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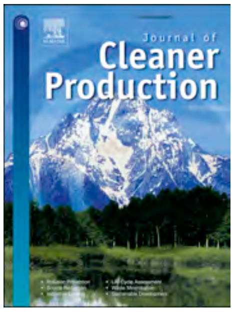

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Intersection of Economic and Environmental Goals of Sustainable Development Initiatives

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Intersection of Economic and Environmental Goals of Sustainable Development Initiatives

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Abstract

There is growing interest in integration of sustainability into business planning decisions under a sustainable development framework. Environmental accounting methodologies for collection, measurement, and disclosure of financial and environmental impacts of strategic and operational managerial decisions are developed and utilized by business entities worldwide for effective management of both organizational and operational environmental protection policies. At the operational level, while extant literature has primarily focused on managerial decision making under different voluntary and regulatory emission pricing schemes, the intersection of economic (monetary) and environmental impact (non-monetary/physical) dimensions of sustainable development goals has received scant attention. This paper examines the intersection of the environmental and economic goals of sustainable development initiatives of a focal firm, which is engaged in the primary activities of production and/or transportation and storage of a single product within a forward supply chain. This paper assumes the presence of a responsive "green market " through modeling of consumer awareness and response induced by the firms' environmental footprint disclosures. Through quantitative modeling approach, normative conclusions are derived on the compatibility of economic and environmental goals of sustainable development initiative. The results indicate the presence of convergence, divergence, and avoidance decision zones in balancing the environmental and economical goals of the firm's sustainable development for production and storage efficiency. The paper explicitly establishes the boundaries of the operational zones within the domain of the firm's environmental reduction and operational efficiency efforts. The results demonstrate that the efficacy of voluntary or regulated emission reduction targets depends on the firm's existing environmental and operational cost structures, and hence emission reduction targets must be well planned to avoid

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adverse environmental impact or operational inefficiencies. Furthermore, it is demonstrated that in a green responsive market, there may exist critical emission reduction thresholds below which the economic and environmental benefits of sustainable development initiatives diverge.

Keywords: Sustainable supply chain, sustainable development, green market, emission cost.

1 Introduction

More companies world-wide are incorporating sustainability into their strategic and operational goals and business planning decisions. According to CDP North America, Inc. (2016) globally over 1200 companies either are currently using or plan to apply an internal proxy carbon price in their business decisions for assessing the financial impact of environmental emissions in company's operation and supply chain, making emission a factor of production, assessing sustainability initiatives for financial and environmental viability, allocating resources toward lower emission activities, research and development investment prioritization, and mitigation of risk from future emission pricing regulations. The list of over 100 North American corporations, across different business sectors, that have embedded carbon pricing in their decision processes include General Motors (Consumer Discretionary), Colgate-Palmolive (Consumer Staples), Exxon-Mobil (Energy), BNY Mellon (Financial), Allergan (Healthcare), General Electric (Industrials), Microsoft Corporation (Information Technology), and Eastman Chemical (Materials). The growing trend in integration of sustainability in corporate decision making and embedding carbon price to quantify financial and environmental impact of firm's activities is also supported by research and development of financial and managerial environmental accounting and protocols for collection and measurement of scope 1 and scope 2 emissions at organizational and product levels and the economic and environmental performance of the firm (Stechemesser and Guenther (2012) and Tsai et al. (2012)).

Cornin et al. (2011), Chabowski and Gonzales-Pardon (2011), Kleindorfer, Kaylan, and Van Wassenhove (2005), Corbett and Kliendorfer (2001), Seuring and Muller (2008), Seuring (2013), Ashby, Leat, and Hudson-Smith (2012),Jaehn (2016) provide recent surveys on sustainability related literature in strategy, management, marketing, and operations, indicating a proliferation of both academic and practitioner research in this area over the past two decades. Relevant to our work, one stream of literature has focused on the economic benefits of sustainability and utilized proxy measures such as return on assets or market valuation to explore the relationship between the firms' financial performance and sustainability initiatives. Klassen and McLaughlin (1996) use first time environmental award announcements to study the impact of environmental management initiatives on the firm's market valuation. Menon and Menon (1997) suggest that higher level of Enviropreneurial Marketing results in higher firm performance. They propose that the companies adopting environmental marketing strategies have better business performance and competitive advantage. Russo and Fouts (1997) demonstrate how companies' environmental performance is significantly related to firms' financial performance. Dowell, Hart, and Yeung (2000) find a significant positive relationship between the market value of the firm and the stringency of environmental standards that it adopts and suggest that the less negative externalities a firm imposes, the higher the firm value would be. King and Lenox (2002) studies the correlation between pollution reduction and financial performance. Their result reinforced the earlier findings by Hart and Ahuja (1996) that reduced emission levels result in higher future financial performance. More recently, the study by Jacobs, Singhal, and Subramanian (2010) provides corroborating evidence for the linkage between environmental initiative announcements and market performance. Additionally, they conclude that third party awards and certifications such as ISO 14001 result in positive market reaction while pledges and voluntary emission reductions cause negative market reaction. Walker (2015) notes that while several studies have identified a relationship between environmental supply chain management and economic performance, the direction of this relationship remains ambiguous. The holistic view of sustainability adopted in this stream of research has understandably failed to provide managerial insights necessary for better understanding and quantifying the directional relationship between the environmental impact and the economic performance of sustainable development strategies.

Use of analytical and quantitative approaches in modeling of sustainable forward supply chains has increased in recent years. Related to our modeling approach, analytical modeling research with focus on the production lot-sizing problem under various carbon control schemes include He et al. (2015), Li et al. (2017), Xu et al. (2016), Toptal and Çetinkaya (2015), Benjaafar et al. (2013), Chen and Monahan (2010), Bouchery et al. (2012), Battini, Persona, and Sgarbossa (2014), and Absi et al. (2013) etc. He et al. (2015) studies lot-sizing under cap-and-trade and carbon tax regulations based on the economic order quantity model. Benjaafar, Li, and Daskin (2013) studies the classical multi-period lot-sizing problem under different regulatory policies including mandatory caps, emission taxation, carbon emission caps with reward/penalty based on emission, and investment in carbon offset to mitigate caps. Chen and Monahan (2010) utilizes the economic order quantity framework to study the impact of operational adjustments on reduction of emissions, and conditions under which the reduction in emission exceeds the relative increase in the firm's total cost. Bouchery et al. (2012) reformulates the economic order quantity model into a sustainable order quantity model, as a multi-objective problem, assuming that the decision-maker can decide on economic, environmental, and social trade-off by taking into account pressure from different sources for environmental and social impact reduction. Battini, Persona, and Sgarbossa (2014) incorporates internal and external transportation costs, vendor and supplier location, and freight vehicle utilization ratio into the traditional economic order quantity model.

Modeling the impact of carbon footprint regulatory policy issues have also attracted much attention. For example, Hua, Cheng, and Wang (2011) investigates how firms can mange their carbon footprint in inventory management under the carbon trading mechanism. He et al. (2015) investigates cap-and-trade and carbon tax regulations and investigates the impact of regulatory parameters on the optimal lot-size and emissions of the firm. Li et al. (2017) examines the production and transportation problems of a two echelon supply chain under cap-and-trade and joint cap-and-trade and carbon tax policies and conclude that the latter is more beneficial for emission reduction especially at lower carbon prices. Xu et al. (2016) analyzes the joint production and pricing problem of a manufacturing firm with multiple products under cap-and-trade and carbon tax regulations under both uniform and discriminatory emission pricing policies. Their study concludes that neither one regulation will always result on more profit and lower carbon emissions than the other one. Toptal and Çetinkaya (2015) studies coordination between a buyer and a vendor under the two emission regulation policies and shows that although coordination mechanism can help the buyer and vendor to lower their cost it may result in increased carbon emission under certain circumstances.

The predominant modeling approach under the sustainable development framework is to formalize the firm's response to sustainability initiatives as a cost minimization problem. Therefore, product demand and price, either or both, are commonly assumed to be exogenous to the model and consumer response to the firm's environmental performance is often ignored. Studies such as

Nouira et al. (2014) and Motoshita et al. (2015) suggest the presence of correlation between the demand of some products and their environmental performance, and hence argue for the development of analytical models that formally link the demand of the product to their environmental attributes, and thus, by extension, to the firm's sustainable development efforts.

A related body of research in social sciences, under the broad thematic category of "Green Customers" (Cornin, Smith, Gleim, and Ramirez 2011) have studied the purchasing behavior of the green customers. The researchers have examined separate and often interrelated constructs of socio-demographic (Diamantopolous and et.al 2003), personal (Mostafa (1997),Tanner and Sybille (2003)), environmental consciousness (Sclegelmilch, Bohlen, and Diamantopolous 1996), impression motivation and consistency of behavior (Yoon et al. 2006), and locus of control (Cleveland, Kalamas, and Laroche 2005) to profile the pro-environmental behavior of customers. Expectedly, given the highly contextual consumer response toward sustainability, the research has been inconclusive to the appropriateness and efficacy of each construct in profiling the green customers. The marketing literature on green customers is generally descriptive. Huang and Rust (2011) have examined the relation between sustainability (pollution) and consumption using analytical economic models. Their work studies sustainability-consumption from a different angle of what impact sustainability should have on consumer consumption.

Literature on analytical modeling of sustainable supply chain that incorporates consumer awareness and behavior and its consequential impact on product demand remains scant. ElSaadany, Jaber, and Bonney (2011) study a two echelon supply chain with the demand assumed to be a function of price and product's environmental quality. Chen (2001) studies green product design for durable products with competing traditional and environmental product attributes. The quality based model in Chen (2001) incorporates preferences of the ordinary and green customers and the effect of environmental standards. Subramanian, Gupta, and Talbot (2009) examines remanufacturable product design under Extended Product Responsibility (EPR) by integrating the impact of environmental legislation into the managerial decision process on product design and pricing. Krass, Nedoregov, and Ovchinnikov (2013) analyzes the technology choice under emission regulation. They consider a profit maximizing monopolistic firm with price dependent demand selecting emission control technology, production quantity, and price in response to taxation, subsidy, and rebate levels set by the regulators. Nouira, Frein, and Hadj-Alouane (2014) considers environmental performance of the finished product in modeling of manufacturing systems. They consider two separate models of manufacturing activities. In the first model, the product demand depends on the greenness level of the finished product; and in their second model, the market is segmented between ordinary and green customers with demand linearly decreasing in the product greenness level. Ji et al. (2017) studies a dual-channel supply chain of a manufacturer and retailer under cap and trade and relates the consumer demand to both the product's retail price and manufacturer's emission reduction decisions. The study assumes that the total carbon emission is linear in production quantity and thus only includes emission produced in production and neglects emission from other activities such as transportation and logistics processes.

In this paper, we examine the intersection between the environmental and economic dimensions of sustainable development initiatives for a focal firm in a forward supply chain which engages activities of production and/or transportation and storage of a product. Customer demand is explicitly modelled as a function of the level of supply chain pollutant emission thus allowing for normative conclusions on the interaction between economic benefits of increased consumer demand and its environmental impact. This research contributes to the existing body of knowledge in a number of directions. First, our modeling approach extends the scope and intricacy of existing quantitative modeling literature by incorporating both the fixed (quantity independent) and the variable (quantity dependent) emissions resulting from both the production and logistics activities of the focal firm. Second, our work provides a new perspective by focusing on the interrelationship between environmental and economic efficiency goals of the firm, and in doing so, addresses an important gap in the existing research. Next, this paper incorporates the consumer awareness by relating the product demand to the total emission of all activities in contrast to either the use of price as a proxy measure for modeling consumer response to environmental efforts or inclusion of product emission attribute which only accounts for variable production and storage emission and neglects the emission from other parts. To our best knowledge, the adoption of the well-known operations management's product and process viewpoint in the modeling of consumer awareness and response by relating the product demand to the total emission level from all activities is not addressed in the literature. Finally, our findings helps to provide justification for the conflicting results in the current sustainable supply chain management literature, which may have contributed toward the prevailing skepticism on economic benefits of sustainability by demonstrating that the economic benefit derived from sustainability initiatives is not monotonic with the improvement in environmental emission, and the domains of both operational efficiency and environmental impact reduction initiatives include zones of avoidance, convergence, and divergence for the two dimensions of sustainable development initiatives. Furthermore, through linkage of the operational level adjustments with financial and environmental performances, our research results provide valuable managerial insights at various level of decision making process and contributes toward reducing a recognized gap between managerial strategic sustainability desire and the operational and tactical decisions Pagell and Gobeli (2009).

Figure 1 depicts the overall framework of our research and the organization of this paper. Section two discusses our modeling framework and assumptions. In section three, the intersection of economic and environmental impacts of sustainable development initiatives under a price control instrument is discussed. Section four extends the results to sustainable development initiatives under the more generalized quantity control pricing instrument. Finally, in section five, we present the summary of findings and conclusions.

Insert Figure 1 here

2 Model Assumptions

We consider a supply chain focal firm engaged in warehousing/storage (Activity 1), production and/or transportation (Activity 2) of a single product. The firm decides the production quantity Q per cycle in response to an annual deterministic demand D. The unit holding cost is h, and s denotes the setup and/or transportation cost per production cycle.

Pagell and Gobeli (2009) indicate that the level of firms' toxic release is also an indicator of employee well being (health and safety) and the eco-system's health, thus suggesting that the firm's environmental emissions is an indirect indicator of social impact as well as the environmental impact of sustainability. Thus, our paper models the combined environmental emission from the above two operational activities as a single indicator of environmental performance. In order to model the firm's total annual pollutant emission, we have adopted the traditional product and process perspective in operations management and draw on an approach similar to that suggested by Nouira, Frein, and Hadj-Alouane (2014) and others, which classify the supply chain decisions affecting the environmental impact of a product into two inter-related categories. The first category consist of decisions that directly affect the environmental attributes of the product (i.e use of eco-friendly raw material, re-usability and recyclability product design, design to reduce life cycle energy and resource consumption), and the second category includes decisions which have an indirect effect on the environmental impact of the product and are commonly related to the manufacturing and delivery processes (i.e green supplier selection, manufacturing technology choice, infra-structure and facilities greening, material handling equipment selection, transportation modal selection).

Thus the scope of this research focuses on scope 1 (direct) and scope 2 (indirect) process and product related emissions resulting from the primary operations of warehousing (Activity 1) and production and/or transportation (Activity 2) of a single product of a single firm within a supply chain. The fixed emission E_f includes the joint total emission from the manufacturing, transportation and warehousing infrastructure and supportive operations (from both activities 1 and 2) such as lighting, ventilation, humidity or other environmental controls. The variable storage emission, E_{1v}, includes the emission from inventory and maintenance of the products within the warehousing facility for Activity 1. Further, the production/transportation fixed process emission E_{2f} includes the emission associated with production setup and the empty vehicle weight and back-haul segment of the product delivery route for Activity 2. Lastly, the variable component of the production emission E_{2v} represent the per unit product emission and transport emission related to product characteristics such as packaging, weight, volume, or density etc. for Activity 2. Note that E_f encompasses both Activities 1 and 2 while others are activity specific representing emission from either Activity 1 or Activity 2 and hence E_f does not have a numeric subscript in the notation.

In this paper, the emission of pollutants is assumed to be a one-dimensional environmental attribute with a decreasing consumer valuation (i.e. green customers derive higher utility from lower emission). Consumer awareness and the market response to changes in firm's total pollutant emission level is modeled by using a linearly decreasing demand function $D(Q) = a - bE$, with $a, b \geq 0$. a represents the market potential and b is the demand sensitivity to the changes in the overall emission level and E is the firm's emission level. When $b = 0$, the market is defined as non-responsive market condition; and $b > 0$, is referred to as the responsive market condition. All emission parameters are assumed to be upper-bounded by the requirement that the firm maintains a positive demand for its product $D(Q) = a - bE(Q) > 0$.

In this paper, a generalized emission pricing model is utilized to study the impact of sustainability initiatives on economical and environmental performance of the firm under both regulatory and voluntary control policies. The emission pricing instrument is modeled as (T, k_1, k_2) where T represents an overall target emission level (inter- or intra-organizational), k_1 is the cost/penalty per unit emission above the target level, and k_2 is interpreted as the reward/revenue per unit emission below the target level. Within this construct, the emission pricing instrument $(0, k, k)$ corresponds to the uniform pricing (emission tax) and $(T, k, 0)$ represents discriminatory emission pricing control. The generalized (T, k_1, k_2) represents the quantity control approach with penalty and revenue/reward structures (cap-and-trade). Similar to He et al. (2015), this research is distinguished from former studies by assuming $k_2 \leq k_1$ to avoid speculative behavior. It is further assumed that T, k_1, k_2 are determined exogenously. Defining p to be the product's unit price, $\Omega = \{E_f, E_{1v}, E_{2f}, E_{2v}, s, h\}$ as the set of exogenous operational and environmental parameters, $\Pi_{T,k_1,k_2}[Q(\Omega)]$ as the firm's total annual profit under the generalized emission pricing (T, k_1, k_2), and $E[(Q(\Omega)]$ as the firm's annual emission, then:

$$E[Q(\Omega)] = E_f + E_{1v}\frac{Q}{2} + E_{2f}\frac{D(Q)}{Q} + E_{2v}D(Q) \tag{1}$$

and

$$\Pi_{(T,k_1,k_2)}[Q(\Omega)] = pD(Q) - s\frac{D}{Q} - h\frac{Q}{2} - k_1(E[Q(\Omega)] - T)^+ + k_2(T - E[Q(\Omega)])^+ \tag{2}$$

Table 1 provides a summary of the notations used in the following sections.

Insert Table 1 here

3 Sustainable Development Initiatives Under Uniform Price Control

Sustainable development initiatives are defined as uni-dimensional emission reduction and/or operational efficiency efforts manifested through the reduction of either the fixed or variable emission coefficient or a single operational cost parameter, with the goal of either enhancing the firm's financial performance (economic dimension), or lowering the firm's emission of pollutants (environmental dimension), or both. Through-out the paper, the term "optimal operational response" is used to denote the production quantity that maximizes the economic benefit and the term "'optimal environmental response"' refers to the production quantity that minimizes the firm's total emission footprint.

3.1 Optimal Operational and Environmental Responses Under Uniform Price Control

Assuming environmental information symmetry and substituting for $E(Q)$ in $D = a - bE(Q)$ results in the functional relationship $D(Q) = \frac{aQ - bQE_f - \frac{b}{2}Q^2E_{1v}}{Q + bE_{2f} + bQE_{2v}}$ between the product demand and the production lot-size (Q). Furthermore, define p as the unit price, and $\Lambda = -\frac{b^2}{2}E_{1v}E_{2f} - a + bE_f - abE_{2v} + b^2E_fE_{2v}$, $A = s(1 + bE_{2v}) + (k + bp)E_{2f}$ as the "effective set-up cost", and $B = h(1+bE_{2v})+(k+pb)E_{1v}$ as the "effective inventory holding cost", the firm's optimal operational responses are described in the following proposition.

Proposition 1 *1. The firm's profit function $\Pi_{0,k,k}[Q(\Omega)]$ is concave in Q and the optimal operational response is given by,*

$$Q^* = -\frac{bE_{2f}}{1 + bE_{2v}} + \frac{1}{1 + bE_{2v}}\sqrt{(-2\Lambda)\frac{A}{B}}$$

2. The firm's total emission $E[Q(\Omega)]$ is convex in Q. The optimal environmental response Q_e is,

$$Q_e = \frac{-bE_{2f}}{(1 + bE_{2v})} + \frac{\sqrt{(-2\Lambda)E_{1v}E_{2f}}}{E_{1v}(1 + bE_{2v})}$$

3. $Q^* = Q_e$ if $\frac{E_{1v}}{h} = \frac{E_2f}{s}$, $Q^* > Q_e$ if $\frac{E_{1v}}{h} > \frac{E_2f}{s}$ and $Q^* \leq Q_e$ if $\frac{E_{1v}}{h} \leq \frac{E_{2f}}{s}$.

The dual goals of achieving operational efficiency and reducing the environmental impact of firm's operations are generally not coordinated. Similar results were also shown in Irina et al. (2011) under non-responsive market condition where the authors suggested that the optimal design based on costs does not necessarily equate to the optimal solution based on emission, and there is a need to address the coordination between the two targets (economical and environmental).

The economic and environmental dimensions of sustainability only become coincidentally coordinated when the contribution of emission cost to the operational holding and setup/ordering costs is proportionally identical (i.e. $\frac{E_{1v}}{h} = \frac{E_{2f}}{s}$). Proposition 1 also suggests that within the rational operating zone as defined by the optimal operational and environmental responses, the firm's production quantity can be adjusted to affect the trade-off and thus coordination between the economic and environmental benefits. However, higher benefits with respect to either dimension may produce a negative impact on the other one. It is noted that lack of general coordination between the economic and environmental goals does not necessarily imply that the firm should adopt operational and/or environmental initiatives to achieve such balance or coordination. The extent of coordination between economic and environmental benefits of sustainability initiatives depends on the firm's operational and environmental cost structures and is discussed in more detail later in this section.

The following two corollaries examine the sensitivity of the optimal operational response to changes in market, operational, and environmental parameters.

