# OPERATIONAL PERSPECTIVES ON EXTENDED PRODUCER RESPONSIBILITY FOR DURABLE AND CONSUMABLE PRODUCTS

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# OPERATIONAL PERSPECTIVES ON EXTENDED PRODUCER RESPONSIBILITY FOR DURABLE AND CONSUMABLE PRODUCTS

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*To my beloved parents, Naciye and Ramadan Alev.*

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# SUMMARY

Growing post-consumer waste and associated environmental and public health concerns have resulted in more regulated waste management. In this context, *Extended Producer Responsibility (EPR)* has emerged as an environmental policy concept that focuses on the "polluter pays" principle. This principle shifts the economic burden of waste management on producers by imposing collection and recycling obligations. EPR aims to decrease the total environmental impact associated with the products by (i) diverting post-consumer products from landfills; and (ii) making producers internalize the environmental cost of their products. Over the last two decades, EPR has gained momentum all around the world from the US to EU, Japan and China for several product categories including batteries, carpet, leftover paint, unused pharmaceuticals, and electronics. This thesis consists of three essays that contribute to the understanding of the economic implications of EPR-based legislation from an operational perspective by analyzing how EPR affects the markets for certain durable (such as electronics) and consumable (such as pharmaceuticals) products.

In the first essay "Extended Producer Responsibility and Secondary Markets", we investigate the effect of EPR-based policy on a durable good producer's secondary market strategy. One of the underlying assumptions of EPR is that it imposes producer responsibility for end-of-life products, i.e., the producers recycle only the end-of-life products under EPR-based obligations. This assumption effectively leads to a conclusion that EPR results in environmental benefits by achieving landfill diversion through recycling and reducing new production. In this essay, we

challenge this premise by taking into account the durable nature of products such as electronics: Durable good producers have incentives to recover used products from the secondary markets and discard them. These incentives arise from two main effects: Used product recovery decreases the cannibalization of new product demand by decreasing substitutability of new products, and increases the value of new products by establishing a resale value for them. Under these effects, producers have adopted various strategies to recover used products, one of the most popular one being the buy-back programs (e.g. Dell, HP, Fujitsu, Apples). These observations suggest that EPR appears to target end-of-life products but durable good producers have a strong incentive to recover used products in working condition from the secondary market and recycle them to meet EPR obligations.

Accordingly, in this essay, we investigate whether and how EPR influences the secondary market strategy of a durable good producer. We develop a discrete-time, sequential, producer-consumer game over an infinite time horizon, where the producer is operationally responsible to meet the collection and recycling obligations of EPR. In our model, we adopt commonly observed assumptions from the durable products literature to provide a comprehensive framework, where a profit-maximizing producer can collect end-of-life products or utilize used products through paying the market-clearing price to comply with EPR obligations. We capture three possible levers of EPR policy: (1) a collection rate as a fraction of sales, (2) a recycling standard and (3) collection infrastructure requirements. Based on this model, we characterize the effect of EPR-based policy on the secondary market interference strategy of the producer. We analyze the environmental effectiveness of EPR for durable products by utilizing three key environmental performance measures by Waste Management Hierarchy: reduce, reuse and recycle.

We demonstrate that the effect of EPR and its associated environmental implications depend on product durability. In the absence of EPR, a producer may choose not to interfere with the secondary market for products with high durability. In that case, EPR may provide producers with an incentive to interfere with the secondary market by recovering and prematurely recycling used products to meet EPR obligations. This in turn leads to lower reuse and higher production levels. For low durability products, a producer may readily interfere with the secondary market even in the absence of EPR, and the effect of EPR depends on its implementation parameters. In particular, EPR increases (reduces) the producer's secondary market interference when collection targets are high (low) and recycling standards are low (high). These observations, in turn, imply that EPR-based take-back legislation may have unintended consequences in a durable product setting: It may diminish environmental goals such as reducing new production and increasing reuse levels. However, we find that such unintended consequences may be attenuated by increased recycling standards, while more stringent collection targets and infrastructure requirements may back fire in EPR implementations for durable products. To the best of our knowledge, our results are first to identify the interaction between EPR and secondary market strategies based on the durable nature of the products

Moreover, we explore the implications of EPR in practice by calibrating our model for iPod Nanos and iPhones. The motivation behind our choice of these products is that Apple buys back these products by paying consumers through its Apple Reuse and Recycling Program and does not re-market these products, implying that the company diverts these products to recycling. This numerical study allows us to highlight several producer strategies taking place in practice by indicating that the practice of several companies is aligned with our analytical and numerical results. To further generalize our results and discussion, we extend our base model into multiple directions including the cases where (i) the producer can refurbish recovered products from the secondary market and sell them back to consumers; (ii) the producer may not access all of the used and end-of-life products; and (iii) a state/non-profit entity manages or operates the recycling system and charges consumers a recycling fee, unlike the case where the producer is operationally responsible in fulfilling the EPR obligations. In all the extensions, we find that the producer may still recover used products from the secondary market and recycle used products to meet EPR obligations and our structural results on new production and reuse levels continue to hold.

In the second essay "A Market-Based Extended Producer Responsibility Implementation - The Case of Minnesota Electronics Recycling Act", we investigate the operational implementation details of EPR-based policy on the ground. In putting the EPR concept into operation, the recently popular approach in the US is the "market-based" approach. This approach employs free market principles and allows for independent stakeholder decisions to promote cost efficiency. It manages the tension between environmental and economic outcomes by setting desirable targets for collection but then providing a lot of flexibility to producers to achieve these targets. This approach has gained significant advocacy from the industry and some NGOs following the argument that allowing flexibility to the private sector enhances the effectiveness of operations as compared to the case where government dictates specific operational choices for implementation of the "central coordination" approach.

In this essay, we investigate whether the advocated benefits of the marked-based approach hold in practice by focusing on the Minnesota Electronics Recycling Act, a prevailing working example of a market-based EPR implementation. Based on publicly available reports and interviews with stakeholders (e.g., policy makers, producers, collectors, recyclers, and local government representatives), we conduct an in-depth analysis of the act along the dimensions of underlying motivations behind its implementation rules, associated stakeholder perspectives and resulting effectiveness. To enrich our analysis, we make comparisons with the Washington E-Waste Recycling Law that represents a comprehensive working system with a central coordination approach, which probably stands at the other end of the spectrum.

Our key finding is that the Minnesota Act achieves the high collection rate and high cost efficiency premises of the market-based approach, but this occurs at the expense of several unintended outcomes. These outcomes include environmental disadvantages due to “selective” collection and recycling rather than handling of e-waste evenly, an increased economic burden on local governments and limited incentives for environmentally benign design. Such unintended outcomes arise from market dynamics at the implementation (execution) stage and unanticipated interactions between stakeholders in response to these. Accordingly, our analysis suggests that the effectiveness of the market-based approach in practice depends significantly on the operational rules chosen for its implementation. This further implies that the market-based approach may not be necessarily effective in all dimensions unless its operational details are carefully managed.

In the third essay “Extended Producer Responsibility for Pharmaceuticals”, we focus on EPR-based policies for unused pharmaceuticals, a category of consumable products. Unused pharmaceuticals have been recognized as an emerging issue with substantial economic, environmental and public health impacts. Consequently, preventing the accumulation of unused pharmaceuticals at households and in the environment has become a serious concern. To address this concern, pharmaceutical policies based on EPR concept have gained traction in practice. For instance, the EU and two counties in the US (Alameda County, CA and King County, WA) passed EPR-based legislation, which require producers to establish and fund pharmaceutical collection programs. Although such legislation appear to be the preferred mode of operation in practice, their effectiveness is unknown since pharmaceuticals and their unique characteristics (e.g. consumable nature, mediated demand structure, limited end-of-use treatment procedures) have not been analyzed in the context of EPR to date.

