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RESEARCH ARTICLE

Optimizing Sustainable Production Quantity Model Incorporating CCS Technology and Mitigating Greenhouse Gas and Wastewater Emissions

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Abstract

Objectives: To examine and validate the investment in Carbon Capture and Storage technology for the production process in an inventory model, focusing on reducing carbon emissions while enhancing sustainable practices. **Methods:** An economic production quantity model along with greenhouse gas and wastewater emissions is formulated under two scenarios: (i) a sustainable model with Carbon Capture and Storage technology, and (ii) a model without Carbon Capture and Storage technology. Secondary data from Hui Ming Wee's research are used to illustrate the efficiency of the proposed model. Lagrangian method is applied to determine the optimal solution of the problem. **Findings:** The proposed model was solved using the given methodology, and the overall cost of the industrial enterprise with Carbon Capture and Storage technology is $27,393,962 whereas the overall cost of the manufacturing industry without Carbon Capture and Storage technology is $30,044,797. This demonstrates that the sustainable economic production quantity model performs better than the traditional one. **Novelty:** Carbon Capture and Storage technology has been implemented, and its efficiency has been examined in an economic production quantity model, whereas earlier researches mostly focused on other green technologies.

2020 Mathematics Subject Classification: 90B05.

Keywords: Carbon Capture And Storage Technology; Carbon Emission; Economic Production Quantity Model; Inventory; Sustainability

1 Introduction

In today's ever-evolving business environment, industries rely on Economic Production Quantity (EPQ) model to optimize stock levels, maintain expenses, and ensure consistent product availability. Sustainable development and the concept of sustainability are receiving much more attention due to the importance of ecological concerns and the deep connection between industrialization and environmental stewardship. Incorporating sustainability into the Economic Production Quantity model is essential for businesses seeking to improve production efficiency, optimize resource utilization, and promote ethical practices. Mashud studied an inventory model that took into considering controllable emissions, degradation, and defects[1]. Su concentrated on a circular economy-based imperfect production inventory model that incorporates scrap returns[2]. Ren investigated an inventory management pricing model under various carbon emission regulations[3]. Sebatjane explores sustainable inventory models in the context of carbon emissions regulations. The paper reviews the literature on the incorporation of carbon limits into inventory management and offers a taxonomy of current approaches. It also identifies research gaps and proposes areas for future research in this field[4]. In many different industries, a great deal of research has been done on sustainability. The pulp and paper mill industry has received significant attention because of its high-energy consumption. Hsieh developed a production decision system for reused paper by employing sustainable cost management[5]. Amandio investigated how to extract value from pulp and paper industry waste in an effort to foster sustainability and a circular economy[6]. Sharma established an inventory model considering sulphur and nitrogen emissions, as well as biological and chemical oxygen requirements, when analysing pollution factors in the pulp and paper industries[7].

The current increase in global warming has an impact on human life because of greenhouse gas emissions, which cause extreme weather, health problems, and changes in water supplies and habitats. It encouraged both enterprises and consumers to take more responsibility in lowering emissions and protecting the surroundings. Manufacturing industries emit hazardous greenhouse gases such as sulphur oxide, nitrogen oxide, carbon dioxide, and methane. These pollutants are released during the manufacture, transportation, and combustion of fossil fuels, and also through a variety of other business operations. Wastewater is one of the major causes of pollution in the environment, ruining ecological systems and water sources. Numerous researchers have launched initiatives to tackle these challenges, employing a variety of strategies to reduce greenhouse gas emissions and water contamination from industrial sites. Hui Ming Wee examined an economic production quantity model that considers greenhouse gas emissions and the release of wastewater in order to improve production sustainability[8]. Nguyen conducted an analysis of the greenhouse gas emissions and environmental effects of energy extraction and recyclable materials in wastewater treatment facilities[9]. Liu reviewed methods for measuring carbon emissions in wastewater treatment and investigating neutralization strategies[10]. Marchi assessed supply chain strategies that include power consumption, greenhouse gas emissions, and process flaws examining the effects of various coordination decisions on operational efficacy and sustainability[11].