Corollary 1 *The firm's optimal operational response Q^*,*

1. *increases when market potential a increases;*
2. *increases in unit price p if $\frac{E_{1v}}{h} \leq \frac{E_{2f}}{s}$ and decreases in p otherwise;*
3. *increases in emission price k if $\frac{E_{1v}}{h} \leq \frac{E_{2f}}{s}$ and decreases in k otherwise.*

The relationship between Q^* and a follows the common intuition that increased market potential require a larger production quantity for demand fulfillment. In a responsive market, increase in demand potential increases both the firm's optimal operational and environmental responses.

Variation in unit price or emission price affects both the firm's effective set-up and holding costs thus affecting the optimal operational response. When $\frac{E_{1v}}{h} \leq \frac{E_{2f}}{s}$, an increase in either the unit profit or emission price causes a higher proportional increase in the firm's effective set-up cost resulting in the increase in optimal production lot-size and reduction in the number of production cycles. Conversely, when $\frac{E_{1v}}{h} \leq \frac{E_{2f}}{s}$, increase in unit profit or emission price causes a higher proportional increase in effective holding cost, and thus the optimal production quantity is reduced to lower the firm's inventory cost.

Corollary 2 *1. The optimal operational response Q^* increases when the set up cost s increases or the holding cost h decreases;*

2. The optimal operational response Q^* is decreasing in E_f, E_{1v}, and E_{2v};

3. Q^* is a concave increasing function of E_{2f}.

The relationship between Q^* and the setup and holding cost parameters is also well known. Increase in the setup cost or decrease in the holding cost raises the firm's optimal operational response Q^*. Reduction in either the fixed manufacturing and warehousing or variable storage emission parameters decreases the effective holding cost and hence increases Q^*. Decreasing the variable production and transportation emission parameter lowers the per unit manufacturing and transportation cost resulting in larger lot-size Q^*. Reduction in fixed manufacturing and transportation emission cost, however, lowers the effective setup cost and allows more frequent production and delivery and thus a lower optimal operational response.

Above discussion explores the optimal operational responses and adjustment based on financial performance optimization. At the same time, when the firm makes decision based on emission minimization, different operational response (optimal environmental response) can be observed. By substituting $Q_e[\Omega]$ into $E[Q_e]$ function, the firm's total pollutant emission under the optimal environmental response in Proposition 1 is,

$$E[Q_e(\Omega)] = \frac{1}{(1+bE_{2v})^2}[\sqrt{-2\Lambda E_{1v}E_{2f}} + (E_f + aE_{2v})(1+bE_{2v}) - bE_{1v}E_{2f}]$$

Proposition 2 *The firm's total pollutant emission function under optimal environmental response, $E[Q_e(\Omega)]$, is increasing in both fixed and variable storage emission parameters (Activity 1), and in both fixed and variable production and transportation emission parameters (Activity 2).*

This proposition suggests that reduction in the firm's environmental footprint can be achieved through initiatives that reduce either the fixed or variable emission coefficients of the firm's storage and production/transportation activities. Strategic focus on sustainability coupled with its integration into operational decision processes, will result in continuous improvement toward lowering the firm's environmental footprint. However, it should be recalled that such reduction in total annual emission may adversely effect the economic dimension of sustainability due to the lack of coordination. The compatibility between economic and environmental goals are discussed in the following section.

3.2 Operational and environmental impact of sustainability initiatives under uniform price control

Under the optimal operational response in Proposition 1, the optimal profit function can be rewritten as a function of parameter set Ω by substituting $Q^*(\Omega)$ into $\Pi[Q]$,

$$\begin{aligned}\Pi_{0,k,k}[Q^*(\Omega)] &= \frac{1}{1+bE_{2v}}[(p-kE_{2v})(a-bE_f)+\frac{b}{2}E_{1v}(s+kE_{2f})+\frac{b}{2}E_{2f}(h+kE_{1v})] \\ &+\frac{b^2E_{1v}E_{2f}}{(1+bE_{2v})^2}(p-kE_{2v})-kE_f-\frac{\sqrt{-2\Lambda AB}}{(1+bE_{2v})^2}\end{aligned}$$

and the corresponding total pollutant emission is,

$$\begin{aligned}E[Q^*(\Omega)] &= \frac{1}{2(1+bE_{2v})^2}\sqrt{-2\Lambda}[E_{1v}\sqrt{\frac{A}{B}}+E_{2f}\sqrt{\frac{B}{A}}] \\ &+\frac{1}{(1+bE_{2v})^2}[(aE_{2v}+E_f)(1+bE_{2v})-bE_{1v}E_{2f}]\end{aligned}$$

The operational domain of the environmental emission and operational parameters is segmented into three possible zones of "convergence", "divergence", and "avoidance". Within a convergence zone, sustainable development initiatives result in increased economic benefit and reduced environmental impact and thus the firm's economic and environmental goals become fully compatible. Reduction of an environmental or operational parameter within a divergence zone necessitates trade-off between environmental and economic benefits with gain in any one dimension causing deteriorated performance in the other. The avoidance zone is characterized as an operational zone where sustainability initiative adversely affects both economical and environmental benefits. Proposition 3 describes the functional properties of $\Pi[Q^*(E_{ij})]$ and $E[Q*(E_{ij})]$, hence providing the basis for the compatibility relationship between the two sustainable development dimensions.

Proposition 3 *Under the optimal response function $Q^*[E_{ij}]$, with $E_{ij} \in \{\Omega\}$,*

1. *the profit function $\Pi_{0,k,k}[Q^*(E_f)]$ is convex in E_f with the minimum profit achieved at $E_f^m = \frac{a}{b} - \frac{b}{2(k+bp)^2}[sh(1+bE_{2v})+s(k+bp)E_{1v}+h(k+bp)E_{2f}]$; the emission function $E[Q^*(E_f)]$ is concave in E_f with the maximum emission achieved at $E_f^e = \frac{a}{b} - \frac{b}{8(1+bE_{2v})}[E_{1v}^2\frac{A}{B}+E_{2f}^2\frac{B}{A} - 2E_{1v}E_{2f}]$.*

2. *the profit function is convex in* E_{1v} *with the minimum achieved at* $E_{1v}^m = \frac{2(a-bE_f)(pb+k)^2 - b^2Ah}{b^2(pb+k)s}$*; the emission function is increasing in* E_{1v}*.*

3. *the profit function is convex in* E_{2f} *with the minimum achieved at* $E_{2f}^m = \frac{2(k+bp)^2(a-bE_f) - b^2Bs}{b^2h(k+bp)}$*; the emission function is increasing in* E_{2f}*.*

4. *the profit function is either decreasing in* $E_{2v} \geq 0$ *or there exist* $E_{2v}^m > 0$ *such that the firm's profit increases in* $E_{2v} \leq E_{2v}^m$ *and decreases in* $E_{2v} > E_{2v}^m$*; the emission function is increasing in* E_{2v}*.*

Insert Figure 2 here

Figure 2 shows the compatibility of sustainability goals for initiatives aimed at reducing the fixed storage emission parameter E_f and the variable production and transportation emission parameter E_{2v}. In a non-responsive demand market, as shown in Figure 2(a), the operational domain of E_f and E_{2v} is comprised of a single compliance zone indicating compatibility of economic and environmental dimensions of sustainability everywhere. Under this market condition, voluntary adoption or regulatory imposition of emission pricing increases the firm's total operational cost and incentivizes the adoption of sustainability initiatives to lower the firm's environmental impact and simultaneously increase the profit by lowering the emission cost. Notice that the implementation cost on sustainability initiatives is not considered in this model and worth further exploration in future research.

Under demand responsive market condition, as shown in Figure 2(b), reduction in firm's fixed storage emission parameter may have adverse economic and environmental effects. Emission parameter reduction within "Avoidance zone" ($[E_f > E_f^e]$) designated as operational zone A, lowers the firm's total profit and increases its environmental footprint. Within the "Divergence zone" ($[E_f^m \leq E_f \leq E_f^e]$) shown as operational zone D, reduction in the firm's environmental impact is achieved at the expense of lower profitability. The economic and environmental dimensions of sustainability initiative are only compatible in the "Convergence zone" ($[E_f < E_f^m]$) referred to as operational zone C.

The firm's total emission function monotonically decreases with the reduction in the variable production and transportation emission (E_{2v}) everywhere. However, the economic benefits from reducing E_{2v} depends on the firm's existing operational and environmental cost structure. As Figure 2(c) depicts, there may exist a threshold level $E_{2v}^m > 0$ such that the firm's total profit decreases with the reduction of E_{2v} in $E_{2v} < E_{2v}^m$, causing divergence of the firm's economic and environmental goals. The economic and environmental benefits from the reduction of the variable production and transportation emission are fully aligned within the convergence zone when $E_{2v} > E_{2v}^m$.

Figure 3 shows the impact of the reduction in fixed production and transportation emission parameter E_{2f} and variable inventory E_{1v} under both responsive and non-responsive market conditions. Under non-responsive market condition, Figure 3(a), the firm's total emission reduces and the total profit increases with the reduction in E_{2f} or E_{1v} suggesting the convergence of sustainability goals everywhere.

Insert Figure 3 here

In a demand responsive market, the operational domains of both emission coefficients include two zones of divergence and convergence as shown in Figure 3(b). In both zones, sustainability initiatives lower the firm's environmental impact, but enhanced economic benefits is only realized when the emission coefficients are reduced below the threshold levels E_{2f}^m and E_{1v}^m, the minimizers of the corresponding profit functions.

In general, Proposition 3 suggests that when consumer demand is not significantly influenced by the firm's environmental efforts (i.e. small b or non-responsive market), sustainability initiatives under uniform price control will always lower the firm's environmental impact and the economic justification of the initiative is primarily based on the trade-offs between the implementation cost and the reduction in firm's total operational cost. In contrast, as shown in Proposition 3, under a responsive market condition, efforts to reduce the fixed production, warehousing, and transportation or variable storage emission parameters are subject to thresholds levels E_f^m, E_{1v}^m, and E_{2f}^m before the compatibility between the economic and environmental goals is achieved. Presence of the avoidance and/or divergence operational zones before the realization of compatibility between sustainability dimensions introduces a higher level of complexity in the selection and justification of sustainable development initiatives. Depending on the current operational and environmental cost structure of the firm, emission reduction efforts may initially result in deteriorating financial performance and/or adverse environmental impact. This result may partially explain the presence of conflicting literature on profitability of sustainability initiatives and may explain why some managers believe that there is a lack of business case for sustainability.

Proposition 3 also suggests that the firm always benefits from adopting a continuous improvement view of sustainability in reducing the fixed production, warehousing, and transportation or variable storage emission parameters. For a firm that initially operates in the avoidance and divergence zones, incremental reduction in emission coefficients may adversely impact it's financial competitive advantage. However, persistence and continuous improvement will ultimately result in both economic and environmental benefits to the firm as the critical threshold levels are crossed and the convergence operational zone is reached.

The threshold levels (E_f^m, E_{1v}^m, and E_{2f}^m) defining the boundaries of the operational zones are increasing in emission price, k. Increment in the emission price k reduces the avoidance and divergence interval lengths and enlarges the domain of convergence zone. Although a higher emission price increases the severity of profit loss by imposing a higher overall operational cost, it reduces the level of emission reduction efforts necessary to reach the convergence zone and thus increases the likelihood that the firm adopts bolder environmental target reductions to mitigate the loss of profit through market share expansion.

Consumer demand sensitivity to the environmental impact of the firm also affects the domain of the operational zones. The operational zones' threshold levels decrease in market sensitivity, b, and hence a higher demand sensitivity factor increases the domain of the avoidance and divergence zones and reduces the domain of the convergence zone. Therefore, higher levels of consumer demand sensitivity encourages adoption of sustainability initiatives with larger target reductions on emission parameters while lower sensitivity factors reduces the level of emission reduction effort necessary to reach the convergence operational zone. A higher demand sensitivity factor (b) causes a higher reduction in product demand requiring a correspondingly higher reduction in emission level to negate the impact on consumer demand.

Reduction of variable production and transportation emission parameter may exhibit a different operational pattern than the other emission coefficients. When the optimal profit function is unimodal in E_{2v}, there exists an optimal threshold level E_{2v}^m such that the reduction of emission level in the divergence zone $[E_{2v} \leq E_{2v}^m]$ lacks economic justification. Therefore, despite the resulting environmental benefits, the firm is less inclined to adopt the strategic view of sustainability with regard to lowering the variable production and transportation emission beyond the critical threshold level E_{2v}^m.

Operational efficiency initiatives for reducing the holding and setup costs also impact the firm's economic and environmental goals by altering the alignment between the environmental and operational cost structures. While the classical inventory theory suggests that reduction of holding and set-up costs improve the economic performance of the firm, this is not always the case in a sustainable supply chain under emission price control and demand responsive market conditions. The following proposition describes the impact of operational efficiency initiatives on the economic and environmental benefits of sustainability. Defining the alignment holding cost $h^e = \frac{E_{1v}s}{E_{2f}}$ and the alignment setup/ordering cost $s^e = \frac{E_{2f}h}{E_{1v}}$;

Proposition 4 *Under the optimal operational response Q^*,*

- *the firm's profit function $\Pi_{0,k,k}[Q^*(h)]$ is convex in h with the minimum profit achieved at $h^m = \frac{1}{1+bE_{2v}}[\frac{(-2\Lambda)A}{b^2E_{2f}^2} - (k+bp)E_{1v}]$, and $h^m \geq 0$. The emission function $E[Q^*(h)]$ is unimodal in h with the minimum emission achieved at $h^e = \frac{sE_{1v}}{E_{2f}}$. Specifically, the optimal emission function is convex in $0 \leq h \leq 3h^e + \frac{2(k+bp)E_{1v}}{1+bE_{2v}}$ with minimum at h^e ; and increasing in $h > 3h^e + \frac{2(k+bp)E_{1v}}{1+bE_{2v}}$. Additionally, $h^e \leq h^m$.*

- *the firm's profit function $\Pi_{0,k,k}[Q^*(h)]$ is convex in s with the minimum profit achieved at $s^m = \frac{1}{1+bE_{2v}}[\frac{(-2\Lambda)B}{b^2E_{1v}^2} - (k+bp)E_{2f}]$, and $s^m \geq 0$. The emission function $E[Q^*(s)]$ is unimodal in s with $s^e = \frac{hE_{2f}}{E_{1v}}$ as the minimum. Specifically, the emission function is convex in $0 \leq s \leq 3s^e + \frac{2(k+bp)E_{2f}}{1+bE_{2v}}$ with minimum obtained at s^e; and increasing in $s > 3s^e + \frac{2(k+bp)E_{2f}}{1+bE_{2v}}$. Additionally, $s^e \leq s^m$.*

Figures 4(a) and 4(b) show the impact of reduction in holding cost on sustainability goals. Reduction in setup cost has similar impact. Under non-responsive market condition, the operational efficiency initiatives may or may not result in the convergence of sustainability goals. Before the alignment level (h^e and s^e), the reduction of operational costs shows joint economical and environmental benefits. However, if the firm decides to further improve operational costs beyond the alignment level, not surprisingly, the firm gains economical advantage, but with increased environmental impact due to the deviation from the alignment cost structure. Figure 4(b) shows the impact of operational efficiency initiatives under responsive market condition. Reduction of the holding cost or setup cost within intervals $[h \geq h^e]$ and $[s \geq s^e]$ respectively will lower both the optimal profit and total emission, and hence, causes divergence between economic and environmental sustainability goals. Further reduction over intervals $[h^e, h^m]$ and $[s^e, s^m]$ will reduce the total emission while increasing the firm's profit causing convergence in sustainability goals. Reduction of operational costs within intervals $[0, h^e]$ and $[0, s^e]$ will again causes divergence of sustainability goals as increased profitability will be achieved simultaneously with increased emission and thus increased environmental impact.

Insert Figure 4 here

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4 Sustainable development Initiatives Under Quantity Control

4.1 Operational response to environmental initiatives

This section extends emission pricing to the broader quantity control pricing scheme (T, k_1, k_2). The firm is internally/externally assigned a target pollutant emission level T with a fixed penalty (k_1) per unit emission exceeding the assigned target and a fixed reward $(0 \leq k_2 \leq k_1)$ per unit emission when the total pollutant emission remains below the target. Define,

$$Q_1^* = arg \max_Q [pD(Q) - \frac{Q}{2}h - \frac{D(Q)}{Q}s - k_1[E(Q(\Omega) - T)]$$
$$Q_2^* = arg \max_Q [pD(Q) - \frac{Q}{2}h - \frac{D(Q)}{Q}s + k_2[T - E[Q(\Omega)]]$$

Q_1^* and Q_2^* are the firm's optimal operational response under (T, k_1, k_1), (T, k_2, k_2) respectively.

By proposition 1,

$$Q_1^* = -\frac{bE_{2f}}{1+bE_{2v}} + \frac{1}{1+bE_{2v}}\sqrt{(-2\Lambda)\frac{A(k_1)}{B(k_1)}}$$

$$Q_2^* = -\frac{bE_{2f}}{1+bE_{2v}} + \frac{1}{1+bE_{2v}}\sqrt{(-2\Lambda)\frac{A(k_2)}{B(k_2}}$$

By Proposition 1, and for given Ω and market sensitivity level b, the firm cannot meet the emission target if $T < E(Q_e)$ and thus for any production quantity Q, it will incur the penalty $k_1[E(Q) - T]$. This operational state, when the emission is higher than the target T, is defined as the emission penalty state. When $T \geq E(Q_e)$, the firm can either meet the target emission or choose to lower its emission to receive the efficiency reward by adjusting its order lot-size. These two operational states are defined as the emission neutral state and the reward state respectively. The production quantity that allows the firm to meet the target emission is obtained by setting $E(Q) = T$ and is the solution to;

$$\frac{E_{1v}}{2}Q^2 - [T - E_f - (a - bT)E_{2v}]Q + E_{2f}(a - bT) = 0$$

Let $\alpha_1 = T - E_f - (a - bT)E_{2v} \geq 0$ and $\alpha_2 = E_{2f}(a - bT) \geq 0$, and Q_{01} and Q_{02} be the roots of the above quadratic equation with $Q_{01} \leq Q_{02}$. For production quantities $Q_{01} < Q < Q_{02}$, the firm operates in the reward state; and for production quantities $Q > Q_{02}$ or $Q < Q_{01}$, the firm falls in the penalty state. The firm exactly meets the target emission when $Q = Q_{01}$ or $Q = Q_{02}$. Q_{01} and Q_{02} are henceforth referred to as emission neutral order quantities.

Low target emission ($T < E(Q_e)$) may encourages the firm to initiate sustainability initiatives as the adjustment to the production quantity alone is not sufficient to avoid the penalty associated with the failure to meet the target emission. When the emission target equals the minimum emission level ($T = E(Q_e)$), the optimal environmental response, Q_e, which minimizes the firm's emission level, becomes equal to the emission neutral production quantities and the firm neither pays a penalty for excessive emission nor receives any reward for emission efficiency. By proposition 1, if the environmental and operational cost structures of the firm are also coincidentally aligned, then the optimal operational response under the profit maximization goal will be the same as the optimal environmental response ($Q_1^* = Q_2^* = Q_e$) and the dual goals of minimizing the environmental impact and maximizing the firm's profit will coincide and simultaneously achieved. Again, caution must be exercised not to interpret this condition as the firm's optimal operational state, as further reduction in pollutant emissions and additional profit may be accrued through sustainability initiatives coupled with the appropriate operational adjustments.

For a given target emission, the firm's profit and the optimal operational response are affected by the emission neutral quantities, Q_{01} and Q_{02}. Reduction in emission parameters through environmental sustainability initiatives decreases Q_{01} and increases Q_{02}, and by proposition 1 and corollary 2, causes a shift in the firm's operational state from the emission penalty state to the emission neutral state, and subsequently to the emission reward state, as shown in Figure 5. Correspondingly, the optimal response under profit maximization goal changes from Q_1^* to Q_{01} or Q_{02}, and then to Q_2^* as the shift in operational states occurs. Lack of operational adjustment to support the sustainability initiatives will thus have a diminishing effect both in the economic and environmental benefits of sustainability.

Proposition 5 *Under quantity control scheme (T, k_1, k_2), the firm's profit function is concave in Q. For given exogenous set $\{\Omega, T, k_1, k_2\}$ and assuming $T \geq E(Q_e)$, the optimal operational response is:*

(a). If $\frac{E_{1v}}{h} \leq \frac{E_{2f}}{s}$,

$$Q^* = \begin{cases} Q_2^* & if \quad Q_{01} \leq Q_2^* \\ Q_{01} & if \quad Q_2^* \leq Q_{01} \leq Q_1^* \\ Q_1^* & \quad\quad otherwise \end{cases}$$

(b). If $\frac{E_{1v}}{h} > \frac{E_{2f}}{s}$,

$$Q^* = \begin{cases} Q_1^* & if \quad Q_{02} < Q_1^* \\ Q_{02} & if \quad Q_1^* \leq Q_{02} \leq Q_2^* \\ Q_2^* & \quad\quad otherwise \end{cases}$$

The above optimal operational policy shows that the firm may choose to operate in either the emission reward state by choosing Q_2^*, or the emission penalty state by choosing Q_1^*, or the emission neutral state by choosing Q_{01} or Q_{02}. Similar to the results obtained under uniform price control, this optimal operational policy aims at reducing the distortion in the firm's operational cost structure resulting from quantity control emission pricing. When the emission costs have proportionally higher impact on the firm's setup cost than the holding cost, the order quantity is increased to reduce the frequency of replenishment and mitigate the increase in setup cost. Conversely, when the proportional increase in holding cost is higher than the setup cost, the production quantity is reduced.