Motivated by this, we investigate the effectiveness of EPR-based policies in addressing the pharmaceutical overage problem. We posit that the consumable and perishable nature of pharmaceuticals allow for a narrow set of policy options. In particular, there are primarily two viable policies to operationalize EPR for pharmaceuticals; (i) Source Reduction (SR), i.e., a form of fee imposed on producers for their sales to limit the amount of dispensed pharmaceuticals (as implemented in British Columbia and Portugal), or (ii) End-of-Pipe Control (EC) where producers establish and operate programs for collecting unused pharmaceuticals (as in Hungary and Belgium). To compare these policies, we develop a game-theoretic model that involves a social planner, a producer, a doctor, and a heterogeneous patient base. In our model, the social planner sets the EPR-based policy, EC vs. SR, the producer sets the price and promotional efforts directed at the doctor and patient; the doctor decides on the prescription amount that maximizes her utility by considering the patient's health, promotional effects and her reputation; and the patient makes his consumption decision. To the best of our knowledge, this is the first analytical model that analyzes the interactions in the pharmaceutical chain as they relate to EPR. Accordingly, this essay contributes at the interface of operations management, health and environmental economics literatures by building an integrated analysis framework.

We find that the pharmaceutical context may imply stronger preference for adopting the EC policy (over SR) when compared to other product categories for which EPR is prevalent. More specifically, we show that EC works better for pharmaceuticals with (i) high social and environmental externalities; (ii) high collection costs (e.g. stringent collection requirements or standards); and (iii) moderate treatment impacts from usage. This result contradicts the results of a similar analysis in the context of durable products, which would suggest that SR policy should be preferred in a similar setting. The reversal in the policy choice is due to the consumable nature and mediated demand of pharmaceuticals, which in turn demonstrates that the characteristics specific to the pharmaceutical supply chain determine the effectiveness of EPR-based policies for pharmaceuticals. Accordingly, our results indicate that there is no one-size-fits-all EPR-based policy in the context of pharmaceuticals. We extend our base model and validate the robustness of our results by considering certain insurance coverage, different consumer usage behavior and alternative promotional effects.

Furthermore, we investigate the perspectives of pharmaceutical stakeholders on the policy choice to understand possible tensions and accordingly inform policy makers. We demonstrate that there are several interrelated factors including the collection cost and healthcare impact of the medicine that influence the stakeholders' perspectives in different ways. Based on these factors, we show that aligning stakeholder preferences for effective EPR-based policy can be significantly harder in the pharmaceutical context. Accordingly, our results collectively suggest that the characteristics of the pharmaceutical supply chain and the associated dynamics within need to be carefully analyzed before undertaking any EPR-based policy decision.

From a methodological perspective, the first and third essays employ techniques and notions from optimization, game theory, and industrial organization. In these essays, we introduce stylized frameworks that capture critical operational factors in the relevant problem setting. Utilizing these frameworks, we characterize the effect of EPR-based policies on business practices, and generate insights for operations strategy on the one hand and policy design on the other. The second essay draws on collaborations with practitioners from industry and the public sector involved in crafting and implementing the EPR-based policies. Analyzing the operational implementation details on the ground, we generate lessons on what can be learned from the existing implementations.

In sum, the three essays in this thesis provide managerial insights and policy guidelines regarding how to obtain economically and environmentally effective EPR-based policies contingent on the nature of the products and market dynamics from an operational perspective. The results have implications for multiple stakeholders, including the society, the industry and the environment, and they can help achieve better environmental and economic outcomes, e.g., developing effective and well-functioning collection and processing infrastructures, improving collection rates, increasing cost efficiency, leading to better outcomes for the society at large and the environment.

# CHAPTER I

# INTRODUCTION

Sustainable operations have become an indispensable part of decision-making at all levels and created irreversible dynamics in the global area. This is due to urgent challenges that our world is now facing, such as growing amounts of waste, elevating levels of pollution, climate change, and resource constraints. Majority of sustainable solutions dealing with these challenges focus on producers, since producers have the greatest control over resource consumption and greatest ability to reduce waste. In this thesis, we focus on one of the related global trends, bringing environmental responsibility for producers so that producers take into account environmental impact of their decisions. The prevalent concept in this context is *Extended Producer Responsibility, EPR.*

EPR is an environmental policy concept first introduced in Sweden in 1990 [63]. As its name implies, it extends producer responsibility for a product beyond the traditional boundaries, to the post-consumer stage of the product life-cycle. In particular, EPR concept adopts "polluter pays" principle and with this principle, it holds producers financially and/or physically responsible for environmentally safe treatment of their end-of-life products [95]. To this end, it uses the mechanism of imposing collection and recycling obligations on producers. This means that producers are now responsible for taking back their post-consumer products and ensuring their proper recycling. EPR has two goals: (i) ensuring the environmentally responsible management of discarded products by diverting them away from landfills and promoting their recycling; and (ii) providing incentives for environmentally benign designs by having producers internalize post-use processing costs associated with their products [100].

Over the last two decades, EPR-based policies have become widespread in many countries around the world (e.g. US, EU, Japan, and China) for several products with high potential to harm the environment such as automobiles, electrical and electronic devices, which have a durable nature. There is a rich body of analysis that focuses on implementation of EPR for these products and associated operational decisions such as product design, new product introduction and supply chain configuration. This suggests that these implementations lead to better environmental outcomes. However, existing analysis and current implementations ignore durable nature of these products and related dynamics in the market, which may have a significant effect on the environmental outcomes. In the first essay, we investigate these ignored aspects and identify the interaction between durability and EPR-based policies with a particular emphasis on electronics. In this context, we consider incentives of durable good producers to recover used products from the secondary markets and discard them. We base our analysis on the buy-back programs of producers that offer consumers a fair market values for the return of their used products (e.g. Dell, HP, Fujitsu, Apple). We find that such secondary market interference may deteriorate environmental outcomes by increasing new production and reducing reuse levels. We provide insights into how to set EPR obligations to avoid these adverse outcomes. Furthermore, we validate our results by calibrating with real-life data and considering a number of extensions that represent different operational environments. Our analysis collectively uncovers possible strategic approach of durable good producers to EPR obligations and suggests that EPR obligations may result in unintended outcomes in a durable setting.

In the implementation of EPR-based policies, "market-based" approach has recently become the mostly advocated approach [83, 28]. Its main premises are to promote cost efficiency and to achieve better environmental outcomes by adopting free market principle and setting desirable targets for collection with broad flexibilities. In the second essay, we analyze whether these premises hold by focusing on the Minnesota Electronics Recycling Act, a prevailing example of marked-based EPR policy implementation in the US. Based on publicly available reports and our interviews with the stakeholders, we explore its implementation rules, stakeholder perspectives, and resulting outcomes together with underlying dynamics. To better evaluate the dynamics, we make comparisons with The Washington E-Waste Recycling Law, where government determines the operational choices with a "central coordination" approach. We find that the Minnesota Act appears to achieve the premises of the market-based approach, but this possibly occurs at the expense of several environmental disadvantages. Our analysis suggests that these disadvantages arise from market dynamics at the implementation stage and associated stakeholder interactions. This implies that the overall effectiveness of the market-based approach in practice depends significantly on the operational rules chosen for its implementation.

Following their widespread adoption for durable products, EPR-based policies have recently gained popularity for pharmaceuticals to address their recently recognized environmental and public health externalities. So far, EU, British Columbia and two states in the United States (California and Washington) have enacted EPR-based policies that mandate producers to operate and fund the pharmaceutical collection and disposal systems [133, 87, 5]. Many other states and countries are in the process of establishing similar policies. However, little is known regarding the effectiveness of these policies for pharmaceuticals and little guidance can be obtained from EPR implementations for durable products, because product characteristics, demand structures and market dynamics are very different. Motivated by this, in the third essay, we analyze how the EPR concept can be effectively operationalized for pharmaceuticals by focusing on major stakeholders (pharmaceutical producers, doctors, patients, the environment and public health) and their unique and complex interactions as well as moderating factors for these interactions (pharmaceutical promotions, mediated demand structure due to doctor-patient interaction). With this framework, we investigate the effectiveness of EPR-based policies and demonstrate that the preferred policy from the welfare perspective depends on the healthcare and externality characteristics of the medicine together with collection-related requirements in place. This shows that experiences and well-established premises learned from EPR implementations for durable products do not necessarily hold for consumables such as pharmaceuticals. Accordingly, our results suggest that identifying ideal EPR implementations for pharmaceuticals requires a careful investigation.