While analyzing environmental challenges, carbon dioxide is recognized as a prominent greenhouse gas, which comes from the combustion of fossil fuels, manufacturing activities, and changes in land use. As customers become more conscious of climate change, organizations must adapt and implement sustainable practices to address the issues caused by carbon emissions in the modern world. Mishra investigated an eco-friendly production quantity model for managing carbon emissions amid shortages[12]. The European Union, China, United Kingdom, Japan, and United States are some of the prominent countries in this endeavor, having implemented comprehensive policies such as carbon taxation, carbon cap and trade, carbon offsets and other emission reduction techniques to combat climate change. Lu evaluated the effects of carbon cap-and-trade and offset regulations on a fragile inventory system, using mitigation technologies to reduce supply chain emissions[13]. Green technology plays a significant part in reducing emissions in inventory. It embraces eco-friendly innovations that strive to reduce environmental harm through ethical procedures and technical improvements. Industries that employ green technologies might not only improve their environmental performance but also gain a strategic advantage in a rapidly evolving, sustainability-driven industry. Sharma demonstrated a two-level supply chain model, emphasizing the value of investing in green technologies and lowering emissions through the use of the Particle Swarm Optimisation technique[14].Since carbon emission (CO_2) is a significant source, it is vital to implement efficient control methods.

In order to reduce carbon emissions and prevent their environmental impact, it becomes crucial to implement modern technology. Sustainable technologies are vital for reducing carbon emissions and fostering a more environmentally responsible mindset. Technological advancements have enabled manufacturers and buyers to minimize costs and expenses by creating green equipment and treatment methods. Carbon Capture and Storage (CCS) technology is emerging as a key tactic as industries prioritize lowering carbon emissions. It is vital for achieving a low-carbon and sustainable future. The adoption of carbon capture and storage technology is beneficial for green initiatives because it prohibits carbon dioxide emissions from being released into the atmosphere by capturing them from industrial activities and keeping them in a safe subterranean facility. This technology has great potential for mitigating climate change and also promoting sustainable production processes. Here, Carbon Capture and Storage technology aims to capture 90 percent of the carbon dioxide emissions before they enter the atmosphere. Schmelz assessed the overall expenditure linked to the deployment of carbon capture and storage at a regional level.[15] Fu discussed the ecological consequences of organic carbon capture in the wastewater treatment process, focussing on its limitations along with integrated procedures[16]. Ding emphasized the significance of assessing the industry's readiness for carbon capture and storage for the purpose to enhance sustainability [17].

To the best of our knowledge, the majority of previous work on economic production quantity models has concentrated on green technologies while ignoring crucial sustainability issues. Among the different strategies for lowering environmental issues, carbon capture and storage technology plays an essential role in reducing carbon emissions. However, exiting EPQ models frequently take a one-dimensional method, focusing on either cost reduction or sustainability compliance without successfully balancing both of these objectives. Also, no research has been conducted on the incorporation of CCS technology into EPQ models, leaving its efficacy and impact unknown. To fill this gap, the proposed research aims to justify the efficiency of Carbon Capture and Storage technology within the economic production quantity model to optimize the overall cost of an organization. Unlike traditional economic production quantity models, this model seeks to strike a balance between environmental responsibility and financial efficiency, providing enterprises with a practical decision-making tool for determining optimal production quantity while abiding to environmental limitations. The proposed model has major advantages. Environmentally, it lowers carbon emissions, which helps to promote worldwide sustainability and mitigate climate change. Economically, it encourages resource optimization, adherence to environmental guidelines, and economically viable production strategies to fulfill competitive market needs. Strategically, it boosts organizational reputation, complies with green technology standards, and promotes circular economy concepts, giving industries a path to a sustainable future while improving their status in environmentally controlled marketplaces. By addressing these challenges, this model offers a foundation for enterprises to embrace sustainable and financially viable production processes, resulting in a more balanced and environmentally responsible industrial landscape. Numerical example is illustrated to demonstrate the efficiency of the proposed model.