Figures 5(a) through 5(f) demonstrate the change in the firm's optimal operational response and consequently the shift in the operational states resulting from reduction in fixed and variable emission coefficients through sustainable development initiatives.

Insert Figure 5 here

4.2 Impact of Emission Reduction on Optimal Operational Response

Reduction in E_f and E_{2v} do not directly impact the alignment between the firm's environmental and operational cost structures, and therefore, two separate cases ($\frac{E_{1v}}{h} \leq \frac{E_{2f}}{s}$ and $\frac{E_{1v}}{h} > \frac{E_{2f}}{s}$) must be considered for these parameters. As shown in Figures 5(a) and (b), at high emission target levels (i.e. $T > E(Q_e)$), the firm is unable to meet the assigned target emission and operates in the penalty state. By proposition 1, the optimal operational response is Q_1^* with $Q_2^* < Q_1^* < Q_e$ when $\frac{E_{1v}}{h} \leq \frac{E_{2f}}{s}$, and $Q_e < Q_1^* < Q_2^*$ for $\frac{E_{1v}}{h} > \frac{E_{2f}}{s}$ by corollary 2. Assuming that unidimensional reduction of environmental parameters is sufficient to meet the assigned target emission level ($T \geq \lim_{E_{ij} \to 0} E(Q_e), E_{ij} \in \Omega$), $\bar{E}_f$ and $\bar{E}_{2v}$ are defined as the emission levels that enable the firm to exactly meet the target emission under optimal environmental response (i.e. $T = E[Q_e(\bar{E}_f)]$). At $\bar{E}_f$ and $\bar{E}_{2v}$ emission parameter levels, $Q_{01} = Q_e = Q_{02}$. Intuitively, $\bar{E}_f$ and $\bar{E}_{2v}$ are the upper bounds of the emission parameters E_f and E_{2v} when the firm is operating in the emission neutral or reward states. Further reduction in E_f and E_{2v} reduces Q_{01} and increases Q_{02}. For $\frac{E_{1v}}{h} \leq \frac{E_{2f}}{s}$, $(\hat{E}_f^1, \hat{E}_{2v}^1)$ and $(\hat{E}_f^2, \hat{E}_{2v}^2)$ are defined as the transitional levels of the emission parameters such that $Q_1^*(E_f) = Q_{01}(E_f)$, $Q_1^*(E_{2v}) = Q_{01}(E_{2v})$, $Q_2^*(E_f) = Q_{01}(E_f)$, and $Q_2^*(E_{2v}) = Q_{01}(E_{2v})$ respectively. The transitional levels uniquely exist by corollary 2. Similarly, $(\check{E}_f^1, \check{E}_{2v}^1)$ and $(\check{E}_f^2, \check{E}_{2v}^2)$ are defined for the case $\frac{E_{1v}}{h} > \frac{E_{2f}}{s}$ by $Q_1^* = Q_{02}$ and $Q_2^* = Q_{02}$. As suggested by proposition 5 and depicted in Figures 5(a) and 5(b), the firm's operational state shifts from the penalty state to the neutral state at emission level $\hat{E}_f^1$ (and $\check{E}_f^1$) or $\hat{E}_{2v}^1$ (and $\check{E}_{2v}^1$), and correspondingly the optimal operational response Q_1^* changes to Q_{01} (and Q_{02}). The next transition in operational state occurs at $\hat{E}_f^2(\check{E}_f^2)$ or $\hat{E}_{2v}^2(\check{E}_{2v}^2)$ with a shift from the emission neutral state to the emission reward state and the change in optimal response from $Q_{01}(Q_{02})$ to Q_2^*.

Initiatives for reducing E_{1v} alter the alignment between environmental and operational cost structures in addition to lowering the firm's pollutant emission. For the exogenous parameter set $\{\Omega - E_{1v}\}$, define $E_{1v}^e = \frac{E_{2f}h}{s}$ as the alignment level of the emission parameter E_{1v}, which aligns the firm's environmental and operational cost structures. As stated earlier, by proposition 1 and corollary 2, $Q_2^* < Q_1^* < Q_e$ for $E_{1v} \leq E_{1v}^e$ and $Q_e < Q_1^* < Q_2^*$ when $E_{1v} > E_{1v}^e$, suggesting that the optimal operational response level is lowered with the reduction in the emission parameter below the alignment level; and vice versa, it is increased with the reduction above the alignment emission level.

Defining $\bar{E}_{1v}$ by $T = E[Q_e(\bar{E}_{1v})]$ as the variable storage emission parameter level that enables the firm to exactly meet the assigned target emission at the optimal environmental response level Q_e, and also as the upper bound of E_{1v} that results in the firm operating in the emission neutral or reward states, two separate scenarios need to be considered corresponding to $\bar{E}_{1v} < E_{1v}^e$ and $\bar{E}_{1v} > E_{1v}^e$. Under each scenario the transitional levels $(\hat{E}_{1v}^1,\ \hat{E}_{1v}^2)$ and $(\check{E}_{1v}^1,\ \check{E}_{1v}^2)$ are defined similar to E_f and E_{2v} as described above with the unique existence of transitional levels guaranteed by corollary 2. The relationship between $\bar{E}_{1v}$, the upper bound for emission neutrality, and the transitional levels under each scenario are shown in Figure 5(c) and Figure 5(d).

Under either of the two scenarios, when the firm's current emission exceeds $\bar{E}_{1v}$ the target emission cannot be met and thus the firm operates in the penalty state with optimal operational response level Q_1^*. The firm remains in the penalty state until the emission level is lowered to a level at or below the transitional level. Upon reaching the transitional level, $\hat{E}_{1v}^1(\check{E}_{1v}^1)$, the firm's operational state shifts to the neutral state and the optimal operational response changes to the emission neutral quantity $Q_{01}(Q_{02})$. The firm's operational state remains in the neutral state as E_{1v} is further reduced and exactly meets the target emission till the next transitional level, $\hat{E}_{1v}^2(\check{E}_{1v}^2)$, is reached. Further reduction in the emission parameter changes the operational response to Q_2^* and the operational state to the emission reward state.

Lowering of the fixed production and transportation emission (E_{2f}) has a similar impact on the operational state and optimal operational response as reduction in E_{1v}. For given exogenous parameter set $\{\Omega - E_{2f}\}$, the alignment level is defined as $E_{2f}^e = \frac{E_{1v}s}{h}$. $\bar{E}_{2f}$ and the transitional levels are defined similar to those for E_{1v}. Figures 5(e) and (f) show the relationship between $\bar{E}_{2f}$ and transitional levels for the two scenarios corresponding to $\bar{E}_{2f} < E_{2f}^e$ and $\bar{E}_{2f} > E_{2f}^e$. As suggested by proposition 5 and assuming that the firm's current fixed transportation emission level exceeds $\bar{E}_{2f}$, reduction of the emission level causes successive shift of operational state from penalty to neutral and reward states with corresponding shift in optimal operational response level from Q_1^* to neutral quantities $Q_{01}(Q_{02})$ and to Q_2^* as the change in operational state occurs.

4.3 Impact of Operational Efficiency Initiatives on Optimal Operational Response

Operational efficiency efforts to reduce the setup or the holding cost impact the alignment in the firm's cost structure and hence affect the economic and environmental goals of sustainable development. Figure 6 illustrates the impact of the operational efficiency efforts on the firm's operational state and optimal operational response.

Insert Figure 6 here

The optimal environmental response Q_e and the emission neutral quantities are independent of the operational cost parameters $\{s, h\}$ and hence they are not impacted by the operational efficiency initiatives. For a given set of exogenous parameters $\{\Omega - s\}$ and target emission level T, a higher setup/ordering cost results in a higher optimal operational response level Q^* (corollary 2) and increased emission level (proposition 4). As shown in Figure 6(a), for a sufficiently high setup cost, the firm would be unable to meet the target emission and operates in the penalty state with optimal operational response Q_1^*. Reduction of setup cost lowers the total emission and when the setup cost equals the transitional setup cost $\check{s}^1$ defined by $E[Q_1^*(\check{s}^1)] = T$, the target emission is exactly met. By proposition 3, the optimal operational response becomes the emission neutral quantity Q_{02} since $\frac{E_{1v}}{h} > \frac{E_{2f}}{s}$ and the operational state is shifted to the emission neutral state. The firm continues to operate in the emission neutral state until the next transitional level $\check{s}^2$ which is defined as $E[Q_2^*(\check{s}^2)] = T$. The operational state is then shifted to the reward state with optimal operational response Q_2^*. The total emission monotonically decreases with further reduction in the setup cost and the minimum emission is achieved at the alignment setup cost s^e by proposition 4. Further reduction of setup cost below the alignment setup cost increases the total emission and alters the firm's cost structure as $\frac{E_{1v}}{h} < \frac{E_{2f}}{s}$ for $s < s^e$. The optimal operational state remains in the reward state while the total emission remains below the assigned target. With further reduction in s, the total emission monotonically increases and again becomes equal to the target emission at transitional setup cost $\hat{s}^2$ causing a shift back to neutral operating state and a change of optimal operational response to Q_{01}. The next transition in the operational state occurs at the transitional setup cost $\hat{s}^1$ when the total emission exceeds the assigned target and the operational state returns to the penalty state.

As depicted in Figure 6 (b), the reduction in holding cost has similar impact on the operational states and the optimal operational response. The operational state shifts from penalty to neutral to reward state and then returns back to neutral and penalty states with continued reduction in holding cost. The optimal operational response successively changes from $Q_1^* \rightarrow Q_{01} \rightarrow Q_2^* \rightarrow Q_{02} \rightarrow Q_1^*$.

Operational efficiency initiatives differ from environmental initiatives as the firm operates in penalty state at both high and low levels of setup and holding costs suggesting that the traditional operations management strategic view of continuous operational cost reduction may not be appropriate in a sustainable supply chain. Responsive supply chain strategies for smaller production lot size or more frequent deliveries must be coupled with sustainability initiatives to ameliorate the adverse environmental impact.

4.4 Impact of Emission Reduction on Economic and Environmental Goals

The following proposition describes how reduction in emission coefficients affect the firm's profit and emission functions.

Proposition 6 *Under quantity control pricing* (T, k_1, k_2),

a. The firm economically and environmentally benefits from the operational strategic goal of continuous reduction in fixed production and warehousing, variable storage, and fixed production and transportation emissions. There exists $\tilde{E}_{ij} \geq 0$ $\{E_{ij} \in \Omega\}$ *such that the economic and environmental goals of sustainability are convergent for* $E_{ij} < \tilde{E}_{ij}$.

b. The firm may not necessarily benefit from the operational strategic goal of continuous reduction in the variable production and transportation emission. For given $\{\Omega - E_{2v}\}$ there may exist a critical threshold $E_{2v}^{critical} > 0$ such the economic and environmental goals of sustainability diverge in $E_{2v} < E_{2v}^{critical}$.

Figure 7(a) and 7(b) show the compatibility between economic and environmental goals as the fixed production and transportation emission is reduced. Define $E_{2f}^{m,1}$ and $E_{2f}^{m,2}$ as the minimizers of the profit function under $(0, k_1.k_1)$ and $(0, k_2, k_2)$ emission pricing respectively, then by proposition 6, when the firm's fixed production and transportation emission exceeds the transitional level, $\hat{E}_{2f}^1$, the firm operates in the penalty state and the total emission exceeds the assigned target emission. By proposition 3, the firm's profit function is increasing in $E_{2f} \geq \max(E_{2f}^{m,1}, \hat{E}_{2f}^1)$ and decreasing in $\hat{E}_{2f}^1 \leq E_{2f} \leq E_{2f}^{m,1}$ when $E_{2f}^{m,1} > \hat{E}_{2f}^1$. Therefore, the environmental and economical benefits diverge in $E_{2f} \geq \max(E_{2f}^{m,1}, \hat{E}_{2f}^1)$ and converge in $\hat{E}_{2f}^1 \leq E_{2f} \leq E_{2f}^{m,1}$.

Insert Figure 7 here

When the fixed production and transportation emission level is between the transitional levels $\hat{E}_{2f}^2$ and $\hat{E}_{2f}^1$, the firm operates in the emission neutral state and meets the assigned target emission T. In this domain, the reduction of fixed production and transportation emission does not affect the firm's environmental impact but the economic benefits are enhanced as the profit function is decreasing in $\hat{E}_{2f}^2 \leq E_{2f} \leq \hat{E}_{2f}^1$ and hence the economic and environmental goals of sustainability are convergent.

By proposition 6, the firm operates in the reward state for $E_{2f} \leq \hat{E}_{2f}^2$ and thus environmentally benefits from reduction in fixed transportation emission. In this domain, the profit function is decreasing when $E_{2f} \leq \min(\hat{E}_{2f}^2, E_{2f}^{m,2})$ and increasing otherwise. Hence, when the minimizer of the profit function, $E_{2f}^{m,2}$, is less than the transitional level, $\hat{E}_{2f}^2$, the sustainability goals diverge in $E_{2f}^{m,2} \leq E_{2f} \leq \hat{E}_{2f}^2$ and converge in $E_{2f} \leq \min(\hat{E}_{2f}^2, E_{2f}^{m,2})$, suggesting both economic and environmental benefits from continuous reduction in firm's fixed production and transportation emission.

Reduction in the variable storage emission, E_{1v} has a similar impact on the firm's environmental and financial impact as lowering the fixed production and transportation emission. Figure 8 illustrates the compatibility of economic and environmental goals as E_{1v} is reduced. Presence of both convergent and divergent zones over the domain of E_{1v}, similar to E_{2f}, again suggests that while the environmental sustainability initiatives for the reduction of variable storage emission may not have a deteriorating effect on the firm's environmental foot-print, they can have adverse short-term financial impact. The environmental and economical benefits become fully compatible once the thresholds level, $\tilde{E}_{1v} = \min(E_{1v}^{m,2}, \hat{E}_{1v}^{2})$, is reached, suggesting the importance of adopting a continuous improvement view for reduction of variable storage emission.

Insert Figure 8 here

Environmental impact from lowering the fixed production and warehousing emission differs from the reduction in fixed production and transportation and variable storage emission coefficients since by proposition 3 the emission function is concave in E_f. Under the optimal operational response, define ($E_f^{m,1}$,$E_f^{m,2}$) as the minimizers of the firm's profit function and ($E_f^{e,1}$,$E_f^{e,2}$) as the maximizers of the emission function in penalty and reward operational states. The environmental impact and compatibility of economic and environmental goals for the case $\frac{E_{1v}}{h} \leq \frac{E_{2f}}{s}$ are depicted in Figure 9(a) and 9(b). Specifically, the firm's emission function is concave decreasing and the profit function is convex increasing (proposition 3) in avoidance operational zone $E_f \geq E_f^{e,1}$ suggesting deterioration in both environmental and economic performance in this interval from reduction in fixed storage emission. The firm's emission function is concave increasing in E_f when $\hat{E}_f^1 \leq E_f < E_f^{e,1}$, and hence sustainability goals diverge in $\max E_f^{m,1}, \hat{E}_f^1 \leq E_f < E_f^{e,1}$ and converge in $\hat{E}_f^1 \leq E_f \leq E_f^{m,1}$ when $\hat{E}_f^1 \leq E_f^{m,1}$.

Sustainability goals converge in the interval between the reward and penalty transitional levels as the total emission remains constant and the profit function is decreasing in $\hat{E}_f^2 \leq E_f \leq \hat{E}_f^1$. Figure 9(a) shows convergence of the goals in $E_f < \hat{E}_f^2$ when $E_f^{m,1} > \hat{E}_f^2$ as the emission function is increasing and the profit function is decreasing in this operational zone. When $E_f^{m,2} < \hat{E}_f^2$, sustainability goals diverge in $E_f^{m,2} < E_f < \hat{E}_f^2$ and converge in $E_f < E_f^{m,2}$.

For the case $\frac{E_{1v}}{h} > \frac{E_{2f}}{s}$, the environmental and economical impacts are identical to the above with transitional levels $\check{E}_f^1$ and $\check{E}_f^2$ replacing $\hat{E}_f^1$ and $\hat{E}_f^2$ respectively. The concavity of the emission function in E_f introduces a new level of complexity in the form of avoidance zones where reduction in the fixed storage emission results in adverse impact both financially and environmentally. Full compatibility of environmental and economic goals is only achieved when magnitude of reduction surpasses the critical level $\tilde{E}_f = \min(E_f^{m,2}, \hat{E}_f^2)$ suggesting that while small reductions in the emission level may have adverse performance impact as the avoidance and divergence zones are crossed, continuous improvement will ultimately result in enhanced environmental and economic performance.

Insert Figure 9 here

The economic impact of reducing the variable production and transportation emission (E_{2v}) differs in structure from the other emission parameters as by proposition 3, the profit function is either decreasing in $E_{2v} \geq 0$ or unimodal with E_{2v}^m as the maximum. When the profit function is decreasing in E_{2v}, the firm's economic and environmental goals converge everywhere as the emission function is increasing in $E_{2v} \geq 0$. In this case, the firm benefits from the reduction in the variable production and transportation emission as it simultaneously accrues economic and environmental benefits from the reduced emission levels (as shown in Figure 10(a)).

When the profit function is unimodal in E_{2v}, the firm may not economically benefit from reduction in the variable production and transportation emission. In this case, compatibility between economic and environmental goals depends on the relationship between the maximizers of the profit function and penalty and reward transitional levels. Figures 10(b) and (c) illustrate the compatibility of the goals when $\frac{E_{1v}}{h} \leq \frac{E_{2f}}{s}$.

Insert Figure 10 here

By propositions 3 and 6, when E_{2v} exceeds the penalty state transitional level, $\hat{E}_{2v}^1$, the firm operates in the penalty state and the profit function is decreasing in $E_{2v} \geq max[E_{2v}^{m,1}, \hat{E}_{2v}^1]$ and increasing in $\hat{E}^1_{2v} \leq E_{2v} \leq max[E^{m,1}_{2v}, \hat{E}^1_{2v}]$. Thus, reduced economic benefits is incurred from emission reduction in divergence zone $\hat{E}^1_{2v}] \leq E_{2v} \leq E^{m,1}_{2v}$ when $E^{m,1}_{2v}$ exceeds $\hat{E}^1_{2v}$(as shown in Figure 10(b)). The profit function is decreasing in $\hat{E}^2_{2v} \leq E_{2v} \leq \hat{E}^1_{2v}$ suggesting that emission reduction effort in this region always enhances the economic benefits of sustainability while enabling the firm to meet the assigned target emission level.

The profit function is decreasing in $min[E^{m,2}_{2v}, \hat{E}^2_{2v}] \leq E_{2v} \leq \hat{E}^2_{2v}$ and increasing in $E_{2v} \leq min[E^{m,2}_{2v}, \hat{E}^2_{2v}]$. In this domain, enhanced economic benefits from reduction in E_{2v} is achieved only when the maximizer of the profit function, $E^{m,2}_{2v}$, is less than the reward transitional level, $\hat{E}^2_{2v}$, and further reduction of the emission below the critical level $E^{critical}_{2v} = min[E^{m,2}_{2v}, \hat{E}^2_{2v}]$ adversely impacts the firm's profitability causing divergence between economic and environmental goals.

4.5 Impact of Operational Efficiency on Economic and Environmental Goals

Beside the sustainable development initiatives in the emission parameters, the firm may also choose to improve the operational efficiency.

Proposition 7 *The firm does not environmentally benefit from adopting operational strategic goals for continuous reduction in setup or storage costs. Sustainable development initiatives for continuously lowering operational cost may result in lower profitability or higher environmental impact.*

Operational efficiency initiatives for the reduction in setup or storage holding costs affects both the financial and environmental impact of the firm by altering the alignment of operational and environmental costs and hence the firm's optimal operational response. Figure 11 shows the impact from the reduction in setup cost on the firm's environmental and economical performance. By proposition 5, when the setup cost exceeds the penalty transitional setup cost level, $\check{s}^1$, the firm operates in the penalty state with optimal operational response $Q^*_1(s)$ and thus, by proposition 3, the emission function is increasing in $s \geq \check{s}^1$. Recall that if $s \geq \check{s}^1 \geq s^e = \frac{E_{2f}h}{E_{1v}}$, then $\frac{E_{1v}}{h} \geq \frac{E_{2f}}{s}$ and $Q^*_1(s) \leq Q^*_2(s)$ as illustrated in Figure 6.

Insert Figure 11 here

Reduction of setup cost over the interval bounded by the penalty and reward transitional setup costs level ($\check{s}^2 \leq s \leq \check{s}^1$) does not change the optimal operational response, Q_{02}, and hence the emission function over this interval remains constant with the firm exactly meeting the assigned target emission, T. When $s^e \leq s \leq \check{s}^2$, the firm operates in the reward state by proposition 5 and the optimal operational response is $Q_2^*(s)$. By proposition 4, the emission function is increasing in s with s^e as the minimizer.

Further reduction in s alters the existing operational and environmental cost alignment as $\frac{E_{1v}}{h} \leq \frac{E_{2f}}{s}$ when $s \leq s^e$. For $\hat{s}^2 \leq s \leq s^e$, the optimal operational response is, by proposition 5, $Q_2^*(s)$ as $Q_1^*(s) \geq Q_2^*(s) \geq Q_{01}$ and the emission function is decreasing in s since s^e is the minimizer of the function.

When $\hat{s}^1 \leq s \leq \hat{s}^2$, the firm operates in neutral state with Q_{01} as the optimal operational response level and constant emission level at T. Finally, with further reduction in the setup cost, the firm re-enters the penalty state for $s \leq \hat{s}^1$ with a decreasing emission function.