# CHAPTER II

# EXTENDED PRODUCER RESPONSIBILITY AND SECONDARY MARKETS

## *2.1 Introduction*

EPR-based approach has been employed prevalently for electronic waste (e-waste) [119] as e-waste has been considered to be the fastest growing and most toxic type of post-consumer waste [107]. Some early examples of EPR-based take-back legislation (hereafter referred to as EPR) for e-waste are The Waste Electrical and Electronic Equipment (WEEE) Directive (Directive 2003/108/EC) in Europe [55], and The Specified Household Appliance Recycling (SHAR) Law passed in Japan in 2005 [17]. Following this global trend, the number of state legislation based on the EPR concept has steadily increased in the U.S. over the last decade, and 26 states have enacted state-wide take-back legislation for discarded electronics [45].

One of the fundamental premises underlying EPR is that it imposes producer responsibility for end-of-life products [95, 18]. In other words, it is implicitly assumed that only end-of-life products that are discarded by end-users will be recycled under EPR-based take-back systems. In this essay, we challenge this premise in the context of durable products such as electronics: Durable goods producers may collect and discard end-of-use products (hereafter referred to as used products) that still have useful life remaining. For example, producers of electronic products such as Dell, HP, Fujitsu and Apple offer buyback programs that pay consumers or businesses for used electronics in working condition, including desktop computers, notebooks, and printers [39, 73, 59, 7] and do not necessarily remarket these recovered products. Such secondary market interference through recovery and disposal of used products helps a producer moderate competition against secondary markets, thereby reducing cannibalization of new product sales. It also increases the resale value of used products, resulting in higher valuation, and in turn, higher sales price of new products [143, 71]. Because EPR implementations do not necessarily specify the condition of products to be recycled, this observation suggests that a producer can utilize end-of-life and/or used products to meet EPR obligations. In other words, a producer may recover used products in working condition from the secondary market and recycle them to meet EPR obligations. Hence, a natural question is whether and how EPR affects a durable good producer's secondary market interference. This is the first question that we address in this essay.

We also note that a producer's secondary market interference may have important environmental implications. In particular, recovering used products in working condition and recycling them effectively curbs product reuse, shortens the average useful life of products, and increases new production in durable goods markets. In other words, secondary market interference diminishes the "reduce" and "reuse" levels in markets for durable goods, which are superior alternatives to recycling in the "reduce-reuse-recycle" waste management hierarchy [142]. Accordingly, the extent to which EPR influences the producer's approach to secondary markets, i.e. whether it moderates or exacerbates secondary market interference, has important environmental implications. Therefore, how EPR-driven secondary market interference influences the environmental effectiveness of EPR implementations is the second question that we address in this essay.

To address these two questions, we develop and analyze a stylized model that considers a durable goods producer subject to EPR. This analysis shows that the effect of EPR on a producer's secondary market strategy and its associated environmental implications depend on product durability. In the absence of EPR, a producer may choose not to interfere with the secondary market for products with high durability. This is because the cost of interference (i.e., the cost of buying/acquiring used products from the secondary market) can outweigh its benefits (e.g., reducing secondary market competition and increasing new product sales). In this case, we find that EPR induces a producer to recover and recycle used products to meet its EPR obligations when the recycling standards are low. For products with low durability, a producer may readily interfere with the secondary market even in the absence of EPR. In this case, the effect of EPR depends on its implementation parameters. In particular, EPR increases the producer's secondary market interference when collection targets are high, increasing the quantity needed to be recycled, and recycling standards are low, making recycling less expensive. Overall, our results suggest an unexplored and undesirable potential effect of EPR for durable goods: It may induce or increase secondary market interference by producers.

These observations, collectively imply that EPR-based take-back legislation may have unintended environmental consequences in a durable goods setting. More specifically, prevalent EPR implementation models' focus on the "recycle" dimension may diminish incentives to "reduce" and "reuse" in markets for durable goods [142]. Nevertheless, we find that such unintended consequences may be attenuated by increased recycling standards, while more stringent collection targets and infrastructure requirements may backfire in EPR implementations for durable products. We also validate these results by calibrating our model with real-life data for two types of consumer electronics (MP3 players and cellular phones). Finally, we consider a number of extensions to analyze the robustness of our results under different operational environments. These extensions suggest that EPR-driven incentives to recycle used products in working condition persist (i) when a producer refurbishes recovered used products, (ii) under state-operated EPR implementations that limit the producer's role in compliance, and (iii) when the producer (or the EPR system) has limited access to used and end-of-life products.

## *2.2 Related Literature*

This essay is closely related to the stream of literature in operations management research that examines the impact of environmental legislation on a firm's decisions such as new product introductions [116], technology choice [41, 90], competitive testing to enforce product standards [115], operating strategies of a waste-to-energy firm [10] and replacement of hazardous substances [88, 89]. A stream in this literature focuses on the effect of EPR-based take-back legislation on operational decisions such as design of recovery processes [149], supply chain configuration choices [85], product design [15, 13, 123, 54], and the welfare implications of these decisions [18, 141, 11, 52]. To the best of our knowledge, this stream of literature does not consider the durable nature of certain product categories that EPR applies to (e.g., electronics). We contribute to this literature by analyzing how product durability and EPR affect a producer's strategic approach to secondary markets and the resulting environmental implications.

Our work also relates to the closed-loop supply chain management literature, particularly to papers that study producers' recycling, remanufacturing, or refurbishing decisions [128, 38, 57, 146, 12, 52, 53] (see [132] for a recent overview). While most papers in this literature do not consider the presence of EPR, a few notable exceptions are [146], [52] and [53], who analyze the effect of EPR on an OEM's competitive refurbishing strategies. However, these papers do not consider the durable nature of products and thus ignore secondary markets. We contribute to this stream of literature by investigating a durable good producer's strategic choices regarding secondary market interference, refurbishing, and recycling to meet EPR obligations.

Finally, our work also relates to the extensive literature on durable goods, which has paid considerable attention to secondary markets as their presence has several important implications for a producer (see [144] for an overview): Secondary markets exert a positive effect on the new product price as they establish a future resale value for new products, and also allow the producer to segment consumers based on the heterogeneity in their willingness to pay for product quality. On the other hand, secondary markets may decrease the demand for new products, i.e., the cannibalization effect, due to the competition between new and used products. In the presence of these two opposing effects arising from the durable nature of products, producers may decrease the availability of used products via planned obsolescence [144, 4], or choose to eliminate secondary markets by using different strategies such as leasing [143, 71, 3], relicensing fees [110], buy-backs, or trade-ins [58, 122]. However, this literature does not analyze the effect of EPR on a durable good producer's secondary market strategy. Our work fills this gap by analyzing this effect and showing that EPR may provide additional incentives to interfere with the secondary market.

## *2.3 Model*

We consider a profit-maximizing monopolist producer that sells a durable product subject to EPR. We develop a discrete-time, infinite horizon, sequential game between the producer and consumers. We begin by outlining our assumptions for the producer and consumer decisions. Periods are indexed by $t \geq 0$.

**Product Characteristics.** The production cost per unit of the durable product is denoted by $c$, where $c \geq 0$. The product depreciates with use. The useful life of the product is assumed to be two periods [40, 79, 3, 4]. We consider a product to be *new* when it has never been used and has two periods of useful life left. We refer to a product as *used* when it only has a period of useful life left, and as *end-of-life* when it has been used for two periods. We use subscripts $n$, $u$, and $eol$ for new, used, and end-of-life products, respectively.

**Consumer Characteristics.** We assume that there is a unit mass of consumers, who are heterogeneous in their valuations for the product. Consumer valuations for the product, denoted by $\theta$, are uniformly distributed on $[0,1]$ [40, 79]. Each consumer uses at most one unit of product at a time, and the consumer population remains constant over time. In every period, a consumer with valuation $\theta$ receives gross utility $U_n(\theta) = \theta$ from using a new product, $U_u(\theta) = \delta\theta$ from using a used product, and $U_i(\theta) = 0$ from remaining inactive, where $\delta \in (0,1]$ represents the level of product durability. This representation captures that every consumer prefers a new product to a used product, and the relative substitutability between new and used products depends on product durability.

