and renewable energy systems such as solar PV, rechargeable batteries, and fuel cells. His email is 100060514@ku.ac.ae.

TOUFIC MEZHER is a professor of Management Science and Engineering at Khalifa University since 2017. Before Joining KUST, he was a Professor of Engineering Systems and Management at Masdar Institute of Science and Technology (2008-2016) and Professor of Engineering Management at the American University in Beirut from 1992 to 2007. His email is toufic.mezher@ku.ac.ae and his website is https://www.ku.ac.ae/college-people/toufic-mezher.

AHMAD MAYYAS is an Assistant Professor of Management Science and Engineering at Khalifa University, Abu Dhabi, UAE. He joined Khalifa University in the fall of 2019. Before that, Dr. Mayyas worked as a clean energy systems analyst at the National Renewable Energy Laboratory (NREL) in Golden, Colorado. He is currently involved in R&D activities of renewable energy systems, design, and manufacturing of fuel cells, water electrolyzers, and Li-ion batteries. His email address is Ahmad.Mayyas@ku.ac.ae and his website is https://www.ku.ac.ae/college-people/ahmad-mayyas.

APPENDIX

Exhibit A1. Matlab code

```
%% Initialization
n = 6; % Number of players
current_year = 2021; target_year = 2050;
t = target_year - current_year; % Project time
% Player names
player_names = {'A', 'B', 'C', 'D', 'E', 'F'};
base_t_co2e = [35207326312 18306972060 2434014200 52567030000 227653950000 26517460000];
increase_factor = 1.02; % increase factor of co2e every year
reduction_factor = [0.96 0.96 0.96 0.99 0.99 0.99]; % assumed reduction in co2e every year
penalty = 0.0220; % price per kg-co2e in US$ decided by government
% Sensitivity Analysis Parameters
co2e_cap_sensitivity = [0.85; 0.90; 0.95; 0.975; 1.0]; % Sensitivity values for co2e_cap
carbon_price_sensitivity = [20; 40; 60]; % Sensitivity values for
```

```
%Continued
% Set positive values to 0 in the excess matrix
    excess(excess > 0) = 0;
% Set negative values to 0 in the allowance matrix
    allowance(allowance < 0) = 0;
% Initialize a matrix to store the borrowed values
    borrowed_matrix = zeros(size(excess));
% Initialize the seller_matrix to keep track of sellers
    seller_matrix = zeros(size(excess));
% Create copies of the old excess and old allowance matrices
    old_excess = excess;
    old_allowance = allowance;
% Loop through each year to perform trading
    for year = 1:t
% Find players with negative excess in the current year
        players_with_negative_excess = find(excess(year, :) < 0);
 % Loop through players with negative excess
```

```
carbon_price
% Initialize matrices to store results
results_co2e_cap = zeros(t, numel(base_t_co2e), numel(co2e_cap_sensitivity));
results_carbon_price = zeros(t, numel(base_t_co2e), numel(carbon_price_sensitivity));
% Initialize a variable to store the number of bids won
num_bids_won = zeros(n, 1);
% Loop through co2e_cap sensitivity values
for cap_idx = 1:numel(co2e_cap_sensitivity)
   co2e_cap = co2e_cap_sensitivity(cap_idx) * base_t_co2e;
   % Initialize matrices to store the updated values and all_t_co2e for each year
   updated_co2e_matrix = zeros(t, numel(base_t_co2e));
   all_t_co2e_matrix = zeros(t, numel(base_t_co2e));
% Loop through each year and update the CO2e values
   for year = 1:t
      all_t_co2e_matrix(year, :) = base_t_co2e; % Store the base_t_co2e values in the matrix
      base_t_co2e = base_t_co2e .* reduction_factor; % Reduce base_t_co2e for the current year
      base_t_co2e = base_t_co2e .* increase_factor; % Increase base_t_co2e for the current year
      updated_co2e_matrix(year, :) = base_t_co2e; % Store the updated values in the matrix
   end
% Store the results for this sensitivity value
   results_co2e_cap(:, :, cap_idx) = updated_co2e_matrix;
end
   end
   % Store the results for this sensitivity value
   results_carbon_price(:, :, price_idx) = seller_matrix;
end
% Display the results for sensitivity analysis
results_co2e_cap
results_carbon_price
total_penalty = penalty * excess;
economics = seller_matrix .* carbon_price;
service_tax = economics * 0.05;
final_profit = economics - service_tax;
% Loop through carbon_price sensitivity values
for price_idx = 1:numel(carbon_price_sensitivity)
   carbon_price = carbon_price_sensitivity(price_idx);
% Initialize matrices to store excess and allowance values
   difference_matrix = co2e_cap - updated_co2e_matrix;
   excess = difference_matrix;
   allowance = difference_matrix;
      for player_idx = 1:length(players_with_negative_excess)
         player = players_with_negative_excess(player_idx);
% Find players with positive allowance in the current year
         players_with_positive_allowance = find(allowance(year, :) > 0);
% Initialize variables for the auction
         highest_bidder = [];
         highest_bid = -Inf;
% Loop through players with positive allowance
         for allow_player_idx = 1:length(players_with_positive_allowance)
            allow_player = players_with_positive_allowance(allow_player_idx);
 % Calculate a random bid for the allow_player
            bid = rand * allowance(year, allow_player);
 % Check if this bid is higher than the current highest bid
            if bid > highest_bid
               highest_bidder = allow_player;
               highest_bid = bid;
            end
         end
% If a highest bidder is found, proceed with the auction
         if ~isempty(highest_bidder)
 % Calculate amount that can be borrowed from the allowance
borrow_amount = min(-excess(year, player), highest_bid);
% Update the excess and allowance matrices
 excess(year, player) = excess(year, player) + borrow_amount;
            allowance(year, highest_bidder) = allowance(year, highest_bidder) - borrow_amount;
 % Update the borrowed_matrix to keep track of borrowing
            borrowed_matrix(year, player) = borrowed_matrix(year, player) + borrow_amount;
% Update the seller_matrix to indicate the seller
            seller_matrix(year, highest_bidder) = seller_matrix(year, highest_bidder) + borrow_amount;

% Increase the number of bids won for the highest bidder
            num_bids_won(highest_bidder) = num_bids_won(highest_bidder) + 1;

% If the player's excess is no longer negative, break inner loop
            if excess(year, player) >= 0
               break;
            end
         end
      end
```