The economic impact of the reduction in setup cost depends on the relationship between the minimizers of the profit function and the transitional setup costs. Defining $s^{m,1}$ and $s^{m,2}$ as the minimizers of the profit functions under $(0, k_1, k_1)$ and $(0, k_2, k_2)$ quantity control emission pricing respectively, the firm's profit function is increasing when $s \geq min(s^{m,1}, \check{s}^1)$ and decreasing when $\check{s}^2 \leq s \leq min(s^{m,1}, \check{s}^1)$. Reduction of setup cost over the former interval results in lower profitability and divergence in economic and environmental goals; while reduction over the latter interval enhances the firm's profitability and simultaneously reduces its environmental impact, resulting in convergence of economic and environmental goals as shown in Figure 11

The profit function is increasing in $min(\check{s}^2, s^{m,2}) \leq s \leq \check{s}^2$ and the reduction of setup cost in this interval causes divergence of economic and environmental goals as the firm's profit is reduced. The firm always economically benefits from setup cost reduction over interval $s \leq min(s^{m,2}, \check{s}^2)$ as the profit function is decreasing by proposition 3. Convergence between financial and environmental goals is again achieved for $s^e \leq s \leq min(s^{m,2}, \check{s}^2)$ as the firm simultaneously enhances its profitability and lowers its environmental impact with reduction in setup cost. The enhanced financial performance over interval $s \leq s^e$ is coupled with higher environmental footprint and hence the economic and environmental goals always diverge in this interval.

In a sustainable supply chain, depending on the existing operational and environmental cost structures of the firm, the reduction of setup cost over the domain $s^e \leq s$ always reduces the firm's emission level but it may also result in lower profitability, This important observation contradicts the traditional operations management view regarding continuous reduction in setup cost as an operational strategic approach toward gaining financial competitive advantage. Additionally, the analysis also shows that the reduction of setup cost over the operational domain $s \leq s^e$ always enhances the firm's profitability but it also causes increased environmental impact. The firm can avoid the trade off between the higher profit and adverse impact on environment by coupling the operational initiatives for the reduction of setup cost with similar initiatives for simultaneous reduction in storage cost as reduction in h lowers $s^e = \frac{E_{2f}h}{E_{1v}}$ and thus reduces the divergence interval length $s \leq s^e$. The environmental and financial impact of uni-dimensional reduction in the holding cost is similar to reduction in setup cost.

5 Summary of Findings and Conclusions

There is growing awareness among businesses for the need to pursue more sustainable and socially responsible business practices. Sustainable development approaches and initiatives with dual goals of lowering environmental impact and achieving economic efficiency are becoming more common at all levels of managerial decision processes.

This paper examines the intersection of the environmental and financial goals of sustainable development initiatives of a focal firm engaging in activities of production, transportation and storage of a single product in a forward supply chain. A quantitative and economic modeling approach is utilized to derive insights to guide managers on the complex task of balancing the environmental impact reduction and profit maximization goals of the firm.

This research contributes to the existing body of knowledge in a number of ways. It extends and complements the quantitative and economic modeling of forward sustainable supply chains, and to the best of our knowledge, uniquely contributes to the modeling of sustainable supply chain under demand responsive market condition with direct relationship between consumer demand and the firm's environmental impact. The extant literature is mostly dominated by a cost minimization approach toward the economic dimension of sustainability and the effect of environmental initiatives on product price and thus indirectly its impact on consumer demand. This research explicitly considered the presence and impact of a "green market" on the managerial decisions.

At the tactical and operational levels, our results corroborate and lend additional support to the existing literature on the lack of coordination between environmental and economic goals of sustainability and the need for adjustment to organizational policies and procedures to reduce the environmental impact of the firm's operations. This research has focused on the impact of emission reduction on the operational states of the firm and demonstrates the potential presence of convergence, divergence, and avoidance zones with respect to the economic and environmental goals of sustainable development initiatives. Explicit boundaries of each operational zone over the domain of emission reduction efforts are established for different sustainable development and operational efficiency initiatives. At the strategic level, our results indicate that internally adopted or externally imposed targets for emission reduction may result in adverse environmental impact and/or economic inefficiencies due to the presence of divergence and avoidance operational zones and effective target for emission reduction is firm specific and contingent on the environmental and operational cost structures of the firm as well as the alignment between the two cost structures.

More specifically, our findings suggest that continuous improvement strategic initiatives for reducing the fixed emissions from warehousing and production and/or transportation activities should be adopted with the recognition that the firm may temporarily observe adverse economic and/or environmental impact as the avoidance and divergence operational zones are being crossed. However, continued focus and improvement in lowering the environmental impact of fixed emissions will ultimately result in simultaneous economic gain and environmental impact reduction as the convergence operational zone is reached and the economic and environmental dimensions of sustainability converge. In contrast, planned targeted emission reduction goals for variable production and transportation emission reduction is preferable to the continuous improvement approach as the results suggest presence of a critical threshold level below which the reduction in variable production and transportation emission may result in adverse economic impact. This research also shows presence of critical threshold levels for operational efficiency initiatives aimed at reduction of production setup and inventory holding costs. The findings contradict the traditional operations management view for continuous reduction of setup and holding cost as an operational strategy for enhancing the firm's competitive advantage. Within a sustainable development framework, uni-dimensional reduction of setup or holding cost below the critical threshold levels may result in increased emission foot-print as the alignment between the operational and environmental cost structure is altered.

The modeling approach used in this paper has a number of limiting assumptions that could be subject of future studies. First, the robustness of the conclusions to different operational and environmental cost structures as well linear market response to the firm's environmental impacts need to be further examined. Second, the impact of the uni-dimensionality assumption in firm's emission reduction efforts needs to be further relaxed as it is more likely that strategic sustainability initiatives are multi-dimensional. Furthermore, firm's efforts to coordinate the economic and environmental goals of sustainable development through alignment of the firm's operational and environmental cost structures also may require multi-dimensional adjustment of operational and environmental parameters. Third, the implicit fixed (implementation) cost assumption of sustainability initiatives need to be relaxed through the inclusion of a cost model related to the scope and magnitude of the reduction effort. Additionally, as proper external financial incentives may be designed to encourage and motivate emission reduction efforts, assessing the impact of such incentives on the managerial decisions would be an obvious direction of extension. Lastly, as the importance of considering emission reduction across the entire supply chain is well established in the literature, the extension of the study from a focal firm to the supply chain examining intersection of sustainability dimensions for different channel members and coordination across the supply chain needs further investigation based on the established framework of this paper.

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Notation	Definition
Q	order quantity;
Q^*	optimal operational response quantity/function;
Q_e	optimal environmental response quantity/function;
Q_{01} and Q_{02}	emission neutral quantity;
E_{ij}	environmental/emission parameter;
h, s	operational cost parameter;
$\hat{E}_{ij}$ and $\check{E}_{ij}$	penalty or reward transitional level of the parameter E_{ij};
E^e_{1v}, E^e_{2f},h^e, s^e	alignment level;
$\bar{E}_{ij}$, $\bar{s}$, $\bar{h}$	upper bound of the parameter set that may achieve target emission level T;
Π, $\Pi[Q]$, $\Pi[Q^*(\Omega)]$	profit function (or financial impact);
E, $E[Q]$, $E[Q^*(\Omega)]$	emission function (or environmental impact);

Table 1: Summary of the notation

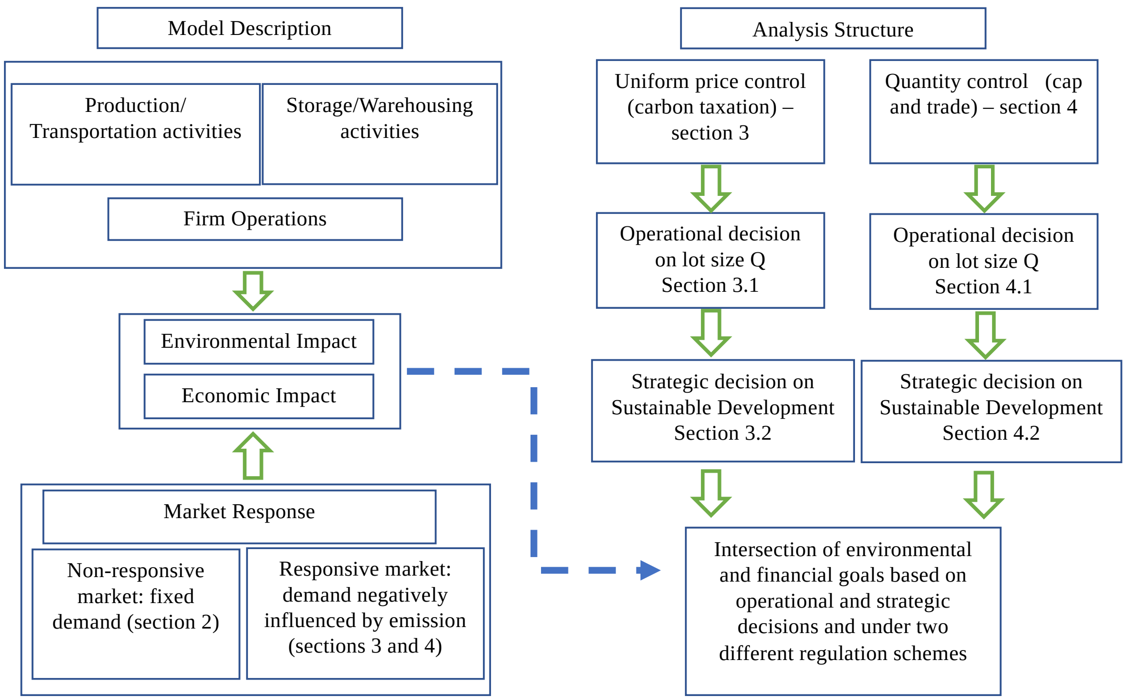


Figure 1: Model and Analysis Structure

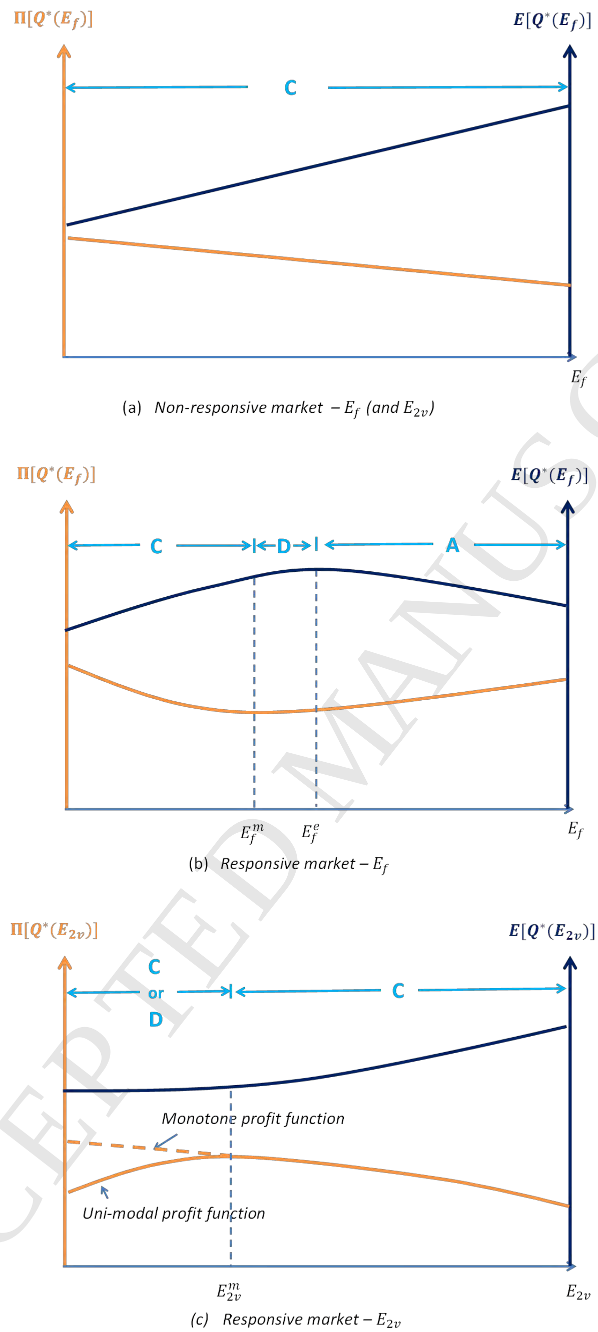
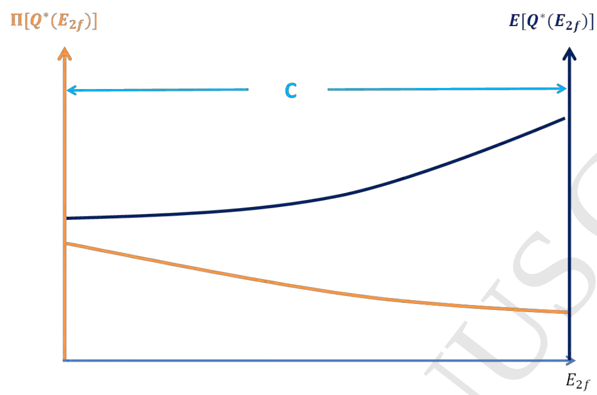
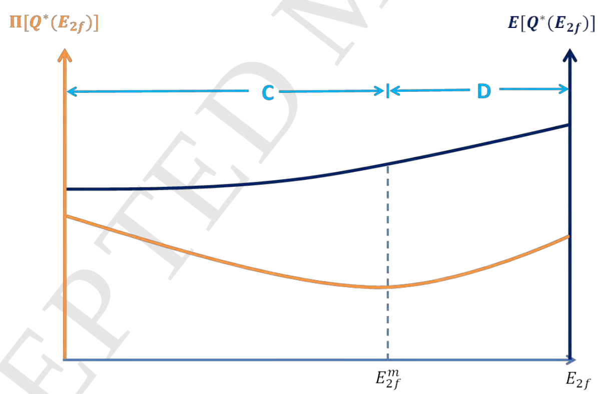


Figure 2: Environmental and Economic Impact of Reduction in E_f and E_{2v} - Price Control



(a) *Non-responsive market - E_{2f} (and E_{1v})*



(b) *Responsive market - E_{2f} (and E_{1v})*

Figure 3: Environmental and Economic Impact of Reduction in E_{2f} and E_{1v} - Price Control

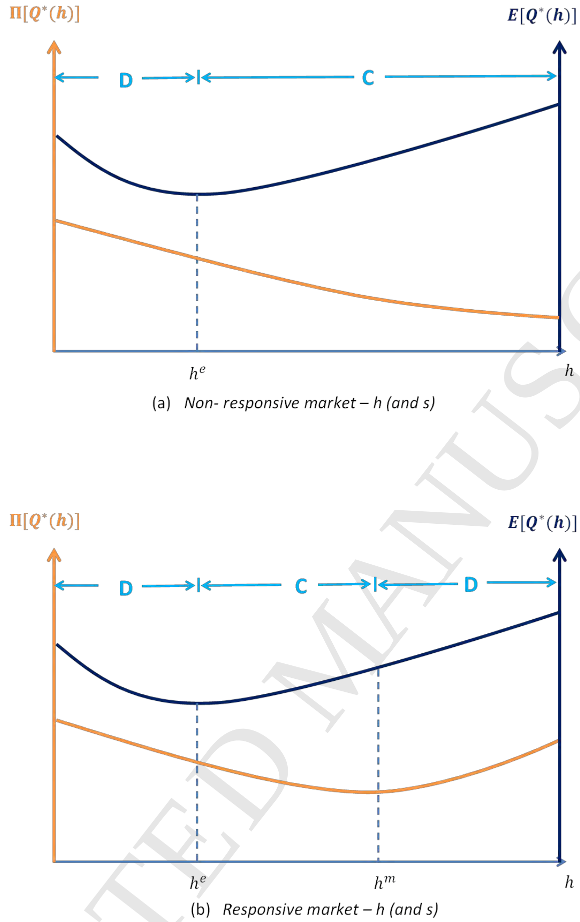


Figure 4: Environmental and Economic Impact of Reduction in Operational Parameters h and s - Price Control

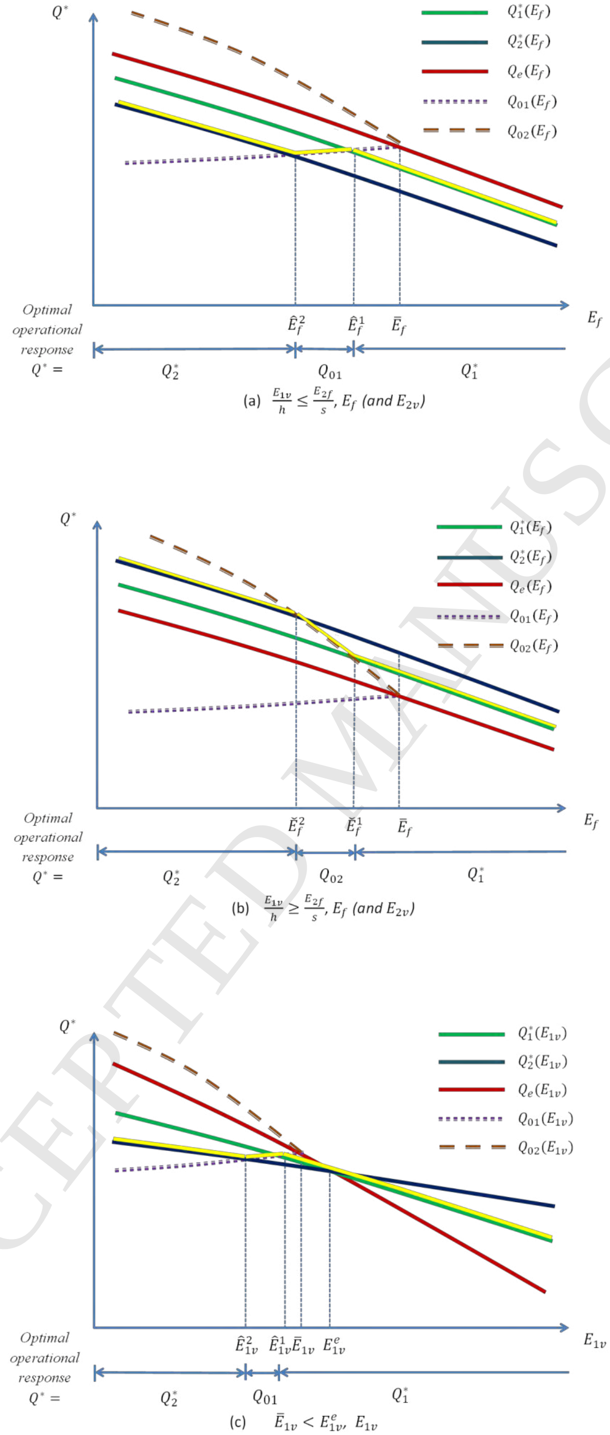


Figure 5: Shift in Operational States with Reduction in Environmental Parameters - Quantity Control

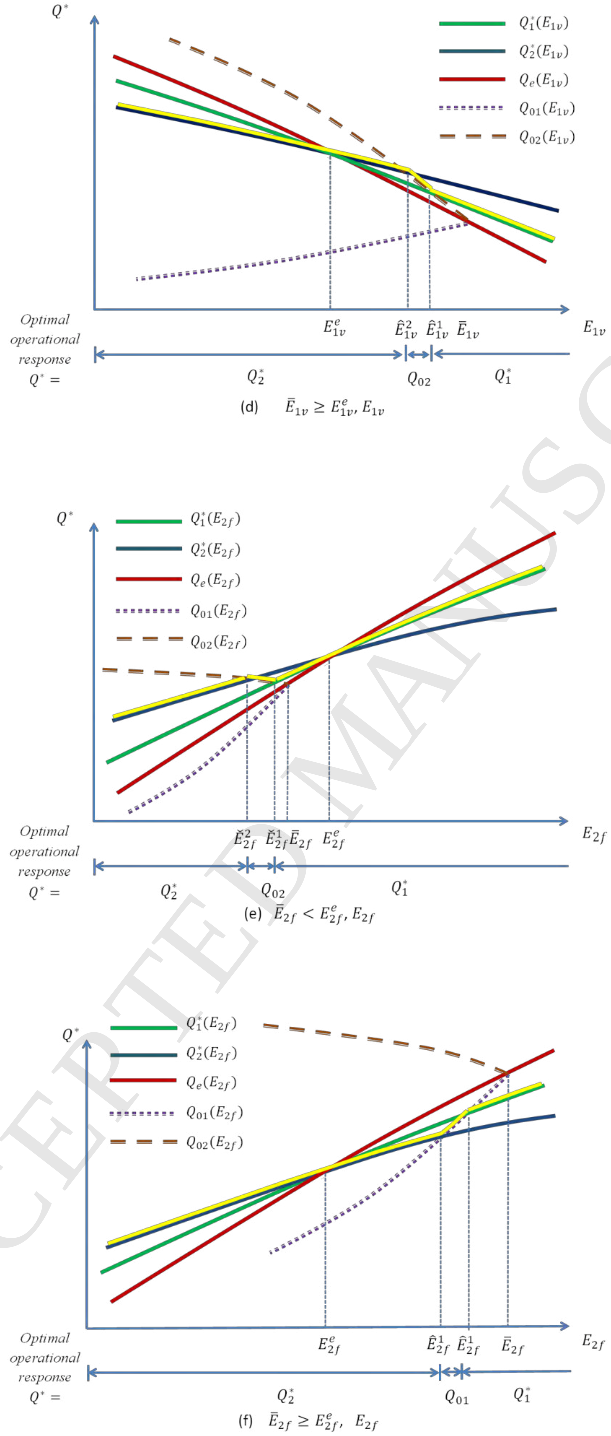


Figure 5: Continued - Shift in Operational States with Reduction in Environmental Parameters - Quantity Control