Let $p_n^t$ denote the sales price for the new product sold by the producer in period $t$. We assume that there exists a secondary market, where consumers can buy and sell used products, and it operates at a market-clearing price denoted by $p_u^t$. Therefore, in every period, a consumer has three available actions: buying a new product from the producer, buying a used product from the secondary market, or remaining inactive.[1] Consumers are forward looking and maximize their net present utility.

**EPR Implementation.** We first formulate a model of EPR implementations where the producer is operationally responsible[2] to meet its EPR obligations defined by the following requirements:

1. *Recycling standards:* Most EPR implementations impose standards for how products have to be recycled, e.g., they may require the producer to utilize better quality recycling processes, certified recyclers, or safer handling of resulting materials. As more stringent recycling standards result in higher recycling costs, we model a more stringent recycling standard through a higher unit recycling cost $s > 0$ incurred by the producer.

[1] In §2.6.1, we consider an extension where the producer can also refurbish recovered used products and sell them back to consumers.

[2] See §2.6.3 for an extension that considers EPR implementations where the producer or consumers are subject to a recycling fee as opposed to the operational responsibility model we consider in our main analysis.

2. *Requirements on collection infrastructure:* EPR implementations also impose certain requirements on how the collection infrastructure is set up. For example, in the Washington state, EPR compliance systems (operated by producers or the state) are required to have at least one collection point in each city or town with more than ten thousand residents [65]. In states such as New York and Michigan [108, 46] producers may manage collection points for end-of-life products, while in other states such as Connecticut and Maine end-of-life product collection is managed only by municipalities [46, 99]. These choices clearly influence collection costs, e.g., establishing collection centers in scarcely-populated locations increases collection costs, and the municipalities may charge higher collection fees to the producers (than they may be able to achieve independently). In our model, we capture the requirements on the collection infrastructure through a per-unit cost $k$ incurred by the producer for collection of end-of-life products.

3. *Collection and recycling targets:* EPR implementations with producer operational responsibility commonly impose collection and recycling rate targets, which are defined as the fraction of sales that the producer has to collect and recycle (e.g., as in Indiana, Minnesota, Michigan, Wisconsin and in the E.U.), respectively. We model those by assuming that if $q_n^{t-1}$ denotes the sales of new products in the previous period, then the producer has to collect and recycle at least $\alpha q_n^{t-1}$ products in period $t$, where $\alpha \in (0, 1]$. For brevity, we refer to this simply as the collection target hereafter.

**Fulfilling EPR Obligations.** In order to meet the EPR obligations, a producer with operational take-back responsibility can recover products from two different sources. First, the producer can recover end-of-life products. This option requires the producer to obtain end-of-life products from households, or municipal or local collection points. Therefore, the producer incurs a unit collection cost $k$ per end-of-life product collected, as defined above. If collecting an end-of-life product requires paying the consumer, it is straightforward to show that this cost can be internalized in the production and collection costs by rearranging the cost terms in our model (see Appendix A §A4 for details). We do not consider possible economies or diseconomies of scale in collection of end-of-life products (cf. [16]) for simplicity, as their presence does not change our structural results or qualitative insights. It can be shown that collection of end-of-life (used) products becomes relatively more attractive under economies (diseconomies) of scale. We denote the volume of end-of-life products collected in period $t$ by $q^t_{eol}$.

Second, the producer can recover used products (which have a period of useful life left) from the secondary market. Let $q^t_u$ denote the quantity of used products recovered by the producer in period $t$. We assume that the producer pays the market-clearing price $p^t_u$ for each used product recovered from the secondary market. Furthermore, because consumers get paid for returning their used products to the firm, we assume that any additional collection costs incurred by the producer are negligible under this option. It is straightforward to show that such a cost can be captured in our model, and it can be internalized in the marginal production cost and end-of-life collection cost by rearranging the cost terms (see Appendix A §A3 for details). Finally, in our main analysis, we assume that all products that reach end-of-use or end-of-life can be collected. In §2.6.2, we generalize our model to consider a situation where a fraction of such products may not be accessible for collection.

**Specification of the Game.** We assume that EPR obligations are specified at the start of the game. In each ensuing period of the dynamic game, the producer first makes its quantity decisions, viz., the quantity of new products to sell, the quantity of used products to recover from the secondary market, and the quantity of end-of-life products to recover. Subsequently, consumers make their purchasing decisions. The producer and consumers maximize their net utility with a common discount factor $\rho \in (0, 1)$. Given the sequential nature of the game within each period, we solve for subgame perfect equilibrium by using backward induction. We restrict our attention to Markov-perfect, stationary equilibria [79, 116, 3, 4], where all decisions remain constant in time, i.e., $q_n^t = q_n$, $q_u^t = q_u$ and $q_{eol}^t = q_{eol}$. Note that the time inconsistency problem does not exist in our model because we consider a product with a finite life cycle over an infinite horizon [79]. We also assume that all information regarding consumer preferences and cost structures are common knowledge.

**Inverse Demand Functions.** We provide a brief sketch of the derivation of the inverse demand functions. For ease of exposition, the proof and details for this section are relegated to Appendix A §A1. For a given price for the new product $p_n$ and price of the used product on the secondary market $p_u$, there are at most three undominated consumer strategies: Consumers of type $\theta \in (\theta_1(p_n, p_u), 1]$ purchase a new product and sell their used product on the secondary market in every period, consumers of type $\theta \in (\theta_2(p_u), \theta_1(p_n, p_u)]$ buy a used product from the secondary market in every period, and the remaining consumers stay inactive, where $\theta_1(p_n, p_u) = \frac{p_n - p_u(1+\rho)}{1-\delta}$ and $\theta_2(p_u) = \frac{p_u}{\delta}$. Accordingly, the demand for new products is given by $q_n = 1 - \theta_1(p_n, p_u)$, and the demand for used products from consumers is given by $q_{ud} = \theta_1(p_n, p_u) - \theta_2(p_u)$.

Given these consumer strategies, we can derive the market-clearing price for used products on the secondary market for a given $p_n$. The supply of used products on the secondary market is from consumers who always buy a new product. The demand for used products on the secondary market is from the consumers who buy a used product in every period ($q_{ud}$), and from the producer, which is denoted by $q_u$. Note that such recovery of used products by the producer is similar to a trade-in or buyback program, where the trade-in/buyback price is equal to the market-clearing price on the secondary market. The market-clearing price can then be found by solving $q_n = q_{ud} + q_u$ or $1 - \theta_1(p_n, p_u) = \theta_1(p_n, p_u) - \theta_2(p_u) + q_u$, and is given by

$p_u(p_n, q_u) \doteq \frac{\delta(2p_n+(q_u-1)(1-\delta))}{1+\delta+2\delta\rho}$. Note that the market-clearing price increases in the quantity of used products acquired by the producer.

The inverse demand function for new products is obtained by solving for $p_n$ in $q_n = 1 - \theta_1(p_n, p_u)$. We find $p_n(q_n, q_u) = 1 + \rho\delta - q_n(1 + \delta + 2\rho\delta) + \delta q_u(1 + \rho)$. The new product price increases in $q_u$ because a higher $q_u$ implies a higher market-clearing price on the secondary market, and hence a higher resale value in the future. Using $p_n(q_n, q_u)$, the market-clearing price for used products can be expressed as $p_u(q_n, q_u) = \delta(1 - 2q_n + q_u)$. In order to eliminate uninteresting cases where the business is not profitable for the producer, we assume that the production cost is not too high, i.e., $c < 1 + \delta - \alpha(s + \min(\delta, k))$, for the rest of the essay. We also assume $\rho = 1$ hereafter for ease of exposition.