The remainder of this study is organized as follows: Section 2 outlines the mathematical formulation of the suggested model and explains the solution methodology. Section 3 provides the result and discussion. Finally, Section 4 concludes the research.

2 Methodology

A sustainable economic production quantity model is formulated by incorporating Carbon Capture and Storage technology alongside greenhouse gas and wastewater emissions. The study compares two scenarios: (i) an economic production quantity model with CCS technology investment and (ii) an economic production quantity model without CCS technology. To show the efficiency of the proposed model, secondary data from Hui Ming Yee's research were applied. [8] The Lagrangian method is used to determine the optimal solution to the problem. The proposed methods were applied and examined to determine their effectiveness and operational performance in managing emissions and lowering expenses. Sections 2.1 and 2.2 outline the notations and assumptions which were used to develop the suggested model.

2.1 Notation

- D_0: Rate of demand
- P_0: Rate of production
- I_1: Cost of setup for each cycle
- I_2: Cost of storing one ton of paper
- I_3: Cost of producing one ton of paper
- I_4: Cost of Carbon emissions
- I_5: Penalty for Nitrogen oxides (NO_X) emission
- I_6: Penalty for Sulphur oxides (SO_X) emission
- I_7: Cost of water treatment each cycle
- I_8: Biochemical Oxygen Demand (BOD) discharge fee
- I_9: Chemical Oxygen Demand (COD) discharge fee
- I_{10}: Dry sludge disposal fee
- I_{11}: Methane release fee
- NO_X: NO_X for each ton of product
- SO_X: SO_X for each ton of product
- V_{BOD}: Biochemical Oxygen Demand per treated wastewater
- V_{COD}: Chemical Oxygen Demand per treated wastewater
- V_{SLD}: Dry sludge percentage per treated wastewater
- V_{CH_4}: Dry sludge
- z: Space needed per ton of product
- I_{EC}: Average inventory energy usage

- I_{PEC}: Average energy used during manufacture
- I_{WO}: Overall wastewater output
- I_{EG}: Standard emissions from power generation
- I_{2c}: Estimated inventory emission fee
- I_{4C}: Cost of carbon emissions in production
- I_{5C}: NO_Xdischarge cost
- I_{6C}: SO_X discharge cost
- I_{8C}: BOD discharge cost
- I_{9C}: COD discharge cost
- I_{11c}: Methane (CH_4) discharge cost
- ISC: Setup cost
- IHC: Warehousing cost
- IPC: Production cost
- IWC: Wastewater cost
- $ISWC$: Solid waste disposal cost
- CCS: Investment in carbon capture and storage technology for production
- OC: Overall cost
- M_{IL}: Maximum amount of inventory
- t_1: Duration of production and consumption
- q_1: Optimal production quantity (Sustainable)
- q_2: Optimal production quantity (Traditional)
- t: Cycle duration

2.2 Assumptions

1. An individual product.
2. The rate of demand and production does not vary.
3. The production process operates continuously.
4. A shortage of supplies is not permitted.
5. Wastewater from the production cycle is collected and treated before being disposed away.
6. The mill doesn't utilise the dry sludge which remains after wastewater treatment as biomass.
7. The plant's carbon emission is determined by the power consumption it consumes in the process of manufacturing one ton of paper.

Sections 2.3 to 2.7 detail the expenses required to evaluate the economic impact within the production process.

2.3 Setup cost

According to the traditional Economic Production Quantity model, the cost of setting up the machinery before production begins.

$$ISC = \frac{I_1}{t} = \frac{I_1 D_0}{q_1} \tag{2.1}$$

2.4 Warehousing cost

This incorporates carbon emission expenses from keeping finished goods and holding charges from the traditional EPQ model. Heating, ventilation, and air conditioning (HVAC) systems were utilized to avoid pulp damage.