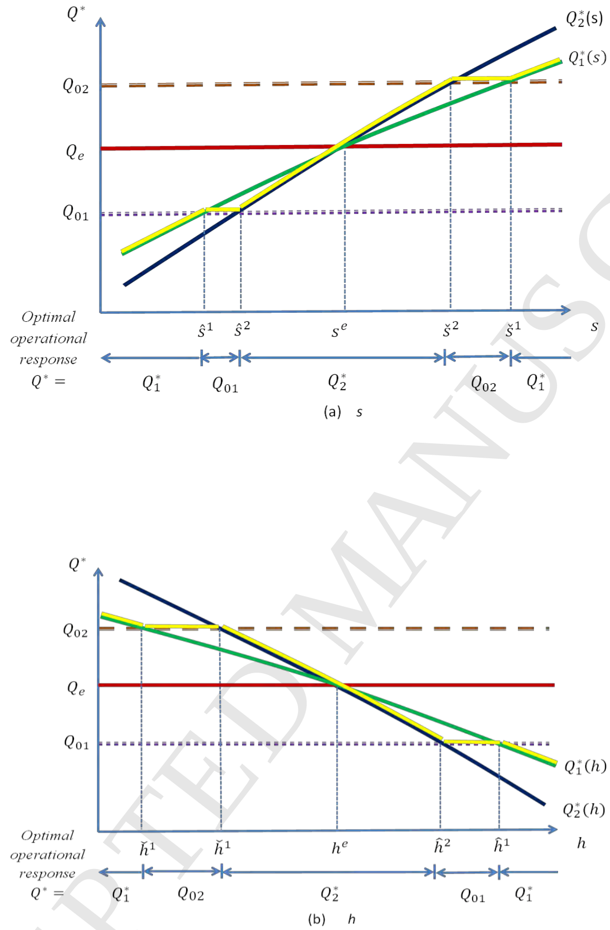


Figure 6: Shift in Operational States with Reduction in Operational Parameters - Quantity Control

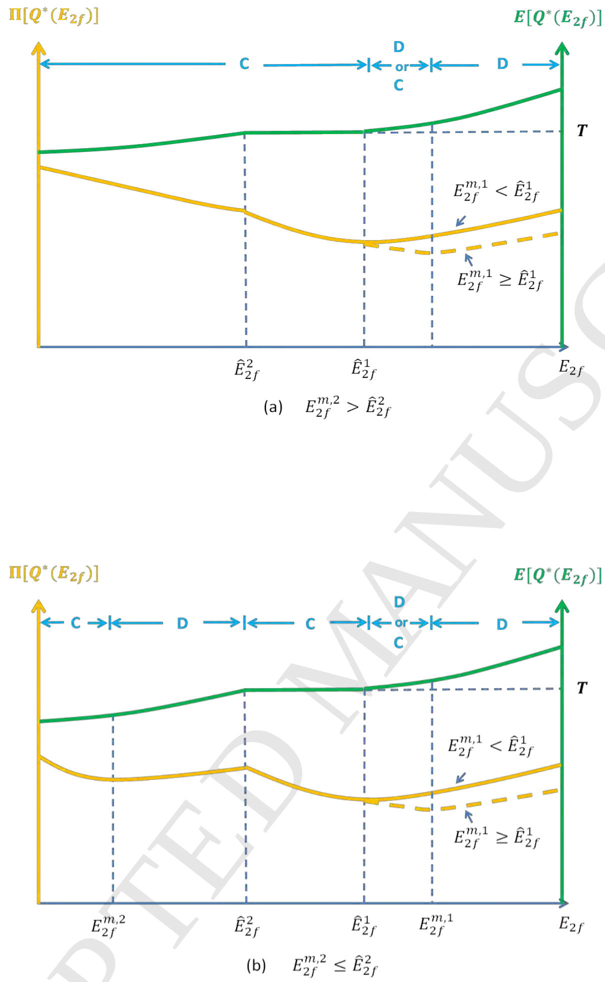


Figure 7: Environmental and Economic Impact of Reduction in E_{2f} under Responsive Market Condition and Quantity Control

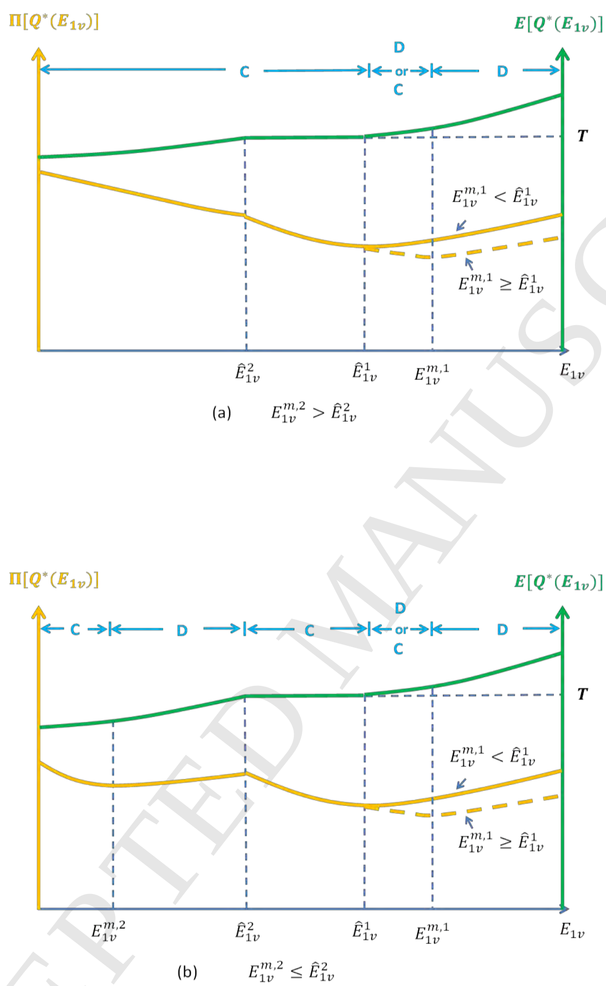
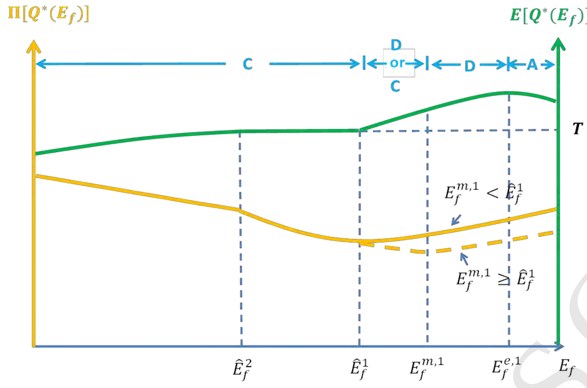
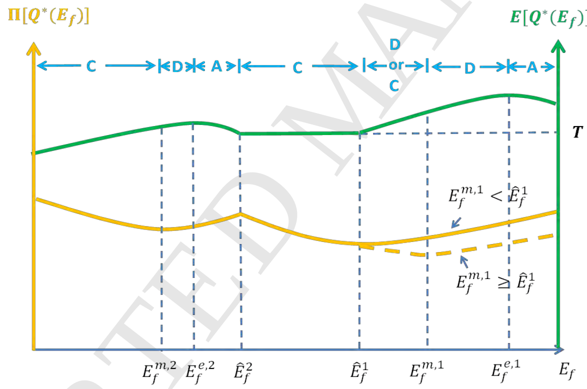


Figure 8: Environmental and Economic Impact of Reduction in E_{1v} under Responsive Market Condition and Quantity Control



(a) $E_f^{m,2} \geq \hat{E}_f^2$



(b) $E_f^{m,2} < \hat{E}_f^2$

Figure 9: Environmental and Economic Impact of Reduction in E_f under Responsive Market Condition and Quantity Control

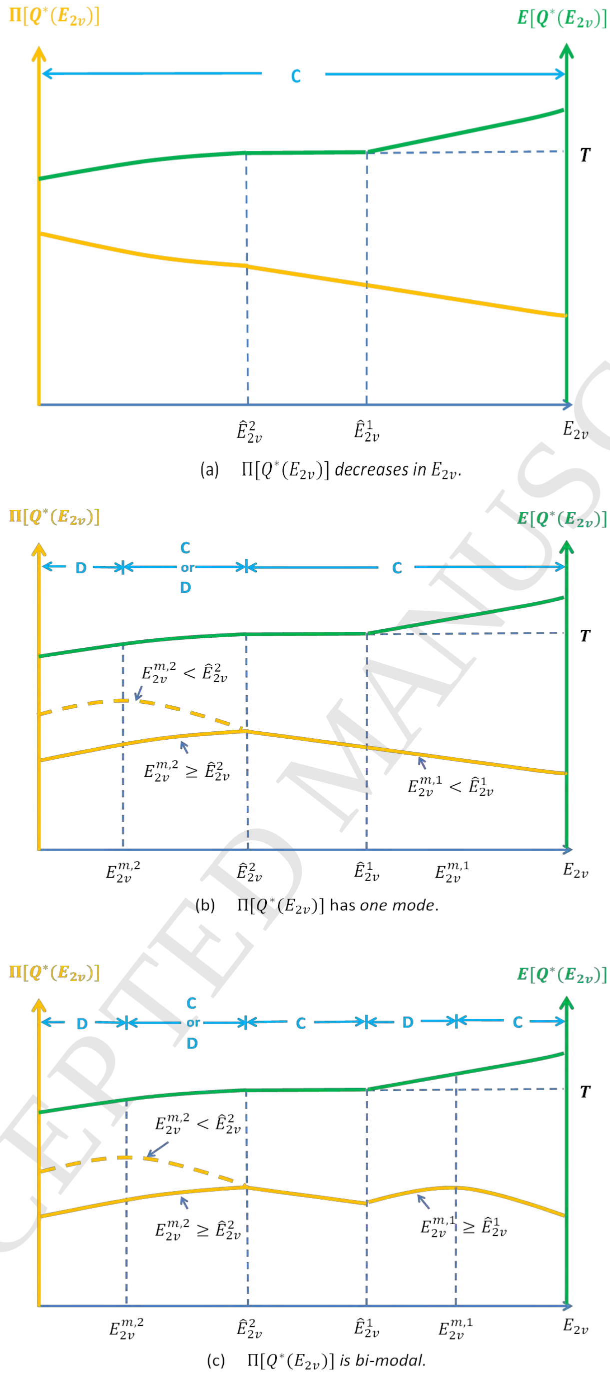


Figure 10: Environmental and Economic Impact of Reduction in E_{2v} under Responsive Market Condition and Quantity Control

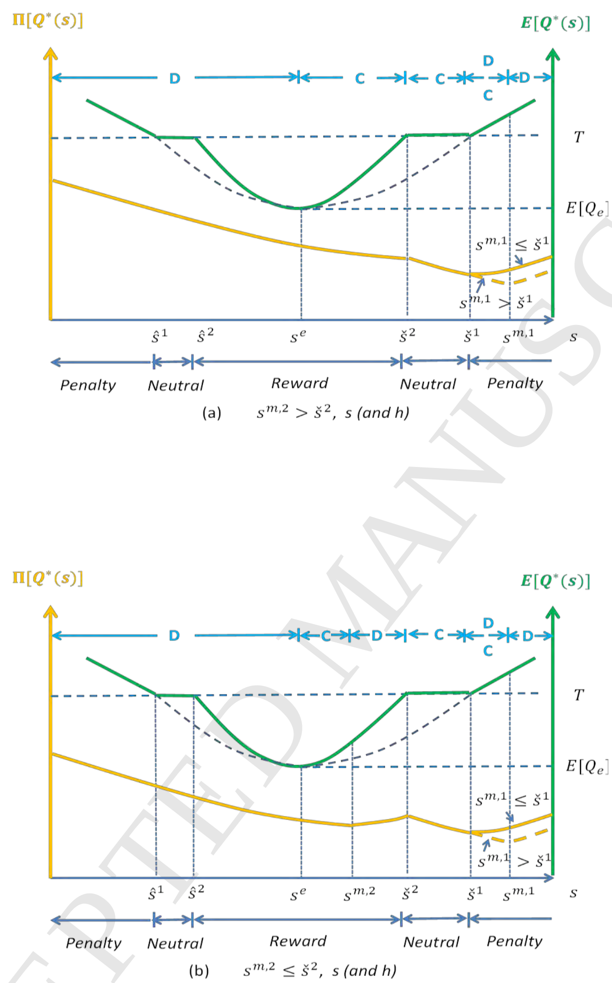


Figure 11: Environmental amd Economic Impact of Reduction in Operational Parameters under Responsive Market Condition and Quantity Control

Supplemental Materials - Proofs

Proof of Proposition 1:

Proof. 1. Substituting for Λ in the first derivative over Q results in,

$$\begin{aligned}\frac{d\Pi_{0,k,k}}{dQ} &= (p-kE_{2v})\frac{a-bE_f-bE_{1v}\frac{Q}{2}}{Q+bE_{2f}+bQE_{2v}}-\frac{h+kE_{1v}}{2}\\ &+[(p-kE_{2v})Q-(s+kE_{2f})]\frac{\Lambda}{(Q+bE_{2f}+bQE_{2v})^2}\end{aligned}$$

Taking the second order derivative and after simplification,

$$\frac{d^2\Pi_{0,k,k}}{dQ^2}=2\Lambda\frac{(pb+k)E_{2f}+(1+bE_{2v})s}{(Q+bE_{2f}+bQE_{2v})^3}$$

The sign of $\frac{d^2\Pi_{0,k,k}}{dQ^2}$ depends on Λ, which may be rewritten as,

$$\Lambda=-\frac{b^2}{2}E_{1v}E_{2f}-(a-bE_f)(1+bE_{2v})$$

Assuming that there is a positive demand regardless of the emission level, $a-bE_f>0$ and hence $\Lambda\leq 0$. Therefore, $\frac{d^2\Pi}{dQ^2}\leq 0$. Further, the first order condition may be rewritten as,

$$\begin{aligned}\frac{d\Pi_{0,k,k}}{dQ} &= \{Q^2[\frac{-bE_{1v}}{2}(1+bE_{2v})(p-kE_{2v})-\frac{(h+kE_{1v})}{2}(1+bE_{2v})^2]\\ &-Q[(h+kE_{1v})bE_{2f}(1+bE_{2v})+(p-kE_{2v})b^2E_{1v}E_{2f}]\\ &+(p-kE_{2v})(a-bE_f)bE_{2f}-\frac{1}{2}(h+kE_{1v})b^2E_{2f}^2\\ &-(s+kE_{2f})\Lambda\}\frac{1}{(Q+bE_{2f}+bQE_{2v})^2}\end{aligned}$$

Therefore, Q^* is the solution to the following quadratic equation,

$$\begin{aligned}&-\frac{1}{2}(1+bE_{2v})Q^2[bE_{1v}(p-kE_{2v})+(h+kE_{1v})(1+bE_{2v})]\\ &-bE_{2f}Q[bE_{1v}(p-kE_{2v})+(h+kE_{1v})(1+bE_{2v})]\\ &+(p-kE_{2v})(a-bE_f)bE_{2f}-\frac{1}{2}(h+kE_{1v})b^2E_{2f}^2-(s+kE_{2f})\Lambda=0\end{aligned}$$

The coefficients of first and second degree terms are both negative and hence the proof for uniqueness of Q^* will be complete if it can be shown that the constant term is positive. The last term $-(s+kE_{2f})\Lambda$ is always non-negative since $\Lambda\leq 0$, Therefore, it is sufficient to show,

$$\begin{aligned}&(p-kE_{2v})(a-bE_f)bE_{2f}-\frac{1}{2}(h+kE_{1v})b^2E_{2f}^2\\ =\ &\frac{1}{2}(p-kE_{2v})(a-bE_f)bE_{2f}+\frac{1}{2}bE_{2f}[(p-kE_{2v})(a-bE_f)-(h+kE_{1v})bE_{2f}]>0\end{aligned}$$

Without loss of generality, we assume that the profit p should at least cover the variable emission costs and the holding cost, i.e., $p \geq kE_{2v}+kE_{1v}+h$, or $p-kE_{2v} \geq h+kE_{1v}$. Also, $a-b(E_f+E_{2f}) > 0$ since it is assumed that there is a positive demand regardless of the emission level, or $a-bE_f > bE_{2f}$. Hence, the constant term of the quadratic equation is positive and the quadratic function has unique non-negative solution,

$$Q^* = -\frac{bE_{2f}}{1+bE_{2v}} + \frac{1}{1+bE_{2v}}\sqrt{(-2\Lambda)\frac{A}{B}}$$

This completes the proof of part 1 of the proposition.

2. Recall that the firm's profit function and total emission are given by:

$$\Pi_{0,k,k,} = pD - h\frac{Q}{2} - s\frac{D}{Q} - kE$$

$$E(Q) = E_f + E_{1v}\frac{Q}{2} + E_{2f}\frac{D}{Q} + E_{2v}D$$

substituting $D = a - bE$ in the emission function and rearranging the terms results in,

$$E = \frac{E_{1v}\frac{Q^2}{2} + (E_f + aE_{2v})Q + aE_{2f}}{(1+bE_{2v})Q + bE_{2f}}$$

The convexity of the emission function in Q follows by showing $\frac{d^2E}{dQ^2} \geq 0$. The minimizer of E is the solution to the first order condition given by,

$$\frac{dE}{dQ} = \frac{\frac{E_{1v}}{2}(1+bE_{2v})Q^2 + bE_{1v}E_{2f}Q - E_{2f}(a-bE_f)}{[(1+bE_{2v})Q + bE_{2f}]^2} = 0$$

The quadratic function in the above numerator has a unique positive solution Q_e which is given by,

$$Q_e = \frac{-bE_{2f}}{(1+bE_{2v})} + \frac{\sqrt{-2\Lambda E_{1v}E_{2f}}}{E_{1v}(1+bE_{2v})}.$$

3. For $Q \geq 0$, this quadratic function is monotonically increasing and Q_e is the only positive solution. Therefore, $\frac{dE}{dQ} < 0$ for $0 \leq Q \leq Q_e$ and $\frac{dE}{dQ} > 0$ when $Q > Q_e$. The condition, $\frac{h}{E_{1v}} = \frac{s}{E_{2f}}$, for Q^* to minimize the total pollutant emissions will be obtained by setting $Q^* = Q_e$. Also, $Q^* \geq Q_e$ if $\frac{E_{1v}}{h} \geq \frac{E_{2f}}{s}$; and vice versa, $Q^* \leq Q_e$ if $\frac{E_{1v}}{h} \leq \frac{E_{2f}}{s}$. ■

Proof of Corollary 1:

Proof. From the explicit form of Q^* in Proposition 1, we have,

$$\frac{dQ^*}{da} = (-2\Lambda)^{-\frac{1}{2}}[\frac{(s+kE_{2f})(1+bE_{2v}) + (p-kE_{2v})bE_{2f}}{(h+kE_{1v})(1+bE_{2v}) + (p-kE_{2v})bE_{1v}}]^{\frac{1}{2}} > 0$$

$$\frac{dQ^*}{dp} = \frac{1}{2}\frac{b(1+bE_{2v})[(h+kE_{1v})E_{2f}-(s+kE_{2f})E_{1v}](-2\Lambda)}{[bE_{2f}(p-kE_{2v})+(s+kE_{2f})(1+bE_{2v})]^{\frac{1}{2}}[bE_{1v}(p-kE_{2v})+(h+kE_{1v})(1+bE_{2v})]^{\frac{3}{2}}}$$

The sign of the above function depends on the sign of $(h+kE_{1v})E_{2f}-(s+kE_{2f})E_{1v}$ and $\frac{dQ^*}{dp} \geq 0$ if $(h+kE_{1v})E_{2f}-(s+kE_{2f})E_{1v} \geq 0$, or after simplification, $\frac{h}{E_{1v}} \geq \frac{s}{E_{2f}}$. Also,

$$\begin{aligned}\frac{dQ^*}{dk} &= \frac{1}{(1+bE2v)}[-2\Lambda\frac{(s+kE_{2f})(1+bE_{2v})+(p-kE_{2v})bE_{2f}}{(h+kE_{1v})(1+bE_{2v})+(p-kE_{2v})bE_{1v}}]^{-\frac{1}{2}} \\ &\quad \frac{-2\Lambda[E_{2f}(h+kE_{1v})-E_{1v}(s+kE_{2f})][(1+bE_{2v})^2-bE_{2v}]}{[(h+kE_{1v})(1+bE_{2v})+(p-kE_{2v})bE_{1v}]^2}\end{aligned}$$

Again, the sign of the above function depends on the sign of $E_{2f}(h+kE_{1v})-E_{1v}(s+kE_{2f})$. Hence, $\frac{dQ^*}{dk} \geq 0$ when $\frac{E_{1v}}{h} \leq \frac{E_{2f}}{s}$. ■

Proof of Corollary 2:

Proof. From the optimal response function Q^*, it can be shown that $\frac{dQ^*}{ds} \geq 0$, $\forall s \geq 0$, $\frac{dQ^*}{dh} \geq 0$, $\forall h \leq 0$, and $\frac{dQ^*}{dE_f} \geq 0$, $\forall E_f \geq 0$. Further, $\frac{dQ^*}{dE_{1v}} = \frac{1}{\sqrt{-2\Lambda AB}}\frac{A}{B}[b^2E_{2f}\frac{h}{2}-(a-bE_f)(pb+k)]$, and $\frac{dQ^*}{dE_{1v}} \leq 0$ since $h \leq p$ and $bE_{2f} \leq a-bE_f$. For E_{2v}, $\frac{dQ^*(E_{2v})}{dE_{2v}} = \frac{b^2E_{2f}}{1+bE_{2v}} - \frac{b}{B(1+bE_{2v})^2\sqrt{-2\Lambda AB}}[-2\Lambda AB-(1+bE_{2v})C]$, where $C = (a-bE_f)sh(1+bE_{2v})^2+2(a-bE_f)(1+bE_{2v})(pb+k)sE_{1v}+(a-bE_f)(pb+k)^2E_{1v}E_{2f}+\frac{b^2E_{1v}E_{2f}}{2}(pb+k)(sE_{1v}-hE_{2f})$. Let us define $f(E_{2v}) = [-2\Lambda AB-(1+bE_{2v})C]^2 - b^2B^2E_{2f}^2(-2\Lambda AB)$, then $\frac{dQ^*(E_{2v})}{dE_{2v}} \leq 0$ if $f(E_{2v}) \geq 0$. After plugging A, B, and C into $f(E_{2v})$ and with further simplification, we have,

$$\begin{aligned}f(2v) &= h^2s^2(a-bE_f)E_{2v}^4 + \left\{2b^2E_{1v}s+2h[2(a-bE_f)(pb+k)-b^2E_{2f}h]\right\}E_{2v}^3 \\ &\quad +\{b^4E_{2f}E1v^2hs^2+b^2E_{1v}^2s^2(a-bE_f)(pb+k)+2E_{1v}s(a-b_f)^2(pb+k)^2 \\ &\quad +b^2E_{2f}E_{1v}hs[(a-bE_f)(pb+k)-b^2E_{2f}h] \\ &\quad +2E_{2f}h(a-bE_f)(pb+k)[2(a-bE_f(pb+k)-b^2E_{2f}h]\}E_{1v}^2 \\ &\quad +\{b^4E_{1v}^2s^2+[4(a-bE_f)^2(pb+k)^2-b^4E_{2f}h^2]\}E_{1v} \\ &\quad +\{\frac{1}{2}b^4E_{2f}E_{1v}hs+[\frac{1}{2}b^2E_{1v}s-(a-bE_f)(pb+k)]^2 \\ &\quad +b^2E_{2f}h[(a-bE_f)(pb+k)-\frac{3}{4}b^2E_{2f}h]\}\end{aligned}$$

$f(E_{2v}) \geq 0$ since the coefficients for all degree terms are positive.