**Formulation of the Producer's Problem.** Recall that we focus on Markov-perfect, stationary equilibria, under which the producer's problem reduces to the following steady-state formulation:

$$\max_{q_n, q_u, q_{eol}} \Pi(q_n, q_u, q_{eol}) = (p_n(q_n, q_u) - c)q_n - p_u(q_n, q_u)q_u - kq_{eol} - s\alpha q_n$$

$$\text{such that } \; q_{eol} \leq q_n - q_u, \;\; \alpha q_n \leq q_u + q_{eol}, \;\; q_n, q_u, q_{eol} \geq 0,$$

where the constraint $q_{eol} \leq q_n - q_u$ captures that the quantity of end-of-life products the producer can recover is constrained by the total quantity of end-of-life products held by consumers. The constraint $\alpha q_n \leq q_u + q_{eol}$ ensures that the amount of products recovered and recycled at least equals the target set by EPR obligations. In the producer's objective, $kq_{eol}$ represents the cost of recovering end-of-life products, and $p_u(q_n, q_u)q_u$ denotes the cost of recovering used products from the secondary market. The producer only recycles the quantity mandated by EPR obligations $\alpha q_n$ at a cost $s\alpha q_n$.

## *2.4 The Effect of EPR on a Producer's Secondary Market Strategy*

In this section, we first analyze a benchmark case in §2.4.1, where EPR is absent. Then, in §2.4.2, we investigate the effect of EPR on the producer's secondary market strategy.

### 2.4.1 Benchmark: No EPR

Consider the absence of EPR by assuming $\alpha = 0$. Note that if there are no EPR obligations, the producer has no reason to recover end-of-life products, i.e., $q_{eol} = 0$. Therefore, the producer's problem reduces to $\max_{q_n,q_u} \Pi(q_n, q_u, 0) = (p_n(q_n, q_u) - c)q_n - p_u(q_n, q_u)q_u$ such that $0 \leq q_u \leq q_n$.

**Lemma 1** *In the absence of EPR, the producer interferes with the secondary market by recovering used products ($q_u > 0$) if and only if $\delta < 1 - 2c$. The producer never shuts down the entire secondary market, i.e., $q_u < q_n$.*

Lemma 1 shows that the producer may choose to interfere with the secondary market by recovering used products in the absence of EPR. This is because it allows the producer to reduce cannibalization of its new products. However, the producer does not interfere with the secondary market if product durability or production cost are high. The reason for this is that higher durability implies higher value from a used product, leading to a higher price ($p_u$) on the secondary market, which makes recovering used products very expensive for the producer. Similarly, a higher production cost requires the producer to charge a higher price for the new product. This reduces the demand for new products, and consequently the availability of used products on the secondary market, increasing the market-clearing price for them. Therefore, a higher production cost also leads to a higher price of used products on the secondary market. Accordingly, when product durability and production cost are high, the cost of recovering used products is prohibitively high for the producer, and interfering with the secondary market is not profitable. We also note that an interfering producer does not shut down the secondary market completely, and maintains some active consumer-to-consumer trade on the secondary market.

### 2.4.2 Secondary Market Interference under EPR

We next analyze the producer's decision to interfere with the secondary market in the presence of EPR. Recall from Lemma 1 that in the absence of EPR, the producer does not interfere with the secondary market if $\delta \geq 1 - 2c$. We begin by focusing on this case as it allows us to isolate the effect of EPR on secondary market interference by the producer. The closed-form expressions for all thresholds defined in the analysis below are provided in the Appendix A.

**Proposition 1** *Let $\delta \geq 1 - 2c$. If $\delta \leq k$, EPR leads the producer to interfere with the secondary market and utilize only used products to meet the EPR obligations (i.e., $q_u = \alpha q_n$ and $q_{eol} = 0$).*

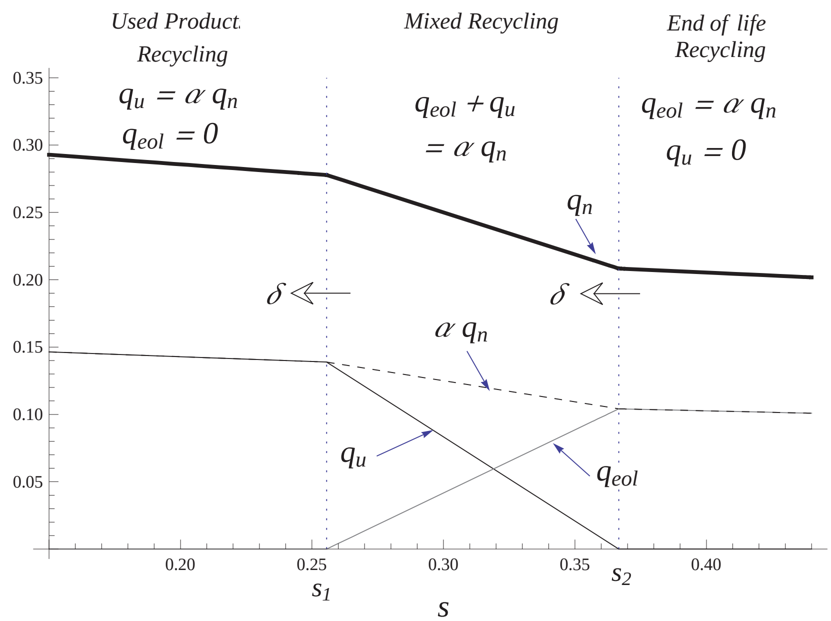
Proposition 1 shows that EPR may induce a durable good producer to interfere with the secondary market. This is an intuitive result when product durability ($\delta$) is relatively lower than the end-of-life product collection cost ($k$). The EPR obligations can be met by recovering used products at a unit price $p_u$ from the secondary market or by recovering end-of-life products at a unit cost of $k$. It is straightforward to show that the maximum market-clearing price for a used product on the secondary market is $\delta$ (see §A1 in the Appendix A). Therefore, when the cost to collect end-of-life products ($k$) is higher than the maximum possible price for a used product ($\delta$), it is clearly cheaper for the producer to recover used products from the secondary market instead of collecting end-of-life products. This result implies that if the collection infrastructure requirements result in a high collection cost, producers may respond to the legislation by exclusively interfering with the secondary market and recycling only used products to fulfill EPR-related obligations. Hereafter, we refer to this strategy, where the producer utilizes only used products to meet her EPR obligations, as the *Used Product Recycling* strategy.

A natural follow-up question is how the producer responds to EPR when the collection cost for end-of-life products is lower than the maximum value of used products on the secondary market (i.e., $\delta > k$), a more likely scenario in practice. Therefore, we next focus on the case where the collection cost for end-of-life products is low and the producer does not interfere with the secondary market in the absence of EPR. The producer's strategy to comply with the EPR obligations under this setting is illustrated in Figure 1 (see §2.4.3 for a similar illustration with calibrated real-life data).

**Proposition 2** *Let $\delta \geq 1 - 2c$ and $k < \delta$. There exists $s_1(\delta, \alpha, c, k) \leq s_2(\delta, \alpha, c, k)$ such that: If $s \leq s_1(\delta, \alpha, c, k)$, then the producer fulfills EPR obligations completely through recycling of used products, i.e., $q_u = \alpha q_n$ and $q_{eol} = 0$. If $s_1(\delta, \alpha, c, k) < s < s_2(\delta, \alpha, c, k)$, then the producer recycles a mix of used and end-of-life products to fulfill EPR obligations, i.e., $q_u, q_{eol} > 0$ and $q_u + q_{eol} = \alpha q_n$. Finally, if $s_2(\delta, \alpha, c, k) \leq s$, then the producer only recycles end-of-life products to fulfill EPR obligations, i.e., $q_u = 0$ and $q_{eol} = \alpha q_n$.*

Proposition 2 shows that the result from Proposition 1 that EPR may induce secondary market interference holds even when the cost to collect end-of-life products $k$ is low. Moreover, in this scenario, the producer's decision of how to comply with the EPR obligations, i.e., whether to utilize used products and/or end-of-life products, depends on the stringency of the recycling standard (see Figure 1). As recycling requirements become more stringent, the recycling cost imposed by EPR increases, leading to a higher per-unit cost faced by the producer. This drives the producer to charge a higher price and reduces the demand for its new products. Consequently, a smaller supply of used products is available for trade on the secondary market, which

**Figure 1:** Producer's decision of how to comply with EPR obligations as a function of recycling cost $s$.




*Note:* In the above figure, $\alpha = 0.5$, $c = 0.2$, $k = 0.1$ and $\delta = 0.6$.

increases the market-clearing price for used products. Therefore, a more stringent recycling requirement (i.e., a higher recycling cost) makes recovering used products more expensive, while it has no influence on the cost to collect end-of-life products. Hence, if the recycling cost is sufficiently low ($s \leq s_1(\delta, \alpha, c, k)$), the producer utilizes the Used Product Recycling strategy, despite the low cost to collect end-of-life products. As recycling cost increases further ($s_1(\delta, \alpha, c, k) < s < s_2(\delta, \alpha, c, k)$), the producer uses a mix of used and end-of-life products to meet the EPR obligations (hereafter referred to as the *Mixed Recycling* strategy). Finally, if the recycling cost is sufficiently high, the producer only uses end-of-life products to comply with EPR (hereafter referred to as the *End-of-life Recycling* strategy). This implies that EPR does not induce secondary market interference only if the recycling requirement is sufficiently stringent.