$$I_{2c} = zI_{EC}I_{EG}\left(I_4\right) \tag{2.2}$$

$$t_1 = \frac{q_1}{P_0} \tag{2.3}$$

$$M_{IL} = (P_0 - D_0)\,t_1 = (P_0 - D_0)\,\frac{q_1}{P_0} \tag{2.4}$$

$$IHC = (I_2 + I_{2c})\,\frac{M_{IL}}{2} \tag{2.5}$$

$$IHC = (I_2 + I_{2c})\,\frac{q_1\,(P_0 - D_0)}{2P_0} \tag{2.6}$$

2.5 Production cost

The production cost is given by

$$I_{4C} = I_{PEC} I_{EG}\,(I_4) \tag{2.7}$$

The NO_Xemission cost is defined as

$$I_{5C} = NO_X I_5 \tag{2.8}$$

Similarly, SO_X emission cost is defined as

$$I_{6C} = SO_X I_6 \tag{2.9}$$

Therefore, the production cost becomes

$$IPC = (I_3 + I_{4C} + I_{5C} + I_{6C})\,\frac{q_1}{t} \tag{2.10}$$

$$IPC = (I_3 + I_{4C} + I_{5C} + I_{6C})\,D_0 \tag{2.11}$$

2.6 Wastewater cost

$$I_{8C} = I_{WO} V_{BOD} I_8 \tag{2.12}$$

$$I_{9C} = I_{WO} V_{COD} I_9 \tag{2.13}$$

The quantity of discharged $BOD$and $COD$is determined by the wastewater output of the plant and the amount generated in each cycle.

$$IWC = \frac{I_7 D_0}{q_1} + (I_{8C} + I_{9C})\,D_0 \tag{2.14}$$

2.7 Solid waste disposal cost

The cost of disposing dry sludge is calculated by the fixed expense transferring waste from the plant to the landfill.

$$I_{11C} = I_{WO} V_{SLD} V_{CH_4} I_{11} \tag{2.15}$$

$$ISWC = \frac{I_{10}}{t} + I_{11c} D_0 \tag{2.16}$$

$$ISWC = \frac{I_{10} D_0}{q_1} + I_{11c} D_0 \tag{2.17}$$

2.8 Sustainable Economic Production Quantity model with CCS technology

A sustainable economic production quantity model is formulated with an incorporation of Carbon Capture and Storage technology along with greenhouse gas and wastewater emissions. Lagrangian method is applied to determine the optimal solution of the problem. In recent times, research has largely focused on green technology, promoting environmentally friendly methods. However, Carbon Capture and Storage technology hold great potential, especially for sectors where cutting carbon emissions is a challenging task. One effective way to harmonize environmental sustainability with financial targets is to incorporate CCS technology into Economic Production Quantity models. Firms may remain competitive by implementing CCS technology to address the growing demand from customers for environmentally friendly products. Businesses that incorporate CCS technology into their manufacturing processes can improve their public perception by proving a commitment to minimizing environmental effects. This may attract buyers, shareholders, and others who value sustainability. From Equation (2.1) -Equation (2.17), the manufacturing firm's overall cost for the EPQ model is defined as

$$OC = ISC + IHC + IPC + IWC + ISWC + CCS \tag{2.18}$$

Thus, the manufacturing industry's total expenses is calculated by

$$OC = \frac{I_1 D_0}{q_1} + (I_2 + I_{2c}) \frac{q_1 (P_0 - D_0)}{2P_0} + (I_3 + I_{4C} + I_{5C} + I_{6C}) D_0$$

$$+ \frac{I_7 D_0}{q_1} + (I_{8C} + I_{9C}) D_0 + \frac{I_{10} D_0}{q_1} + I_{11c} D_0 + CCS \tag{2.19}$$

$$OC = \frac{I_1 D_0}{q_1} + (I_2 + zI_{EC} I_{EG} (10\% (I_4))) \frac{q_1 (P_0 - D_0)}{2P_0}$$

$$+ (I_{WO} V_{BOD} I_8 + I_{WO} V_{COD} I_9) D_0 + \frac{I_{10} D_0}{q_1} + I_{WO} V_{SLD} V_{CH_4} I_{11} D_0 + CCS \tag{2.20}$$

$$+ (I_3 + I_{PEC} I_{EG} (10\% (I_4)) + NO_X I_5 + SO_X I_6) D_0 + \frac{I_7 D_0}{q_1}$$

Taking the first-order partial derivative of Equation (2.20),

$$\frac{doc}{dq_1} = -\frac{I_1 D_0}{q_1^2} + \frac{(I_2 + zI_{EC} I_{EG} (10\% (I_4))) (P_0 - D_0)}{D_0 P_0} - \frac{I_7 D_0}{q_1^2} - \frac{I_{10} D_0}{q_1^2} \tag{2.21}$$

Equating Equation (2.21) to zero, q_1 can be derived.