Finally,

$$\begin{aligned}\frac{dQ^*}{dE_{2f}} &= \frac{1}{1+bE_{2v}}[-b+\frac{1}{\sqrt{-2\Lambda AB}}[\frac{b^2}{2}E_{1v}s(1+bE_{2v}) \\ &\quad +b^2E_{1v}E_{2f}(pb+k)+(a-bE_f)(1+bE_{2v})(pb+k)]]\end{aligned}$$

The first order solution corresponds to the roots of, $b^4hE_{1v}(pb+k)E_{2f}^2+2b^2h(1+bE_{2v})[(a-bE_f)(pb+k)+\frac{b^2E_{1v}s}{2}]E_{2f}+(1+bE_{2v})\{2b^2s(a-bE_f)[h(a-bE_f)+E_{1v}(pb+k)]-[(a-bE_f)(pb+k)+\frac{b^2E_{1v}s}{2}]^2\} = 0$, which can only have a maximum of one non-negative root since the coefficients of the first and second degree terms are positive. Taking second order derivative,

$$\frac{d^2Q^*(E_{2f})}{dE_{2f}^2} = \frac{1}{(1+bE_{2v})\sqrt{(-2\Lambda)AB}}\{b^2E_{1v}(pb+k) - \frac{1}{-2\Lambda A}[\frac{b^2E_{1v}A}{2} - \Lambda(pb+k)]^2\}$$

$\frac{d^2Q^*(E_{2f})}{dE_{2f}^2} \leq 0$ iff $b^2E_{1v}(pb+k)(-2\Lambda)A \leq [\frac{b^2E_{1v}A}{2} - \Lambda(pb+k)]^2$ which can be simplified to $[\frac{b^2E_{1v}s}{2} - (a-bE_f)(pb+k)]^2 \geq 0$ and hence $Q^*(E_{2f})$ is concave in E_{2f}.

Proof of Proposition 2:

Proof. The firm's total pollutant emission under the optimal environmental response Q_e in proposition 1 is,

$$E[Q_e(\Omega)] = \frac{1}{(1+bE_{2v})^2}[\sqrt{-2\Lambda E_{1v}E_{2f}} + (E_f + aE_{2v})(1+bE_{2v}) - bE_{1v}E_{2f}]$$

Considering E_f,

$$\frac{dE[Q_e(\Omega)]}{dE_1f} = \frac{1}{(1+bE_{2v})}[1 - \frac{bE_{1v}E_{2f}}{\sqrt{-2\Lambda E_{1v}E_{2f}}}]$$

$$\frac{dE[Q_e(\Omega)]}{dE_1f} \geq 0 \quad if \quad 1 - \frac{bE_{1v}E_{2f}}{\sqrt{-2\Lambda E_{1v}E_{2f}}} \geq 0$$

plugging for Λ and squaring both sides reduces to $2(a-bE_f)(1+bE_{2v})E_{1v}E_{2f} \geq 0$ which holds over the domain $E_f \in a, \frac{b}{a}$

For E_{1v},

$$\frac{\partial E[Q_e(\Omega)]}{\partial E_{1v}} = \frac{1}{(1+bE_{2v})^2}\{-bE_{2f} + \sqrt{\frac{E_{2f}}{E_{1v}(-2\Lambda)}}[b^2E_{1v}E_{2f} + (a-bE_f)(1+bE_{2v})]\}$$

Therefore, to show $\frac{\partial E}{\partial E_{1v}} \geq 0$, the terms inside the braces need to be non-negative, i.e., $[b^2E_{1v}E_{2f} + (a-bE_f)(1+bE_{2v})] \geq b\sqrt{(-2\Lambda)E_{1v}E_{2f}}$. This inequality may be simplified to be $(a-bE_f)^2(1+bE_{2v})^2 \geq 0$. The proof of $\frac{\partial E[Q_e(\Omega)]}{\partial E_{2f}}$ is similar to that of E_{1v}.

For E_{2v},

$$\frac{\partial E[Q_e(\Omega)]}{\partial E_[2v]} = \frac{1}{(1+bE_{2v})^3}[b(1+bE_{2v})\sqrt{\frac{E_{1v}E_{2f}}{-2\Lambda}} - 2b\sqrt{(-2\Lambda)E_{1v}E_{2f}} + (a-bE_f)(1+bE_{2v}+2b^2E_{1v}E_{2f}]$$

To show $\frac{\partial E}{\partial E_{2v}} \geq 0$, it is sufficient to show that,

$$-2b\sqrt{(-2\Lambda)E_{1v}E_{2f}} + (a-bE_f)(1+bE_{2v}) + 2b^2E_{1v}E_{2f} \geq 0$$

Or, $2(-2\Lambda) - 3(a - bE_f)(1 + bE_{2v}) \geq 2b\sqrt{(-2\Lambda)E_{1v}E_{2f}}$. After simplification, this inequality is satisfied if $a - bE_f \geq \frac{4b^2 E_{1v}E_{2f}}{1+bE_{2v}}$. For a significant market potential, i.e. $a - bE_f$ is large; the above inequality can be shown for E_{2v}. ■

Proof of Proposition 3:

Proof. Under the optimal operational response in Proposition 1, the optimal profit function can be rewritten as the function of parameter set Ω,

$$\begin{aligned}\Pi_{0,k,k}[Q^*(\Omega)] &= \frac{1}{1+bE_{2v}}[(p-kE_{2v})(a-bE_f) + \frac{b}{2}E_{1v}(s+kE_{2f}) + \frac{b}{2}E_{2f}(h+kE_{1v})] \\ &\quad + \frac{b^2E_{1v}E_{2f}}{(1+bE_{2v})^2}(p-kE_{2v}) - kE_f - \frac{\sqrt{-2\Lambda AB}}{(1+bE_{2v})^2}\end{aligned}$$

The corresponding total pollutant emission is,

$$\begin{aligned}E[Q^*(\Omega)] &= \frac{1}{2(1+bE_{2v})^2}\sqrt{-2\Lambda}[E_{1v}\sqrt{\frac{A}{B}} + E_{2f}\sqrt{\frac{B}{A}}] \\ &\quad + \frac{1}{(1+bE_{2v})^2}[(aE_{2v}+E_f)(1+bE_{2v}) - bE_{1v}E_{2f}]\end{aligned}$$

1. First, for E_f,

$$\frac{d\Pi_{0,k,k}[Q^*(E_f)]}{dE_f} = -k - \frac{b(p-kE_{2v})}{1+bE_{2v}} + \frac{b\sqrt{AB}}{1+bE_{2v}}\frac{1}{\sqrt{-2\Lambda}}$$

The first order solution is,

$$E_f^m = \frac{a}{b} - \frac{b}{2(k+bp)^2(1+bE_{2v})}AB + \frac{bE_{1v}E_{2f}}{2(1+bE_{2v})}$$

And,

$$\frac{d^2\Pi_{0,k,k}[Q^*(E_f)]}{dE_f^2} = \frac{b^2\sqrt{AB}}{(-2\Lambda)^{\frac{3}{2}}} \geq 0$$

Further,

$$\frac{dE[Q^*(E_f)]}{dE_f} = \frac{-b}{2(1+bE_{2v})\sqrt{-2\Lambda_1}}[E_{1v}\sqrt{\frac{A}{B}} + E_{2f}\sqrt{\frac{B}{A}}] + \frac{1}{1+bE_{2v}}$$

The first order solution is,

$$E_f^e = \frac{a}{b} - \frac{b[E_{2f}^2\frac{B}{A} + E_{1v}^2\frac{A}{B} - 2E_{1v}E_{2f}]}{8(1+bE_{2v})}$$

And,

$$\frac{d^2E[Q^*(E_f)]}{dE_f^2} = -\frac{b^2}{2}[E_{1v}\sqrt{\frac{A}{B}} + E_{2f}\sqrt{\frac{B}{A}}]\frac{1}{(-2\Lambda)^{\frac{3}{2}}} \leq 0$$

Comparing E_f^m and E_f^e, it can be shown $E_f^e \geq E_f^m$ if;

$$E_{2f}^2 \frac{B}{A} + E_{1v}^2 \frac{A}{B} + 2E_{1v}E_{2f} \leq 4\frac{AB}{(k+bp)^2}$$

After further simplifications,

$$\frac{E_{1v}(k+bp)}{B} + \frac{E_{2f}(k+bp)}{A} \leq 2$$

which is true based on the definition of A and B. Hence, $E_f^{m,e} \geq E_f^m$.

2. Next,consider E_{1v}.

$$\frac{d\Pi_{0,k,k}(Q^*(E_{1v}))}{dE_{1v}} = \frac{b}{2(1+bE_{2v})}(s+2kE_{2f}) + \frac{b^2E_{2f}(p-kE_{2v})}{(1+bE_{2v})^2} - \frac{1}{2(1+bE_{2v})^2}\frac{A[b^2E_{2f}B - 2\Lambda(pb+k)]}{\sqrt{(-2\Lambda AB)}}$$

The first order solution is given by:

$$E_{1v}^m = \frac{2(a-bE_f)(pb+k)^2 - b^2Ah}{b^2(pb+k)s}$$

$E_{1v}^m \geq 0$ for all k if $2(a-bE_f)p^2 \geq Ah$. $(a-bE_f)p \geq A$ since the maximum firm's revenue must exceed the revised setup/ordering cost and $p > h$ by definition. Thus, $E_{1v}^m \geq 0$.

$$\frac{d^2\Pi_{0,k,k}[Q^*(E_{1v})]}{dE_{1v}^2} = \frac{\sqrt{A}}{4(-2\Lambda)^{\frac{3}{2}}B^{\frac{3}{2}}(1+bE_{2v})^2}[b^2E_{2f}B - (-2\Lambda)(pb+k)]^2 \geq 0$$

Therefore, $\Pi_{0,k,k}[Q^*(E_{1v})]$ is convex in E_{1v} with the minimum profit achieved at E_{1v}^m. Furthermore,

$$\begin{aligned}\frac{dE[Q^*(E_{1v})]}{dE_{1v}} =& \frac{\sqrt{\frac{B}{-2\Lambda A}}}{2(1+bE_{2v})^2}\{(bE_{2f} - \sqrt{\frac{-2\Lambda A}{B}})^2 \\ &+ \frac{(1+bE_{2v})^2}{B^2}(E_{1v}s - E_{2f}h)[-\frac{b^2E_{2f}h}{2} + (a-bE_f)(Pb+k)]\}\end{aligned}$$

$\frac{dE(Q^*(E_{1v}))}{dE_{1v}} \geq 0$ if,

$$(bE_{2f} - \sqrt{\frac{-2\Lambda A}{B}})^2 \geq \frac{(1+bE_{2v})^2}{B^2}(E_{1v}s - E_{2f}h)\theta$$

where,

$$\theta = -\frac{b^2E_{2f}h}{2} + (a-bE_f)(Pb+k) \geq 0,$$

which simplifies to,

$$E_{1v}^4\{b^4[E_{2f}^2(pb+k)^2 - AE_{2f}(pb+k)]^2\} + E_{1v}^3\{4b^4E_{2f}^2hs^2(pb+k)(1+bE_{2v})^3\}$$

$$E_{1v}^2\{4h^2b^4E_{2f}^2s^2(1+bE_{2v})^2 + \theta s^2(1+bE_{2v})^4 + 4E_{2f}^2\theta^2(1+bE_{2v})^2(pb+k)^2 +$$

$$4b^2E_{2f}h\theta s^2(1+bE_{2v})^4 + 8b^4E_{2f}^4h^2(1+bE_{2v})^2(pb+k)^2 + 2b^2E_{2f}^2h\theta s(1+bE_{2v})^3(pb+k) +$$

$$4b^2E_{2f}^3h\theta(1+bE_{2v})^2(pb+k)^2 + 4E_{2f}\theta^2 s(1+bE_{2v})^3(pb+k) + 4b^2E_{2f}h\theta s^2(1+bE_{2v})^4 +$$

$$4b^2E_{2f}^2h\theta(1+bE_{2v})^3(pb+k) + 2b^4E_{2f}^2h^2s^2(1+bE_{2v})^4 + 2b^4E_{2f}^3h^2s(1+bE_{2v})^3(pb+k)\} +$$

$$E_{1v}\{2b^2E_{2f}h^2s^2(1+bE_{2v})^5(a-bE_f) + \theta s^2h(1+bE_{2v})^5(a-bE_f) + b^2E_{2f}^2h^2\theta s(1+bE_{2v})^4 +$$

$$E_{2f}h\theta^2 s(1+bE_{2v})^4 + 2E_{2f}hs\theta(1+bE_{2v})^4(a-bE_f)(pb+k) + 2E_{2f}^2h\theta^2(1+bE_{2v})^3(pb+k)\} +$$

$$\{4h^2s^2(a-bE_f)^2(1+bE_{2v})^6 + 9E_{2f}^2h^2\theta^2(1+bE_{2v})^4 + 12E_{2f}h^2\theta s(a-bE_f)(1+bE_{2v})^5 +$$

$$4b^2E_{2f}^3h^3\theta(1+bE_{2v})^4\} \geq 0$$

The coefficient of all terms in the fourth degree polynomial is nonnegative and hence $\frac{dE[Q^*(E_{1v})]}{dE_{1v}} \geq 0 \;\; \forall \;\; E_{1v} \geq 0$.

3. For the variable transportation emission, E_{2v},

$$\begin{aligned}\frac{d\Pi_{0,k,k}[Q^*(E_{2v})]}{dE_{2v}} = &-\frac{1}{(1+bE_{2v})^3}\{(a-bE_f)(pb+k)(1+bE_{2v}) + \frac{b^2}{2}(1+bE_{2v})(E_{1v}s+E_{2f}h)\\ &+2b^2E_{1v}E_{2f}(pb+k) + \frac{b}{\sqrt{-2\Lambda AB}}[-3(a-bE_f)(1+bE_{2v})AB\\ &-2b^2E_{1v}E_{2f}AB - \Lambda(1+bE_{2v})(Bs+Ah)]\}\end{aligned}$$

The first order solutions correspond to the roots of the third degree polynomial,

$$\begin{aligned}H(E_{2v}) = &-b^4h^2s^2(a-bE_f)^2(1+bE_{2v})^3 + 2hs\theta_3(a-bE_f)(1+bE_{2v})^2\\ &+[\theta_2\theta_3 + 2b^2\theta_1E_{1v}E_{2f}hs(a-bE_f)(pb+k)](1+bE_{2v})\\ &+[2\theta_1\theta_3E_{1v}E_{2f}(pb+k) + 4b^4E_{2f}^2E_{1v}^2hs(a-bE_f)(pb+k)^2]\end{aligned}$$

where:

$$\theta_1 = (a-bE_f)(pb+k) + \frac{b^2}{2}(E_{1v}s+E_{2f}h)$$

$$\theta_2 = 2(a-bE_f)(pb+k)(E_{1v}s+E_{2f}h) + b^2E_{1v}E_{2f}hs$$

$$\theta_3 = \theta_1^2 - b^2\theta_2$$

Two separate cases will be considered. First, if $\theta_3 \geq 0$, then the coefficient of the first, second, and the constant terms of the third degree polynomial are positive and therefore there exists a unique $E^m_{2v} > -\frac{1}{b}$ such that $H(E_{2v}) > 0$ for $E_{2v} < E^m_{2v}$, and $H(E_{2v}) < 0$ for $E_{2v} \geq E^m_{2v}$. $E^m_{2v} \in (-\frac{1}{b}, 0]$ if $H(E_{2v} = 0) \leq 0$ and $E^m_{2v} > 0$ if $H(E_{2v}) \leq 0$. Second, if $\theta_3 < 0$ then the coefficients of both the second and third degree terms of the polynomial are negative and two subcases must now be considered. (1) When the coefficient of the first degree term is negative then if the coefficient of the constant term is also non-positive,$H(E_{2v}) < 0$ for $E_{2v} \geq 0$ since coefficients of all terms of the polynomial are non-positive. Alternatively, if the coefficient of the constant term is positive, then there exists $E^m_{2v} \geq -\frac{1}{b}$ such that $H(E_{2v}) > 0$ for $E_{2v} < E^m_{2v}$ and $H(E_{2v}) < 0$ for $E_{2v} \geq E^m_{2v}$. Similar to case 1, $E^m_{2v} \in (-\frac{1}{b}, 0]$ if $H(E_{2v} = 0) \leq 0$ and $E^m_{2v} > 0$ if $H(E_{2v}) \leq 0$. (2) when the coefficient of the first degree term is positive, then,

$$2b^2 E_{1v} E_f hs(a - bE_f)(pb + k) \geq \frac{\theta_2\theta_3}{\theta_1}$$

Now considering the coefficient of the constant term,

$$2E_{1v}E_{2f}(pb+k)[\theta_1\theta_3 + 2b^4 E_{2f} E_{1v} hs(a-bE_f)(pb+k)] \geq 2E_{1v}E_{2f}(pb+k)[\theta_1\theta_3 - b^2\frac{\theta_2\theta_3}{\theta_1}] \geq 2E_{1v}E_{2f}\frac{\theta_3^2}{\theta_1} > 0$$

hence if the coefficient of the first degree term is positive, then the coefficient of the constant term will also be positive and thus again there exists $E^m_{2v} > -\frac{1}{b}$ such that $H(E_{2v}) > 0$ for $E_{2v} < E^m_{2v}$ and $H(E_{2v}) < 0$ for $E_{2v} \geq E^m_{2v}$.

Depending on the exogenous operational and environmental parameters, the firm's profit function either monotonically decreases in $E_{2v} > 0$ or it increases in $E_{2v} \leq E^m_{2v}$ and decreases in $E_{2v} > E^m_{2v}$.

$$\begin{aligned}\frac{dE[Q^*(E_{2v})]}{dE_{2v}} &= \frac{b\sqrt{\frac{-2\Lambda B}{A}}}{(1+bE_{2v})^2}\{\frac{E_{2f} + E_{1v}\frac{A}{B}}{1+bE_{2v}} \\ &+ \frac{1}{2(-2\Lambda)}[(a-bE_f)(E_{2f} + E_{1v}\frac{A}{B}) - \frac{\Lambda(Pb+k)(hE_{2f} - sE_{1v})^2(1+bE_{2v})}{AB^2}]\} \\ &\frac{2b^2E_{2f}E_{1v}}{(1+bE_{2v})^3} + \frac{(a-bE_f)}{(1+bE_{2v})^2}\end{aligned}$$

and $\frac{dE[Q^*(E_{2v})]}{dE_{2v}} > 0$ for $E_{2v} > 0$.