Note that the above result shows that even when the collection cost of end-of-life products is substantially low, (i.e., $k \ll \delta$), the producer may recycle used products to meet EPR obligations. In order to explain the rationale behind this, consider the case where the producer utilizes a Mixed Recycling strategy. In this setting, it can be shown that the cost to recover used products $p_u$ is always higher than the cost to collect end-of-life products $k$ (see Appendix A §A2). However, the producer still recovers some used products to meet the target because doing so reduces the cannibalization of new products due to the trade on the secondary market. This positive benefit of secondary market interference makes recovering used products overall more attractive for the producer, despite the cost of recovering used products ($p_u$) being higher than that for end-of-life products ($k$).

We next focus on the setting where the producer readily recovers used products by interfering with the secondary market even in the absence of EPR, i.e., $\delta < 1 - 2c$ (see Lemma 1). In this case, it can be shown that the producer's recycling strategy to meet EPR is almost identical to those outlined in Propositions 1-2 and Figure 1 above (see proofs of Propositions 1-3 for details). The only difference is that when $\delta < 1 - 2c$, the producer may collect more used products than the volume required to meet EPR obligations if $s < s_0(\delta, \alpha, c)$, where $s_0(\delta, \alpha, c) < s_1(\delta, \alpha, c, k)$. However, the producer's EPR compliance strategy does not change under $\delta < 1 - 2c$: the producer recycles used products to meet EPR obligations for $s < s_1(\delta, \alpha, c, k)$, both used and end-of-life products for $s_1(\delta, \alpha, c, k) \leq s \leq s_2(\delta, \alpha, c, k)$, and only end-of-life products otherwise.

The next proposition analyzes whether EPR increases secondary market interference in this case. Let $\widehat{\alpha}(\delta, c)$ denote the fraction of used products collected in the absence of EPR.

**Proposition 3** *Let $\delta < 1 - 2c$. EPR increases secondary market interference if the collection target is above the fraction of used products that the producer collects in the* *absence of EPR ($\alpha \geq \widehat{\alpha}(\delta, c)$) and $s < \widehat{s}(\delta, \alpha, c, k)$, where $\widehat{s}(\delta, \alpha, c, k) < s_2(\delta, \alpha, c, k)$. Otherwise, EPR reduces interference.*

Proposition 3 suggests that the implications of EPR on the producer's secondary market interference are slightly different for a product with lower durability, i.e., when $\delta < 1 - 2c$: In this case, when the producer already has a strong incentive to recover used products and the collection target set by EPR is low, EPR reduces secondary market interference ($\alpha < \widehat{\alpha}(\cdot)$). This result can be explained by the fact that the presence of EPR imposes a requirement to recycle recovered products as opposed to discarding them at no cost in the absence of EPR. This additional cost effectively implies a lower net profit margin for the producer, reducing the sales volume, and in turn, increasing the market-clearing price of used goods. This makes secondary market interference less attractive for the producer. In contrast, when the collection target set by EPR is high ($\alpha \geq \widehat{\alpha}(\cdot)$), it can increase secondary market interference because the producer has to recover a larger quantity of used products to meet the target. In particular, this happens when the recycling cost is sufficiently low ($s < \widehat{s}(\cdot)$), such that the producer prefers to recover used products to meet EPR obligations (i.e., utilizes a Used Product or Mixed Recycling strategy, similar to Figure 1).

To the best of our knowledge, Propositions 1-3 are the first to identify the interaction between EPR and secondary market strategies of a producer, which is driven by the durable nature of the product. Hence, a natural follow-up question is how product durability influences this interaction, which is explained in Proposition 4.

**Proposition 4** *$s_0(\delta, \alpha, c)$, $s_1(\delta, \alpha, c, k)$ and $s_2(\delta, \alpha, c, k)$ are decreasing in $\delta$.*

Proposition 4 shows that the producer's recycling cost thresholds for secondary market interference are higher for a product with lower durability. This is because lower durability implies a lower price for used products on the secondary market, making it less expensive for the producer to recover them. Therefore, as the product durability decreases, the producer moves from the End-of-life Recycling strategy to the Mixed Recycling strategy, and then to the Used Product Recycling strategy. In other words, the lower the product durability, the more attractive it is for the producer to interfere with the secondary market and recycle used products.

### 2.4.3 Numerical Study

While the analysis so far clearly demonstrates EPR's potential to increase secondary market interference from a theoretical perspective, a natural question is whether EPR implementations in practice are likely to induce such an outcome. In order to address this question, we calibrate our model based on real-life data by following a similar approach to [116] and [19]. In this analysis, we focus on Apple MP3 players and smartphones; in particular, $5^{th}$ generation iPod Nanos and iPhones. Our choice of these products is motivated by three different reasons: First, Apple currently buys back used products in these categories by paying consumers through its Apple Reuse and Recycling program [7]. Moreover, Apple currently does not remarket those $5^{th}$ generation iPod Nanos and iPhones, suggesting that they are diverted to recycling as implied by the program's name. Second, Apple is subject to EPR for these products in many countries or states with EPR-based take-back legislation. Third, relevant consumer valuation, cost, and EPR implementation data is readily available for these products.

In order to calibrate our model and estimate the product durability $\delta$, we first generalize our model by considering the consumer willingness to pay to be distributed between $[0, B]$, where $B \geq 1$ represents the maximum willingness to pay for a new product in the market. We also modify the consumer's per-period net utility to include a price sensitivity term $b > 0$ (see Appendix A §A5 for details).[3] Second, we determine new product sales prices from Apple's website [8]. Third, we determine

[3]Note that all our structural results also hold for this general model.

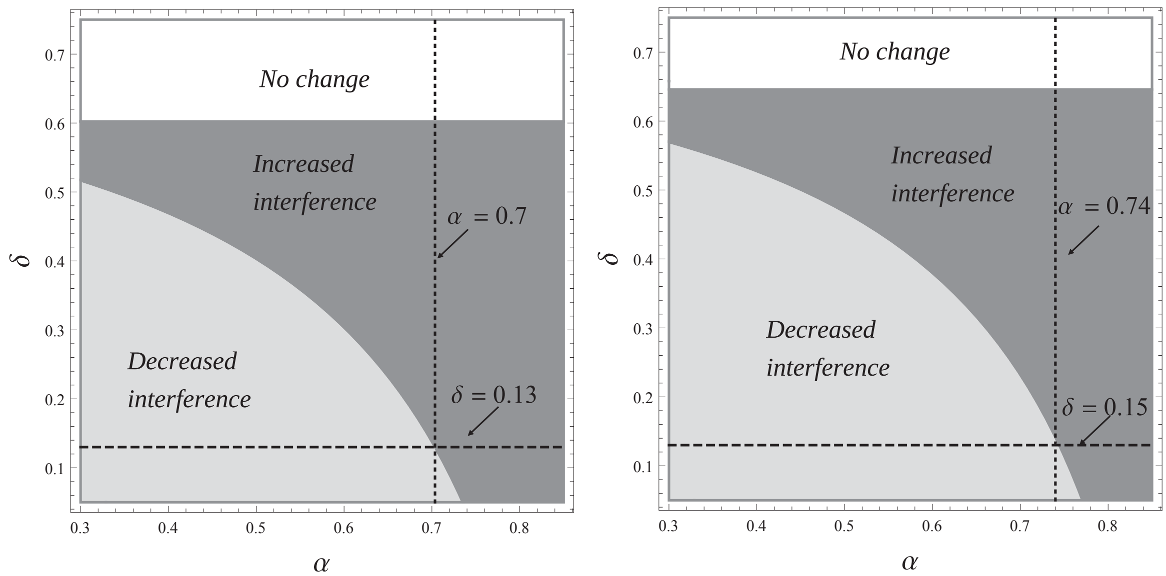
the maximum consumer willingness to pay $B$ for these two product categories using existing experimental data in [2]. Finally, we determine the buyback prices paid for used versions of these products from the website of Apple and its buyback partner [9, 25]. Subsequently, we assume that these new and used product price estimates correspond to those obtained from our general model, which allows us to estimate the product durability $\delta$. Please see Appendix A §A5 for further details regarding the calibration procedure and estimates.