Therefore,

$$q_1 = \sqrt{\frac{2D_0 P_0 (I_1 + I_7 + I_{10})}{(I_2 + zI_{EC} I_{EG} (10\% (I_4))) (P_0 - D_0)}} \tag{2.22}$$

$$t = \frac{q_1}{D_0} \tag{2.23}$$

2.9 Economic Production Quantity model without CCS technology

The optimal production quantity and cycle duration are derived using the traditional EPQ model. Lagrangian method is applied to determine the optimal solution of the problem.

$$q_2 = \sqrt{\frac{2D_0 P_0 I_1}{I_2 (P_0 - D_0)}} \tag{2.24}$$

$$t = \frac{q_2}{D_0} \tag{2.25}$$

If investment is not spent on CCS technology, the manufacturing firm's overall cost for the EPQ model is defined as

$$OC = ISC + IHC + IPC + IWC + ISWC \tag{2.26}$$

Thus, the manufacturing industry's total expenses are calculated by

$$OC = \frac{I_1 D_0}{q_2} + (I_2 + I_{2c}) \frac{q_2 (P_0 - D_0)}{2P_0} + (I_3 + I_{4C} + I_{5C} + I_{6C}) D_0 + \frac{I_7 D_0}{q_2} + (I_{8C} + I_{9C}) D_0 + \frac{I_{10} D_0}{q_2} + I_{11c} D_0 \tag{2.27}$$

$$OC = \frac{I_1 D_0}{q_2} + (I_2 + z I_{EC} I_{EG}(I_4)) \frac{q_2 (P_0 - D_0)}{2P_0} + (I_3 + I_{PEC} I_{EG}(I_4) + NO_X I_5 + SO_X I_6) D_0 + \frac{I_7 D_0}{q_2} + (I_{WO} V_{BOD} I_8 + I_{WO} V_{COD} I_9) D_0 + \frac{I_{10} D_0}{q_2} + I_{WO} V_{SLD} V_{CH_4} I_{11} D_0 \tag{2.28}$$

3 Result and discussion

The existing research has extensively investigated the economic production quantity model under diverse operational conditions; nevertheless, it does not adequately address the incorporation of sustainability initiatives such as carbon capture and storage technology [1,3,7,10,11]. However, no study has been conducted to investigate how effective CCS technology can be smoothly implemented in EPQ models to accomplish environmentally friendly production methods while maintaining financially viable [14,16].So, this research aims to justify the efficiency of Carbon Capture and Storage technology within the economic production quantity model to optimize the overall cost of an organization.

3.1 Example

To numerically demonstrate the idea, the proposed model is examined using parameters taken from Hui Ming Wee's research [8].

D_0= 84,000 ton/year; P_0= 3,36,000 ton/year; I_1= 5000 USD/cycle; I_2= 2.5 USD/ton; I_3= 275 USD/ton; I_4= 65 USD/tonCO_2; I_5= 5 USD/kgNO_X; I_6= 5 USD/kgSO_X; I_7= 2000 USD/cycle; I_8= 0.02 USD/kg BOD; I_9= 0.02 USD/kg COD; I_{10}= 500 USD/cycle; I_{11}= 65 USD/ton; NO_X= 1.12 kg/ton; SO_X= 1.9 kg/ton; V_{BOD}= 23.5 kg/m^3; V_{COD}= 44 kg/m^3; V_{SLD}= 0.5 ton dry sludge /m^3; V_{CH_4}= 0.24 ton CH_4/m^3; z= 3.71 m^3/ton; I_{EC}= 1.5 kWh/m^3; I_{PEC}= 1078 kWh/ton; I_{WO}= 3.49 m^3/ton; I_{EG}= 0.0005 tonCO_2/kWh; CCS= 73 USD