4. Finally consider the fixed transportation emission, E_{2f}.

$$\frac{d\Pi_{0,k,k}[Q^*(E_{2f})]}{dE_{2f}} = \frac{b(h+2kE_{1v})}{2(1+bE_{2v})} + \frac{1}{(1+bE_{2v})^2}\{b^2E_{1v}(p-kE_{2v}) - \frac{\sqrt{B}}{2\sqrt{-2\Lambda A}}[b^2E_{1v}A - 2\Lambda(pb+k)]\}$$

The first order solution is $E^m_{2f} = \frac{2(k+bp)^2(a-bE_f)-b^2Bs}{b^2h(k+bp)}$.

$$\frac{d^2\Pi_{0,k,k}[Q^*(E_{2f})]}{dE_{2f}^2} = \frac{\sqrt{B}}{4\sqrt{-2\Lambda A}(1+bE_{2v})^2}\frac{[b^2E_{1v}A-(-2\Lambda)(pb+k)]^2}{-2\Lambda A} \geq 0$$

Further,

$$\frac{dE[Q^*(E_{2f})]}{dE_{2f}} = \frac{\sqrt{\frac{B}{-2\Lambda A}}}{2(1+bE_{2v})^2}[\theta_1 E_{2f} + \frac{\Lambda(pb+k)}{A}E_{2f} + \theta_2] - \frac{bE_{1v}}{(1+bE_{2v})^2}$$

where:

$$\theta_1 = \frac{3b^2E_{1v}}{2} + \frac{b^2E_{1v}^2(pb+k)}{B} \geq 0$$
$$\theta_2 = (1+bE_{2v})[\frac{b^2sE_{1v}^2}{2B} + 2(a-bE_f) + \frac{(a-bE_f)(pb+k)E_{1v}}{B}] \geq 0$$

$\frac{dE[Q^*(E_{2f})]}{dE_{2f}} \geq 0$ if,

$$B[\theta_1 E_{2f} + \frac{\Lambda(pb+k)}{A}E_{2f} + \theta_2] - 4b^2E_{1v}^2A[2(a-bE_f)(1+bE_{2v}) + b^2E_{1v}E_{2f}] \geq 0$$

After further algebraic simplifications and when $(a-bE_f)p > bE_{1v}s$,the left-hand-side of the inequality simplifies to a fourth degree polynomial in E_{2f} with positive coefficients for all degree terms including the constant term. Therefore, the optimal emission function is increasing in E_{2f} if $(a-bE_f)p > bE_{1v}s$. ■

Proof of Proposition 4:

Proof. $\Pi_{0,k,k}[Q^*(h)]$ is clearly convex in h since only B is related to h.

$$\frac{d\Pi_{0,k,k}[Q^*(h)]}{dh} = \frac{bE_{2f}}{2(1+bE_{2v})} - \frac{1}{2(1+bE_{2v})}\sqrt{\frac{A(-2\Lambda)}{B}}.$$

The first order solution is $h^m = \frac{1}{1+bE_{2v}}[\frac{(-2\Lambda)A}{b^2E_{2f}^2} - (k+bp)E_{1v}] \geq 0$. Further,

$$\frac{d^2\Pi_{0,k,k}[Q^*(h)]}{dh^2} = \frac{1}{4B}\sqrt{\frac{A(-2\Lambda)}{B}} \geq 0$$

$\frac{dE[Q^*(h)]}{dh} = \frac{1}{4(1+bE_{2v})}\sqrt{\frac{-2\Lambda}{AB}}[E_{2f} - E_{1v}\frac{A}{B}]$ and h^e is the unique solution to the first order condition. When $h \leq h^e$, $\frac{dE[Q^*(h)]}{dh} \leq 0$ and conversely, when $h > h^e$, $\frac{dE[Q^*(h)]}{dh} > 0$. Therefore, the emission function is unimodal in h with h^e as the minima. Furthermore, $\frac{d^2E[Q^*(h)]}{dh^2} = \frac{\sqrt{(-2\Lambda)}}{8B^2\sqrt{AB}}[3AE_{1v} - BE_{2f}]$, which is non-negative if $h \leq 3h^e + \frac{2(k+bp)E_{1v}}{1+bE_{2v}}$. When $h > 3h^e + \frac{2(k+bp)E_{1v}}{1+bE_{2v}}$, $\frac{dE[Q^*(h)]}{dh} > 0$. From the obtained explicit forms, it can be shown $h^e \leq h^m$.

The proof for the results on s is similar.

$$\frac{d\Pi_{0,k,k}[Q^*(s)]}{ds} = \frac{bE_{1v}}{2(1+bE_{2v})} - \frac{1}{2(1+bE_{2v})}\sqrt{\frac{B(-2\Lambda)}{A}}.$$

The first order solution is $s^m = \frac{1}{1+bE_{2v}}[\frac{(-2\Lambda)B}{b^2E_{1v}^2} - (k+bp)E_{2f}] \geq 0$. Further,

$$\frac{d^2\Pi_{0,k,k}[Q^*(s)]}{ds^2} = \frac{1}{4A}\sqrt{\frac{B(-2\Lambda)}{A}} \geq 0$$

After some simplification, it can be easily shown $s^e \leq s^m$.

$\frac{dE[Q^*(s)]}{ds} = \frac{1}{4(1+bE_{2v})}\sqrt{\frac{-2\Lambda}{AB}}[E_{1v} - E_{2f}\frac{B}{A}]$, s^e is the unique solution to the first order condition. When $s \leq s^e$, $\frac{dE[Q^*(s)]}{ds} \leq 0$ and conversely, when $s > s^e$, $\frac{dE[Q^*(s)]}{ds} > 0$. Therefore, the emission function is unimodal in s with s^e as the minima. Furthermore, $\frac{d^2E[Q^*(s)]}{ds^2} = \frac{\sqrt{(-2\Lambda)}}{8A^2\sqrt{AB}}[3BE_{2f} - AE_{1v}]$, which is non-negative if $s \leq 3s^e + \frac{2(k+bp)E_{2f}}{1+bE_{2v}}$. When $s > 3s^e + \frac{2(k+bp)E_{2f}}{1+bE_{2v}}$, $\frac{dE[Q^*(s)]}{ds} > 0$. With the obtained explicit functional forms, it can be shown $s^e \leq s^m$. ■

Proof of Proposition 5:

Proof. $\Pi_{T,k_1,k_1}[Q(\Omega)] = \Pi_{0,k_1,k_1}[Q(\Omega)] + k_1T$, therefore $\Pi_{T,k_1,k_1}[Q(\Omega)]$ is concave in Q by proposition 1. Similarly, $\Pi_{T,k_2,k_2}[Q(\Omega)]$ is also concave in Q. When $Q < Q_{01}(\Omega)$ or $Q > Q_{02}(\Omega)$, the firm's emission exceeds the assigned target level T; and therefore, the firm's profit $\Pi_{T,k_1,k_2}[Q(\Omega)] = \Pi_{T,k_1,k_1}[Q(\Omega)]$. When $Q_{01}(\Omega) \leq Q \leq Q_{02}(\Omega)$, the firm's emission level remains below the assigned target and thus $\Pi_{T,k_1,k_2}[Q(\Omega)] = \Pi_{T,k_2,k_2}[Q(\Omega)]$. Depending on the cost alignment structure, we discuss the optimal operational response Q^* in the following two cases.

Case 1: If $\frac{E_{1v}}{h} \leq \frac{E_{2f}}{s}$, then $Q_2^*(\Omega) \leq Q_1^*(\Omega) \leq Q_e(\Omega) \leq Q_{02}(\Omega)$ by proposition 2 and corollary 1. We further study three subcases depending on the position of $Q_{01}(\Omega)$.

1-1: When $Q_{01}(\Omega) \leq Q_2^*(\Omega)$

- When $Q < Q_{01}(\Omega)$, the firm operates in the emission penalty state. $\Pi_{T,k_1,k_2}[Q(\Omega)] = \Pi_{T,k_1,k_1}[Q(\Omega)]$. The firm's profit function is concave increasing in Q since $Q_1^*(\Omega)$ is the maximizer of $\Pi_{T,k_1,k_1}[Q(\Omega)]$ and $Q < Q_1^*(\Omega)$. In another word, the firm operates in the penalty state on the left hand side of (before) $Q_1^*(\Omega)$.
- When $Q_{01}(\Omega) \leq Q \leq Q_2^*(\Omega)$, $\Pi_{T,k_1,k_2}[Q(\Omega)] = \Pi_{T,k_2,k_2}[Q(\Omega)]$. Thus, the profit function is concave increasing in $Q(\Omega)$ since $Q_2^*(\Omega)$ is the maximizer of $\Pi_{T,k_2,k_2}[Q(\Omega)]$. In this case, the firm operates in the reward state on the left hand side of (before) $Q_2^*(\Omega)$.

- When $Q_2^*(\Omega) \leq Q \leq Q_{02}(\Omega)$, $\Pi_{T,k_1,k_2}[Q(\Omega)] = \Pi_{T,k_2,k_2}[Q(\Omega)]$ and the profit function is concave decreasing in Q. The firm operates in the reward state on the right hand side of (after) $Q_2^*(\Omega)$.
- Finally, when $Q \geq Q_{02}(\Omega)$, $\Pi_{T,k_1,k_2}[Q(\Omega)] = \Pi_{T,k_1,k_1}[Q(\Omega)]$ and the profit function is concave decreasing in Q since $Q(\Omega) > Q_1^*(\Omega)$. The firm operates in the penalty zone on the right hand side of(after) $Q_1^*(\Omega)$.

Therefore, the firm's profit function is increasing for $Q \leq Q_2^*(\Omega)$, and decreasing in $Q \geq Q_2^*(\Omega)$. $Q_2^*(\Omega)$ is the maximizer of the profit function and the optimal order quantity is $Q_2^*(\Omega)$.

1-2: $Q_2^*(\Omega) \leq Q_{01}(\Omega) \leq Q_1^*(\Omega)$

- When $Q < Q_{01}(\Omega)$, $\Pi_{T,k_1,k_2}[Q(\Omega)] = \Pi_{T,k_1,k_1}[Q(\Omega)]$ and the firm's profit function is concave increasing in Q since $Q < Q_1^*(\Omega)$.
- When $Q_{01}(\Omega) \leq Q \leq Q_1^*(\Omega)$, $\Pi_{T,k_1,k_2}[Q(\Omega)] = \Pi_{T,k_2,k_2}[Q(\Omega)]$. Thus, the profit function is concave decreasing in Q since $Q_2^*(\Omega)$ is the maximizer of $\Pi_{T,k_2,k_2}[Q(\Omega)]$ and $Q > Q_2^*(\Omega)$.
- Finally, when $Q \geq Q_{02}(\Omega)$, $\Pi_{T,k_1,k_2}[Q(\Omega)] = \Pi_{T,k_1,k_1}[Q(\Omega)]$, the profit function is concave decreasing in Q since $Q > Q_1^*(\Omega)$.

Therefore, the firm's profit function is concave increasing for $Q \leq Q_{01}(\Omega)$ and decreasing in $Q \geq Q_{01}(\Omega)$. $Q_{01}(\Omega)$ is the maximizer of the profit function and the optimal order quantity.

1-3: $Q_{01}(\Omega) \geq Q_1^*(\Omega)$

- When $Q < Q_1^*(\Omega)$, $\Pi_{T,k_1,k_2}[Q(\Omega)] = \Pi_{T,k_1,k_1}[Q(\Omega)]$; and the firm's profit function is concave increasing in Q.
- When $Q_1^*(\Omega) \leq Q < Q_{01}(\Omega)$, $\Pi_{T,k_1,k_2}[Q(\Omega)] = \Pi_{T,k_1,k_1}[Q(\Omega)]$ and the profit function is concave decreasing in Q since $Q_1^*(\Omega)$ is the maximizer of $\Pi_{T,k_2,k_2}[Q(\Omega)]$.
- When $Q_{01}(\Omega) \leq Q \leq Q_{02}(\Omega)$, $\Pi_{T,k_1,k_2}[Q(\Omega)] = \Pi_{T,k_2,k_2}[Q(\Omega)]$ and the profit function is concave decreasing in Q since $Q(\Omega) > Q_2^*(\Omega)$.
- Finally, when $Q > Q_{02}(\Omega)$, $\Pi_{T,k_1,k_2}[Q(\Omega)] = \Pi_{T,k_1,k_1}[Q(\Omega)]$ and the profit function is concave decreasing in Q since $Q > Q_1^*(\Omega)$.

Therefore, the firm's profit function is increasing in $Q \leq Q_1^*(\Omega)$ and decreasing in $Q \geq Q_1^*(\Omega)$. $Q_1^*(\Omega)$ is the maximizer of the profit function and the optimal order quantity.

Case 2: If $\frac{E_{1v}}{h} \geq \frac{E_{2f}}{s}$, $Q_{01}(\Omega) \leq Q_e(\Omega) \leq Q_1^*(\Omega) \leq Q_2^*(\Omega)$ by proposition 2 and corollary 1. The remainder of the proof is similar to case 1. ■

Proof of Proposition 6

Proof. Define,

$$
\begin{aligned}
\hat{E}_{ij}^1 &= \{E_{ij} | Q_{01}(E_{ij}) = Q_1^*(E_{ij})\} \quad i = 1,2; j = v, f \\
\hat{E}_{ij}^2 &= \{E_{ij} | Q_{01}(E_{ij}) = Q_2^*(E_{ij})\} \quad i = 1,2; j = v, f \\
\check{E}_{ij}^1 &= \{E_{ij} | Q_{02}(E_{ij}) = Q_1^*(E_{ij})\} \quad i = 1,2; j = v, f \\
\check{E}_{ij}^2 &= \{E_{ij} | Q_{02}(E_{ij}) = Q_2^*(E_{ij})\} \quad i = 1,2; j = v, f \\
E_{ij}^{m,1} &= argmin_{E_{ij}} \Pi_{T,k_1,k_1}[Q_1^*(E_{ij})] \quad (i,j) \in \{(1,f),(2,f),(1,v)\} \\
E_{ij}^{m,2} &= argmin_{E_{ij}} \Pi_{T,k_2,k_2}[Q_2^*(E_{ij})] \quad (i,j) \in \{(1,f),(2,f),(1,v)\} \\
E_{2v}^{m,1} &= argmax_{E_{2v}} \Pi_{T,k_1,k_1}[Q_1^*(E_{2v})] \\
E_{2v}^{m,2} &= argmax_{E_{2v}} \Pi_{T,k_2,k_2}[Q_2^*(E_{2v})]
\end{aligned}
$$

First, consider the fixed storage emission (E_f).

Case 1 - $\frac{E_{1v}}{h} \leq \frac{E_{2f}}{s}$: For given parameter set $\{\Omega - E_f\}$, $Q_2^*(E_f) \leq Q_1^*(E_f) \leq Q_e(E_f) \leq Q_{02}(E_f)$ by proposition 2 and corollary 1. Assume that $T \geq \lim_{E_f \to 0} E[Q_e(E_f)]$ and define $\bar{E}_f$ as $T = E[Q_e(\bar{E}_f)]$. $\bar{E}_f$ uniquely exists since $E[Q_e(E_f)]$ is decreasing in E_f and $Q_e(E_f)$ is increasing in E_f.

- For $E_f > \bar{E}_f$, $T < E[Q_e(E_f)]$ and the firm cannot meet the target emission level. Therefore, the optimal order quantity is $Q_1^*(E_f)$ and the corresponding optimal profit is $\Pi_{T,k_1,k_2}[Q^*(E_f)] = \Pi_{T,k_1,k_1}[Q_1^*(E_f)]$.
- When $E_f = \bar{E}_f$, $Q_{01}(\bar{E}_f) = Q_{02}(\bar{E}_f) = Q_e(\bar{E}_f)$ and $Q_2^*(\bar{E}_f) \leq Q_1^*(\bar{E}_f) \leq Q_{01}(\bar{E}_f)$.
- Further, when $E_f < \bar{E}_f$, the transition levels of E_f from the penalty state to the neutral state, then to the reward state need to be studied.

We first show the continuity during the state transition. It is shown that $\frac{dQ_{01}(E_f)}{dE_f} = \frac{1}{E_{1v}}[\frac{2\alpha_1}{\sqrt{\alpha_1^2 - 2\alpha_2 E_{1v}}}] \geq 0$. Thus, $Q_{01}(E_f)$ is increasing in E_f. Additionally, $Q_1^*(E_f)$ and $Q_2^*(E_f)$ are both decreasing in E_f by corollary 2. Therefore, $\hat{E}_f^1$ and $\hat{E}_f^2$ both uniquely exist. Further, $\Pi_{T,k_1,k_2}[Q_{01}(\hat{E}_f^1)] = \Pi_{T,k_1,k_2}[Q_1^*(\hat{E}_f^1)]$ and similarly $\Pi_{T,k_1,k_2}[Q_{01}(\hat{E}_f^2)] = \Pi_{T,k_1,k_2}[Q_2^*(\hat{E}_f^2)]$. Hence, the firm's profit function is continuous at $\hat{E}_f^1$ and $\hat{E}_f^2$ with $\hat{E}_f^1 \geq \hat{E}_f^2$.

By proposition 5 for given $\{\Omega - E_f\}$, the optimal order quantity and the optimal profit as a function of E_f are respectively given by,

$$Q^*(E_f) = \begin{cases} Q_1^*(E_f) & E_f \geq \bar{E}_f \\ Q_1^*(E_f) & \hat{E}_f^1 \leq E_f < \bar{E}_f \\ Q_{01}(E_f) & \hat{E}_f^2 \leq E_f < \hat{E}_f^1 \\ Q_2^*(E_f) & E_f \leq \hat{E}_f^2 \end{cases}$$

And,

$$\Pi_{T,k_1,k_2}[Q^*(E_f)] = \begin{cases} \Pi_{T,k_1,k_1}[Q_1^*(E_f)] & E_f \geq \hat{E}_f^1 \\ \Pi_{T,0,0}[Q_{01}(E_f)] & \hat{E}_f^2 \leq E_f < \hat{E}_f^1 \\ \Pi_{T,k_2,k_2}[Q_2^*(E_f)] & E_f < \hat{E}_f^2 \end{cases}$$

By proposition 3, $\Pi_{T,k_1,k_1}[Q_1^*(E_f)]$ and $\Pi_{T,k_2,k_2}[Q_2^*(E_f)]$ are both convex in E_f. Hence, $\Pi_{T,k_1,k_2}(Q^*(E_f))$ is continuous everywhere.

Next, we show the property of the profit function within each operational state. The properties of $\Pi_{T,k1,k_2}[Q^*(E_f)]$ are described in proposition 3 when $E_f \geq \hat{E}_f^1$ or $E_f < \hat{E}_f^2$ as the firm operates in the penalty and reward states respectively. Now, we focus on the case when the firm operates in the emission neutral state ,i.e., $\hat{E}_f^2 \leq E_f < \hat{E}_f^1$. Within emission neutral state,

$$\begin{aligned} \frac{d\Pi_{T,0,0}[Q_{01}(E_f)]}{dE_f} &= \frac{dQ_{01}}{dE_f} \frac{1}{[Q_{01}(E_f)(1+bE_{2v}) + bE_{2f}]^2} \\ &\quad \{(a - bE_f)[pbE_{2f} + s(1+bE_{2v})] - \\ &\quad [\frac{Q_{01}^2(E_f)}{2}(1+bE_{2v}) + bQ_{01}(E_f)][bpE_{1v} + h(1+bE_{2v})] + \\ &\quad \frac{b^2 E_{2f}}{2}(E_{1v}s - E_{2f}h)\} - \frac{b(pQ_{01}(E_f) + s)}{Q_{01}(E_f)(1+bE_{2v}) + bE_{2f}} \end{aligned}$$

$\Pi_{T,0,0}[Q_{01}(E_f)]$ is decreasing in E_f within $\hat{E}_f^2 \leq E_f < \hat{E}_f^1$ if the following condition is satisfied,

$$\begin{aligned} &(a - bE_f)[pbE_{2f} + s(1+bE_{2v})] - [\frac{Q_{01}^2(E_f)}{2}(1+bE_{2v}) + bQ_{01}(E_f)][bpE_{1v} + h(1+bE_{2v})] + \\ &\frac{b^2 E_{2f}}{2}(E_{1v}s - E_{2f}h) \leq 0 \end{aligned}$$

Since $Q_2^*(E_f) \leq Q_{01}(E_f) \leq Q_1^*(E_f)$ for $\hat{E}_f^2 \leq E_f \leq \hat{E}_f^1$, it would be sufficient to show the above condition by showing,

$$(a - bE_f)[pbE_{2f} + s(1 + bE_{2v})] - [\frac{Q_2^*(E_f)}{2}(1 + bE_{2v}) + bQ_2^*(E_f)][bpE_{1v} + h(1 + bE_{2v})] + \frac{b^2 E_{2f}}{2}(E_{1v}s - E_{2f}h) \leq 0$$

Plugging in the closed form of $Q_2^*(E_f)$ (from proposition 1) and after algebraic simplifications, it can be shown that the above inequality holds and $\Pi_{T,0,0}[Q_{01}(E_f)]$ is decreasing in E_f within $\hat{E}_f^2 \leq E_f < \hat{E}_f^1$ if $k_2(1 + bE_{2v})(sE_{1v} - hE_{2f}) \leq 0$ is satisfied, which holds true under the case 1 assumption $sE_{1v} \leq hE_{2f}$.