Given these estimates, we explore the implications of EPR for these two product categories using our analytical model. We determine the recycling cost $s$ and the collection cost $k$ from [65], which provides an estimate of the collection cost as 5 cents/lb and the recycling cost as 2 cents/lb for small consumer electronics. For the collection target, we consider a range of values for $\alpha \in [0.3, 0.85]$, which contains values observed in different implementations in practice. For example, the collection target is 45% for 2016 and 65% in 2019 in the EU [55], and 80% currently in the states of Minnesota and Wisconsin [46].

We first analyze the effect of EPR for iPod Nanos. The production cost for an iPod Nano is \$45 [81] and its weight is approximately 0.1 lb, which results in a per-unit recycling cost of 0.2 cents or \$0.002 and a per-unit collection cost of 0.5 cents or \$0.005. Using these estimates, we illustrate the effect of EPR in Figure 2a. When the product durability and collection targets are both low (light gray region in Figure 2a), EPR decreases secondary market interference, which also coincides with the region where the producer prefers a Used Product Recycling strategy.[4] For higher durability (gray region in Figure 2b), EPR increases secondary market interference, which also coincides with the region where the producer prefers a Mixed Recycling strategy. Finally, for sufficiently high durability (white region in Figure 2a), the

[4]Note that this alignment of the producer's recycling strategies and regions of decreased and increased interference only holds for these specific estimates, and may not hold in general.

**Figure 2:** The effect of EPR on secondary market interference for iPods and iPhones.




(a) iPods (b) iPhones

*Note:* In panel (a) for iPods, $B = 190$, $b = 0.84$, $s = 0.002$, $c = 45$ and $k = 0.005$. In panel (b) for iPhones, $B = 948.23$, $b = 0.84$, $s = 0.005$, $c = 200$ and $k = 0.0125$. The producer utilizes a Used Product Recycling strategy in the light gray region, Mixed Recycling strategy in the gray region and End-of-life Recycling strategy in the white region. In the absence of EPR, the producer interferes with the secondary market if $\delta < 0.6$ for iPod Nanos and $\delta < 0.65$ for iPhones.

producer only recycles end-of-life products and does not interfere with the secondary market regardless of whether it is subject to EPR or not. Note that the calibration procedure explained above provides an estimate for the durability of a $5^{th}$ generation iPod Nano as $\delta = 0.13$. As illustrated in Figure 2a, our analysis suggests that the producer will interfere with the secondary market for any $\alpha$ if $\delta < 0.6$, which is satisfied for our estimate of durability $\delta = 0.13$. Therefore, our results from the calibration study are consistent with Apple's strategy in practice of recovering iPods through a buyback program. For iPod Nanos (with $\delta = 0.13$), Figure 2a suggests that a collection target above 70%, such as the current target in Minnesota and Wisconsin, may lead to increased interference. Figure 2a also suggests that an increase in the collection target may result in increased interference by the producer for even lower collection targets if the product durability were higher.

We next analyze the effect of EPR for iPhones. The production cost for an iPhone is \$200 [82] and its weight is approximately 0.25 lb, which results in a per-unit recycling cost of 0.5 cents or \$0.005 and a per-unit collection cost of 1.25 cents or \$0.0125. Using these estimates, we illustrate the effect of EPR for iPhones in Figure 2b, which is similar to that for iPods as shown in Figure 2a. Using the calibration procedure explained above provides an estimate for the durability of a $5^{th}$ generation iPhone as $\delta = 0.15$. As illustrated in Figure 2b, our analysis suggests that the producer will interfere with the secondary market for iPhone 5 for all $\alpha$ if $\delta < 0.65$, which is satisfied for our estimate of durability $\delta = 0.15$. Therefore, our results are also consistent with Apple's strategy of recovering iPhones through a buyback program. Similar to Figure 2a, Figure 2b suggests that a collection rate target above 74% may lead to increased interference for iPhones.

In sum, this numerical study demonstrates how our results relate to practice for these two product categories. The key observation from this analysis is that even for such high margin products with low collection and recycling costs that may appear inconsequential, EPR may influence the producer's secondary market strategy. In particular, stringent collection targets (e.g., above 75%) may lead the producer to increase secondary market interference, implying reduced reuse and increased consumption. Finally, it is important to note that electronic firms in other product categories facing EPR also utilize buyback practices similar to that of Apple. For example, HP is currently utilizing a third-party service provider, Market Velocity, to buy back used HP products from end-users and recycle them [73] for profit or WEEE compliance [72]. Fujitsu states that their trade-in programs pay for used products, and some of these products are recycled for WEEE compliance [59]. We expect that the implications of our results will be stronger for these product categories as they have lower profit margins (i.e., higher $c$) and they are heavier, and therefore, more expensive to collect at end-of-life (i.e., higher $k$).

## 2.5 Designing Effective EPR Implementations for Durable Products

The insights from the previous section suggest that results from the existing operations management literature on EPR [18, 15, 54] does not fully characterize the impact of EPR on durable goods. This stream of literature ignores the effect of secondary markets for durable goods and implicitly assumes that the producers will only recycle end-of-life products. This assumption effectively leads one to conclude that EPR brings environmental benefits by reducing new production and achieving higher recycling and landfill diversion. However, our results show that when the product durability is accounted for, EPR may lead to recycling of only end-of-life products for a limited set of conditions, viz., when the recycling costs are high or the imposed collection rate is high. Otherwise, EPR may achieve only the “recycle” goal at the expense of the “reduce” and “reuse” goals, the negative implications of which are explored next.

In order to analyze the environmental effectiveness of EPR for durable products, we first define three key environmental performance measures utilized by the Waste Management Hierarchy (WMH). WMH ranks the most environmentally-sound waste management strategies, in order of environmental preference, as reduce, reuse and recycle [142]. Recycling products has the lowest priority because it only ensures environmentally-sound disposal of products, and does not influence the impact of products in production or use. In our model, the recycling level is determined by EPR and is fixed at $\alpha$ as defined in §2. Encouraging product reuse is the next preferred strategy in the WMH, as reusing products decreases customers’ replacement frequency, and extends their useful life. Note that reuse may be environmentally undesirable for some products such as refrigerators, whose use impact may increase over time [86]. However, we focus on the setting where reuse is environmentally desirable, as suggested by the WMH. In our model, the level of product reuse can be defined as $(q_n - q_u)/q_n$, where $q_n - q_u$ is the quantity of products that are reused after the first period of their useful life. A higher value indicates that a larger fraction of products manufactured by the producer are reused. Finally, reducing new production is the most desirable option in the WMH. It not only reduces the environmental impact of production, but also lowers the environmental impact during use and eventual disposal of products. In our setting, these combined effects can be measured by the new production level $q_n$. In sum, analyzing the effectiveness of EPR under the WMH effectively boils down to an investigation of new production $q_n$ and used good collection $q_u$ volumes, which we analyze in detail below.[5]

As identified by Propositions 1-3, EPR may lead to increased secondary market interference, which may in turn result in increased new production (negating the highest priority reduce objective), and premature recycling of products (negating the next highest priority reuse objective).