By applying the method described in Section 2.8, optimal production quantity, cycle duration and the overall cost of the industrial sector adopting CCS technology are as follows.

q_1= 25,829.68; t= 0.307

OC= 16260.36+24,390.55+24,662,694+6,504.15+395,766+1,626.04+2,286,648+73

= $27,393,962

By applying the method described in Section 2.9, optimal production quantity, cycle duration and the overall cost of the production industry without CCS technology are determined as follows.

q_2= 21,166.01; t= 0.252

OC= 19843.14+21,278.97+27,311,340+7,937.25+395,766+1,984.31+2,286,648

= $30,044,797

The efficiency of the suggested model is displayed in Table 1.

Table 1. Displays the efficiency of the suggested model

Overall cost of the production industry	With CCS Technology Investment	Without CCS Technology Investment
	$27,393,962	$30,044,797

3.2 Sensitivity analysis

In this subsection, sensitivity analysis has been performed on the system parameters of Example 3.1. Specifically, the impact of the parameters I_1, I_2, I_4, I_7, I_{10} was assessed by varying them from -20% to +20%. The optimal values of q_1, t, OC are evaluated. The results that were obtained are shown in Table 2.

Table 2. Sensitivity analysis of q_1, t, OC

Parameter	Results	-20%	-10%	Base Value	+10%	+20%
I_1	q_1	24,046.14	24,953.86	25,829.68	26,676.80	27,497.81
	t	0.286	0.297	0.307	0.318	0.327
	OC	27,390,593	27,392,879	27,393,962	27,395,561	27,397,112
I_2	q_1	28,852.59	27,216.04	25,829.68	24,635.70	23,593.31
	t	0.343	0.324	0.307	0.293	0.281
	OC	27,388,851	27,391,477	27,393,962	27,396,326	27,398,585
I_4	q_1	25,848.27	25,838.98	25,829.68	25,820.43	25,811.17
	t	0.308	0.308	0.307	0.307	0.307
	OC	27,335,068	27,364,515	27,393,962	27,423,408	27,452,855
I_7	q_1	25,131.47	25,482.98	25,829.68	26,171.83	26,509.54
	t	0.299	0.303	0.307	0.316	0.316
	OC	27,392,643	27,393,307	27,393,962	27,394,535	27,395,245
I_{10}	q_1	25,656.92	25,743.46	25,829.68	25,915.65	26,001.33
	t	0.305	0.306	0.307	0.308	0.310
	OC	27,393,635	27,393,799	27,393,962	27,394,124	27,394,286

4 Conclusion

In the modern industrial environment, setting sustainability as a top priority is essential for organizations looking to prosper in a changing marketplace. Carbon emissions are a major cause of environmental change and reducing them is essential for long-term sustainability. Several research have concentrated on other green technology investments in production models. However, no research has been conducted to examine the performance of carbon capture and storage technology in production model. The implementation of carbon capture and storage technology can reduce both carbon emissions and total operational expenses. This strategy seeks to balance financial efficiency with environmental responsibility. Hence, this research aims to fill the gap by demonstrating the efficiency of CCS technology within the production model. A sustainable production quantity model is formulated with the incorporation of Carbon Capture and Storage technology along with greenhouse gas and wastewater emissions. Lagrangian method is applied to determine the optimal solution of the problem. In order to validate the suggested model, this study examines the cost-benefits of traditional and sustainable EPQ models and proving that the sustainable model is more effective. The industrial enterprise that uses CCS technology has a total cost of $27,393,962, while the manufacturing firm that does not use CCS technology has a total cost of $30,044,797. This study offers valuable perspectives to industries and is a trustworthy source for manufacturing firms to consider when making decisions. Future studies may investigate issues like a product's lifespan and the effects of deteriorating items.

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