With the understanding of the profit functions with each of the operational state. Now we discuss the different scenarios of E_f. Noting that $E_f^{m,2} < E_f^{m,1}$ and $\hat{E}_f^2 < \hat{E}_f^1$, two subcases are considered.

1. $\hat{E}_f^2 > E_f^{m,2}$ - there are three possible scenarios of the relative positions among $\hat{E}_f^2$, $\hat{E}_f^1$, $E_f^{m,1}$, and $E_f^{m,2}$.

   1-1: If $\hat{E}_f^2 \geq E_f^{m,1}$, then $E_f^{m,2} \leq E_f^{m,1} \leq \hat{E}_f^2 \leq \hat{E}_f^1$. The optimal profit function is convex decreasing for $E_f \leq E_f^{m,2}$, convex increasing for $E_f^{m,2} \leq E_f \leq \hat{E}_f^2$, decreasing for $\hat{E}_f^2 \leq E_f \leq \hat{E}_f^1$, and convex increasing for $E_f \geq \hat{E}_f^1$. The optimal profit function is thus bimodal with $E_f^{m,2}$ and $\hat{E}_f^1$ as minimizers,and thus $\tilde{E}_f = E_f^{m,2}$.

   1-2: If $\hat{E}_f^2 < E_f^{m,1}$, then $E_f^{m,2} \leq \hat{E}_f^2 \leq E_f^{m,1} \leq \hat{E}_f^1$. The optimal profit function is convex decreasing for $E_f \leq E_f^{m,2}$, convex increasing for $E_f^{m,2} \leq E_f \leq \hat{E}_f^2$, decreasing for $\hat{E}_f^2 \leq E_f \leq \hat{E}_f^1$, and convex increasing for $E_f \geq \hat{E}_f^1$. The optimal profit function is thus again bimodal with $E_f^{m,2}$ and $\hat{E}_f^1$ as minimizers. $\tilde{E}_f = E_f^{m,2}$.

   1-3: If $\hat{E}_f^1 \leq E_f^{m,1}$, then $E_f^{m,2} \leq \hat{E}_f^2 \leq \hat{E}_f^1 \leq E_f^{m,1}$. The optimal profit function is convex decreasing for $E_f \leq E_f^{m,2}$, convex increasing for $E_f^{m,2} \leq E_f \leq \hat{E}_f^2$, decreasing for $\hat{E}_f^2 \leq E_f \leq E_f^{m,1}$, and convex increasing for $E_f \geq E_f^{m,1}$. The optimal profit function is thus bimodal with $E_f^{m,2}$ and $E_f^{m,1}$ as minimizers. $\tilde{E}_f = E_f^{m,2}$

2. $\hat{E}_f^2 \leq E_f^{m,2}$ - there are another three possible scenarios.

- When $\hat{E}_f^1 \geq E_f^{m,1}$, $\hat{E}_f^2 \leq E_f^{m,2} \leq E_f^{m,1} \leq \hat{E}_f^1$. The optimal profit function is decreasing for $E_f \leq \hat{E}_f^1$ and convex increasing for $E_f \geq \hat{E}_f^1$. The optimal profit function is unimodal with $\hat{E}_f^1$ as the minimizer.$\tilde{E}_f = \hat{E}_f^1$.
- When $E_f^{m,2} \leq \hat{E}_f^1 \leq E_f^{m,1}$, $\hat{E}_f^2 \leq E_f^{m,2} \leq \hat{E}_f^1 \leq E_f^{m,1}$. The optimal profit function is decreasing for $E_f \leq E_f^{m,1}$ and convex increasing for $E_f \geq \ E_f^{m,1}$. The optimal profit function is unimodal with $E_f^{m,1}$ as the minimizer. $\tilde{E}_f = E_f^{m,1}$.
- When $\hat{E}_f^1 \leq E_f^{m,2}$, $\hat{E}_f^2 \leq \hat{E}_f^1 \leq E_f^{m,2} \leq E_f^{m,1}$. The optimal profit function is decreasing for $E_f \leq E_f^{m,1}$ and convex increasing for $E_f \geq E_f^{m,1}$. The function is unimodal with $E_f^{m,1}$ as minimizer.$\tilde{E}_f = \hat{E}_f^{m,1}$.

These three different scenarios depict the profit functions with respect to E_f under (T, k_1, k_2) scheme. By proposition 3 and the knowledge of operational state transitions described, $E[Q^*(E_f)]$ is non-decreasing in E_f and $E[Q^*(E_f)] = T$ when the firm operates in the emission neutral state.

Case 2 - $\frac{E_{1v}}{h} > \frac{E_{2f}}{s}$

In this case, we know that $Q_{01}(E_f) \leq Q_e(E_f) \leq Q_1^*(E_f) \leq Q_2^*(E_f)$ by proposition 2 and corollary 1. The remainder of proof is the same as case 1 noting that $\frac{dQ_{02}(E_f)}{dE_f} \leq 0$ and $\frac{d\Pi_{T,0,0}[Q_{02}(E_f)]}{dE_f} \leq 0$ for $\check{E}_f^2 \leq E_f \leq \check{E}_f^1$.

Next consider the fixed transportation emission (E_{2f}).

For given $\{\Omega - E_{2f}\}$, assume that $T \geq \lim_{E_{2f} \to 0} E[Q_e(E_{2f})]$ and define,

$$\begin{aligned} \bar{E}_{2f} &= \{E_{2f} | \ \ T = E[Q_e(E_{2f})]\} \\ E_{2f}^e &= \frac{sE_{1v}}{h} \end{aligned}$$

Two possible cases are considered.

Case 1 - $\bar{E}_{2f} \geq E_{2f}^e$

In this case, $\frac{E_{1v}}{h} \leq \frac{E_{2f}}{s}$ for $E_{2f} \geq \bar{E}_{2f}$ and $E_{2f}^e \leq E_{2f} \leq \bar{E}_{2f}$. By Proposition 2 and corollary 1, $Q_2^*(E_{2f}) \leq Q_1^*(E_{2f}) \leq Q_e(E_{2f}) \leq Q_{02}(E_{2f})$ and the firm's optimal profit is given by proposition 5 as:

$$\Pi_{T,k_1,k_2}[Q^*(E_{2f})] = \begin{cases} \Pi_{T,k_1,k_1}[Q_1^*(E_{2f})] & \hat{E}_{2f}^1 \leq E_{2f} \\ \Pi_{T,0,0}[Q_{01}(E_{2f})] & \hat{E}_{2f}^1 \leq E_{2f} < \hat{E}_{2f}^2 \\ \Pi_{T,k_2,k_2}[Q_2^*(E_{2f})] & E_{2f} < \hat{E}_{2f}^2 \end{cases}$$

$Q_{01}(E_{2f})$ is increasing in E_{2f} since $\frac{dQ_{01}(E_{2f})}{dE_{2f}} = \frac{2(a-bT)}{\sqrt{\alpha_1^2 - 2\alpha_2 E_{1v}}} \geq 0$.

$$\begin{aligned} \frac{d\Pi_{T,0,0}(Q_{01}(E_{2f}))}{dE_{2f}} \quad = \quad & \frac{dQ_{01}(E_{2f})}{dE_{2f}} \frac{1}{[Q_{01}(E_{2f})(1+bE_{2v}) + bE_{2f}]^2} \\ & \{(a - bE_f)[pbE_{2f} + s(1 + bE_{2v})] - \\ & [\frac{Q_{01}^2(E_{2f})}{2}(1 + bE_{2v}) + bQ_{01}(E_{2f})][bpE_{1v} + h(1 + bE_{2v})] + \\ & \frac{b^2 E_{2f}}{2}(E_{1v}s - E_{2f}h)\} - \\ & [p - \frac{s}{Q_{01}(E_{2f})}]bQ_{01}(E_{2f})[a - bE_f - \frac{b}{2}E_{1v}Q_{01}(E_{2f})] \end{aligned}$$

It can be shown that $\Pi_{T,k_1,k_2}[Q_{01}(E_{2f})]$ is decreasing in $\hat{E_{2f}^2} \leq E_{2f} \leq \hat{E_{2f}^1}$ by substituting the lower bound $Q_2^*(E_{2f})$ for $Q_{01}(E_{2f})$ similar to the proof under case 1 of the fixed warehouse emission (E_f). The remainder of the proof is also analogous to case 1 under the fixed transportation emission, E_f. Thus, three scenarios summarize the results on E_{2f}.

$$\tilde{E}_{2f} = \begin{cases} E_{2f}^{m,2} & E_{2f}^{m,2} \leq \hat{E}_{2f}^2 & \\ \hat{E}_{2f}^1 & E_{2f}^{m,2} > \hat{E}_{2f}^2 & \hat{E}_{2f}^1 \geq E_{2f}^{m,1} \\ E_{2f}^{m,1} & E_{2f}^{m,2} > \hat{E}_{2f}^2 & \hat{E}_{2f}^1 < E_{2f}^{m,1} \end{cases}$$

Case 2 - $\bar{E}_{2f} \leq E_{2f}^e$

In this case, $\frac{E_{1v}}{h} \geq \frac{E_{2f}}{s}$ for $E_{2f}^e \leq E_{2f}$ and $Q_{01}(E_{2f}) \leq Q_e(E_{2f}) \leq Q_1^*(E_{2f}) \leq Q_2^*(E_{2f})$ by proposition 2 and corollary 1. The optimal profit function is given by proposition 5 as:

$$\Pi_{T,k_1,k_2}[Q^*(E_{2f})] = \begin{cases} \Pi_{T,k_1,k_1}[Q_1^*(E_{2f})] & E_{2f} \geq \check{E}_{2f}^1 \\ \Pi_{T,0,0}[Q_{01}(E_{2f})] & \check{E_{2f}^1} \leq E_{2f} \leq \check{E_{2f}^2} \\ \Pi_{T,k_2,k_2}[Q_2^*(E_{2f})] & E_{2f} \leq \check{E}_{2f}^1 \end{cases}$$

$Q_{02}(E_{2f})$ is decreasing in E_{2f} since $\frac{dQ_{02}(E_{2f})}{dE_{2f}} = \frac{-2(a-bT)}{\sqrt{\alpha_1^2 - 2\alpha_2 E_{1v}}} \leq 0$ and $\Pi_{T,0,0}[Q_{02}(E_{2f})]$ is decreasing in $\check{E}^2_{2f} \leq E_{2f} \leq \check{E}^1_{2f}$ since

$$\begin{aligned}\frac{d\Pi_{T,0,0}[Q_{02}(E_{2f})]}{dE_{2f}} &= \frac{dQ_{02}}{dE_{2f}} \frac{1}{[Q_{02}(E_{2f})(1+bE_{2v})+bE_{2f}]^2} \\ &\{(a-bE_f)[pbE_{2f}+s(1+bE_{2v})] - \\ &[\frac{Q^2_{02}(E_{2f})}{2}(1+bE_{2v})+bQ_{02}(E_{2f})][bpE_{1v}+h(1+bE_{2v})] + \\ &\frac{b^2E_{2f}}{2}(E_{1v}s-E_{2f}h)\} - \\ &(p-\frac{s}{Q_{02}(E_{2f})})bQ_{02}(E_{2f})(a-bE_f-\frac{b}{2}E_{1v}Q_{02}(E_{2f})\end{aligned}$$

It can be shown that $\Pi_{T,0,0}[Q_{02}(E_{2f})]$ is decreasing in $\check{E}^2_{2f} \leq E_{2f} \leq \check{E}^1_{2f}$ by substituting the lower bound $Q^*_1(E_{2f})$ for $Q_{02}(E_{2f})$, the remainder of the proof is analogous to case 2 under fixed transportation emission (E_f).

Next consider the variable storage emission, E_{1v}. For given $\{\Omega - E_{1v}\}$, and similar to the proof under fixed transportation emission, E_{2f}, define:

$$\begin{aligned}\bar{E}_{1v} &= \{E_{1v}|T = E[Q_e(E_{1v})]\} \\ E^e_{1v} &= \frac{hE_{2f}}{s}\end{aligned}$$

If $\hat{E}_{1v} \leq E^e_{1v}$, $\frac{E_{1v}}{h} \leq \frac{E_{2f}}{s}$ for $E_{1v} \leq \hat{E}_{1v}$; and if $\hat{E}_{1v} \geq E^e_{1v}$, then $\frac{E_{1v}}{h} \geq \frac{E_{2f}}{s}$ for $E_{1v} \geq E^e_{1v}$. Furthermore,

$$\begin{aligned}\frac{dQ_{01}(E_{1v})}{dE_{1v}} &= \frac{-1}{E^2_{1v}}[\alpha_1 - \frac{\alpha^2_1 - \alpha_2 E_{1v}}{\sqrt{\alpha^2_1 - 2\alpha_2 E_{1v}}}] \geq 0 \\ \frac{dQ_{02}(E_{1v})}{dE_{1v}} &= \frac{1}{E^2_{1v}}[-\alpha_2 E_{1v}(\alpha^2_1 - 2\alpha_2 E_{1v})^{-\frac{1}{2}} - \alpha_1 - (\alpha^2_1 - 2\alpha_2 E_{1v})^{\frac{1}{2}}] \leq 0 \\ \frac{d\Pi_{T,0,0}[Q_{01}(E_{1v})]}{dE_{1v}} &= \frac{dQ_{01}}{dE_{1v}} \frac{1}{[Q_{01}(E_{1v})(1+bE_{2v})+bE_{2f}]^2} \\ &\{(a-bE_f)[pbE_{2f}+s(1+bE_{2v})] - \\ &[\frac{Q^2_{01}(E_{1v})}{2}(1+bE_{2v})+bQ_{01}(E_{1v})][bpE_{1v}+h(1+bE_{2v})] + \\ &\frac{b^2E_{2f}}{2}(E_{1v}s-E_{2f}h)\} - \\ &\frac{bQ_{01}(E_{1v})(pQ_{01}(E_{1v})-s)}{2[Q_{01}(E_{1v})(1+bE_{2v})+bE_{2f}]}\end{aligned}$$

Similar to the former proof, it can be shown that $\frac{d\Pi_{T,0,0}(Q_{01}(E_{1v}))}{dE_{1v}} \leq 0$ and $\frac{d\Pi_{T,0,0}(Q_{02}(E_{1v}))}{dE_{1v}} \leq 0$. The rest of the proof and results are similar to those under the fixed transportation emission, E_{2f}.

Finally, consider the variable transportation emission, E_{2v}. For given $\{\Omega - E_{2v}\}$ two cases are considered:

Case 1 - $\frac{E_{1v}}{h} \leq \frac{E_{2f}}{s}$

In this case, $Q_2^*(E_{2v}) \leq Q_1^*(E_{2v}) \leq Q_e(E_{2v}) \leq Q_{02}(E_{2v})$ by proposition 2 and corollary 1. $Q_{01}(E_{2v})$ is increasing in E_{2v} since:

$$\frac{dQ_{01}(E_{2v})}{dE_{2v}} = \frac{(a-bT)}{E_{1v}} \frac{(2\alpha_1 - \sqrt{\alpha_1^2 - 2\alpha_2 E_{1v}})}{\sqrt{\alpha_1^2 - 2\alpha_2 E_{1v}}} \geq 0$$

By proposition 5, the firm's optimal ordering policy is:

$$Q^*(E_{2v}) = \begin{cases} Q_1^*(E_{2v}) & \hat{E}_{2v}^1 \leq E_{2v} \\ Q_{01}(E_{2v}) & \hat{E}_{2v}^2 \leq E_{2v} \leq \hat{E}_{2v}^1 \\ Q_2^*(E_{2v}) & E_{2v} \leq \hat{E}_{2v}^2 \end{cases}$$

By proposition 4, there exists $E_{2v}^{m,1} \geq 0$ such that the firms's optimal profit under the optimal operational response, $Q_1^*(E_{2v})$, is increasing in $0 \leq E_{2v} \leq E_{2v}^{m,1}$ and decreasing in $E_{2v} \geq E_{2v}^{m,1} \geq 0$. Similarly, there exists $E_{2v}^{m,2}$ such that the firm's optimal profit,$\Pi_{T,k_1,k_2}[Q_2^*(E_{2v})0]$, under optimal response $Q_2^*(E_{2v})$, is increasing in $0 \leq E_{2v} \leq E_{2v}^{m,2}$ and decreasing in $E_{2v} \geq E_{2v}^{m,2} \geq 0$.

$$\begin{aligned} \frac{d\Pi_{T,0,0}[Q_{01}(E_{2v})]}{dE_{2v}} \quad = \quad & \frac{dQ_{01}(E_{2v})}{dE_{2v}} \frac{1}{[Q_{01}(E_{2v})(1+bE_{2v}) + bE_{2f}]^2} \\ & \{(a - bE_f)[pbE_{2f} + s(1+bE_{2v})] - \\ & [\frac{Q_{01}^2(E_{2v})}{2}(1+bE_{2v}) + bQ_{01}(E_{2v})][bpE_{1v} + h(1+bE_{2v})] + \\ & \frac{b^2E_{2f}}{2}(E_{1v}s - E_{2f}h)\} - \\ & \frac{bQ_{01}(E_{2v})[pQ_{01}(E_{2v}) - s]}{2[Q_{01}(E_{2v})(1+bE_{2v}) + bE_{2f}]} \end{aligned} \tag{3}$$

Similar to the proof for other emission parameters, it can be shown $\Pi_{T,k_1,k_2}[^*_{01}(E_{2v})]$ is decreasing in $\hat{E}_{2v}^2 \leq E_{2v} \leq \hat{E}_{2v}^1$ by substituting the lower bound $Q_2^*(E_{2v})$ for $Q_{01}(E_{2v})$.

Different subcases must now be considered depending on the properties of the profit functions on E_{2v} described in proposition 3.

1 When both $\Pi_{T,k_1,k_2}(Q_1^*(E_{2v})$ and $\Pi_{T,k_1,k_2}(Q_2^*(E_{2v})$ are decreasing in E_{2v}, the firm's profit function $\Pi_{T,k_1,k_2}(Q^*(E_{2v}))$ is decreasing in $E_{2v} \geq 0$ and $E_{2v}^* = 0$.

2 When $E_{2v}^{m,1} > 0$ and $E_{2v}^{m,2} > 0$, then,

2-1 $E_{2v}^{m,2} \leq \hat{E}_{2v}^{2}$

a. If $E_{2v}^{m,1} \leq \hat{E}_{2v}^{1}$, the firm's profit decreases in $E_{2v} \geq E_{2v}^{m,2}$ and increases in $E_{2v} \leq E_{2v}^{m,2}$. Therefore, $E_{2v}^{*} = E_{2v}^{m,2}$.

b. When $E_{2v}^{m,1} > \hat{E}_{2v}^{1}$, the firm's profit decreases in $E_{2v} \geq E_{2v}^{m,1}$, increases in $\hat{E}_{2v}^{1} < E_{2v} < E_{2v}^{m,1}$, decreases in $E_{2v}^{m,2} \leq E_{2v} \leq \hat{E}_{2v}^{1}$, and increases in $E_{2v} < E_{2v}^{m,2}$. Both $E_{2v}^{m,1}$ and $E_{2v}^{m,2}$ are maximizers of the profit function; and thus,

$$E_{2v}^{*} = \begin{cases} E_{2v}^{m,1} & \Pi_{T,k_1,k_2}(Q_1^*(E_{2v}^{m,1})) > \Pi_{T,k_1,k_2}(Q_2^*(E_{2v}^{m,2})) \\ E_{2v}^{m,2} & otherwise \end{cases}$$

2-2 $E_{2v}^{m,2} > \hat{E}_{2v}^{2}$

a. If $E_{2v}^{m,1} \leq \hat{E}_{2v}^{1}$, the firm's profit decreases in $E_{2v} \geq \hat{E}_{2v}^{2}$ and increases in $E_{2v} < \hat{E}_{2v}^{2}$ and therefore $E_{2v}^{*} = \hat{E}_{2v}^{2}$

b. If $E_{2v}^{m,1} > \hat{E}_{2v}^{1}$; the firm's profit decreases in $E_{2v} \geq E_{2v}^{m,1}$, increases in $\hat{E}_{2v}^{1} < E_{2v} < E_{2v}^{m,1}$, decreases in $\hat{E}_{2v}^{2} \leq E_{2v} \leq \hat{E}_{2v}^{1}$, and increases in $E_{2v} < \hat{E}_{2v}^{2}$. Both $E_{2v}^{m,1}$ and $\hat{E}_{2v}^{2}$ are maximizers of the profit function and thus:

$$E_{2v}^{*} = \begin{cases} E_{2v}^{m,1} & \Pi_{T,k_1,k_2}[Q_1^*(E_{2v}^{m,1})] \geq \Pi_{T,k_1,k_2}[Q_{01}(\hat{E}_{2v}^{2})] \\ \hat{E}_{2v}^{2} & otherwise \end{cases}$$

Case 2 - $\frac{E_{1v}}{h} \geq \frac{E_{2f}}{s}$ The proof is similar to case 1, noting that $Q_{01}(E_{2v}) \leq Q_e(E_{2v}) \leq Q_1^*(E_{2v}) \leq Q_2^*(E_{2v})$, $Q_{02}(E_{2v})$ is decreasing in E_{2v} and $\frac{d\Pi_{T,0,0}[Q_{02}(E_{2v})]}{dE_{2v}} \leq 0$. ■