Hence, an EPR implementation needs to take these unintended outcomes into account in setting instruments for effective policy implementation, the conditions for which are explored below. We start by analyzing the setting of effective recycling standards under EPR for durable goods.

**Proposition 5** *A more stringent recycling standard, i.e., a higher recycling cost $s$, leads to a higher reuse level and reduces the new production level.*

The above result parallels the intuition from Proposition 2 and the illustration in Figure 1. Recall from the discussion of Proposition 2 that as the recycling cost increases due to a more stringent recycling standard, the price of used products on the secondary market increases. This makes recovery of used products less attractive

[5]We note that a combined measure of total environmental impact can be derived as a function of new production $q_n$ and used good collection $q_u$ volumes, and used in a total welfare analysis leading to similar insights, which we omit here for brevity (see Appendix A §A6 for details).

to meet EPR obligations. As a result, there is a larger fraction of products that are reused. Similarly, as the recycling cost increases, new production becomes more expensive for the producer due to the EPR obligations, leading to a lower level of new production. Therefore, a more stringent recycling standard may achieve better outcomes along all three environmental performance measures under the WMH. Nevertheless, it is important to note that given the recent trends in the economics of recycling [93], the effectiveness of increased recycling stringency may be limited: Due to rising prices for materials that can be recovered from e-waste, the effective recycling cost can be low even for very stringent recycling standards. This implies that while recycling standards may be able to attenuate the negative effect of lower reuse and higher new production levels due to EPR, they may not be able to completely overcome them.

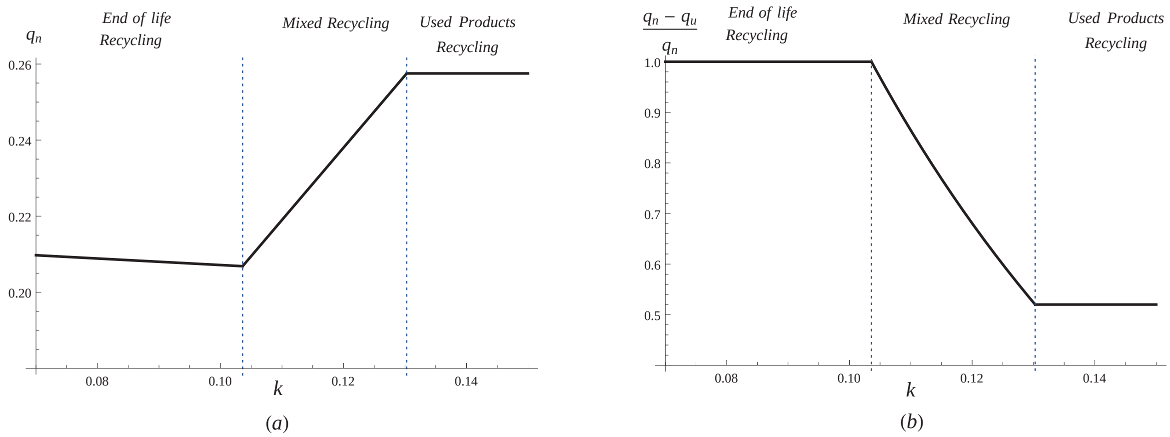
We next explore the effect of collection infrastructure requirements. Conventional wisdom may suggest that similar to the effect of recycling standard, a more stringent collection infrastructure requirement will lead to a higher end-of-life collection cost for the producer and reduce the production level. However, the next result shows that higher collection costs or more stringent requirements on the collection infrastructure may backfire by leading to increased secondary market interference, and in turn, higher new production and reduced reuse levels. Note that collection infrastructure requirements do not influence the producer if it does not collect any end-of-life products as under the Used Product Recycling strategy; hence the next result focuses on the cases where $k$ has an impact on the reuse and production levels.

**Proposition 6** *A more stringent collection infrastructure requirement, i.e., a higher collection cost $k$, leads to a lower level of production only under the End-of-life Recycling strategy ($q_{eol} > 0, q_u = 0$). Under a Mixed Recycling strategy ($q_u, q_{eol} > 0$), a more stringent collection infrastructure requirement leads to a higher level of new production and lower level of reuse.*

Proposition 6 states that a more stringent requirement on the collection infrastructure (i.e., a higher collection cost $k$) may lead to the environmentally beneficial outcome of reducing the level of new production only if the producer utilizes the End-of-life Recycling strategy (see Figure 3). Otherwise, increasing the stringency of collection infrastructure requirements may actually increase the level of new production. The intuition behind this result is as follows: If the producer finds it optimal to utilize the End-of-life Recycling strategy, more stringent collection infrastructure requirements lower the producer's margins and imply a lower production level. The firm shifts from the End-of-life Recycling strategy to the Mixed Recycling strategy as $k$ increases beyond a threshold, and the producer finds it attractive to begin interfering with the secondary market, leading to a lower reuse level and a higher production level. Furthermore, once $k$ increases beyond a threshold, the producer switches to recycling only used products. This implies that if EPR dictates more stringent collection infrastructure requirements such as enforcing a broader collection network (i.e., requiring end-of-life product collection from scarcely-populated locations) or allowing only local municipalities to collect end-of-life products, and charge high collection costs to the producers with the intention to support local economies, EPR may backfire by curtailing reuse and increasing the level of new production. Moreover, when the producer finds it optimal to utilize the Mixed Recycling strategy, it may even be environmentally beneficial to decrease the stringency of collection infrastructure requirements as illustrated by Figure 3.

This brings us to perhaps the easiest to implement and enforce, and most popularly utilized EPR instrument, i.e., the collection target, which is used throughout Europe and in several U.S. states. The conventional wisdom is that increasing collection targets is environmentally beneficial, which is exactly why the WEEE Directive Recast has increased collection targets to be imposed on European Member States (45% by

**Figure 3:** Levels of production $q_n$ (panel a) and reuse $(q_n - q_u)/q_n$ (panel b) as a function of cost to collect end-of-life products $k$.



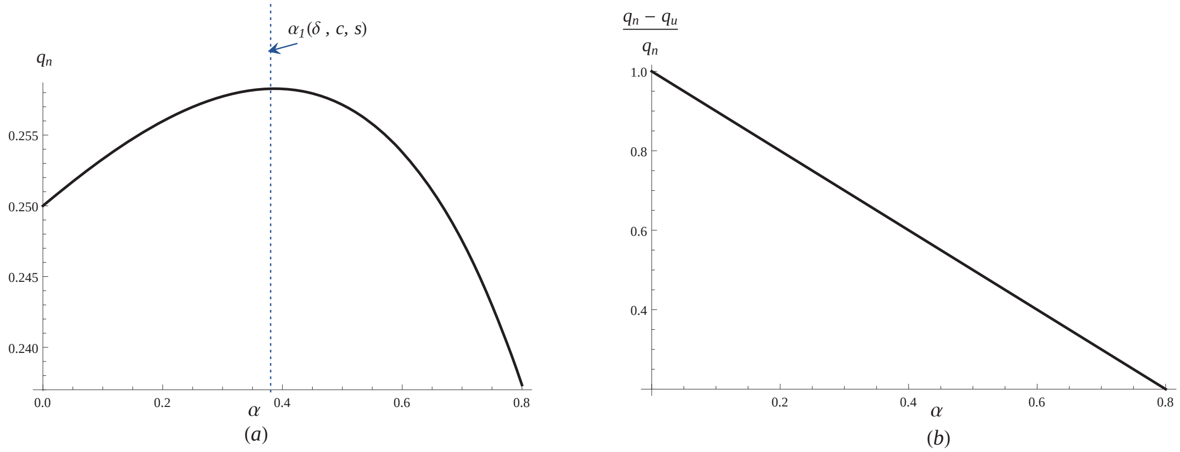

*Note:* In the above figure, $\alpha = 0.48$, $c = 0.2$, $s = 0.4$ and $\delta = 0.6$.

2016 and then to 65% by 2019, see [55]). One would expect that a higher collection target $\alpha$ makes new production more expensive, leading to lower new production and a higher reuse level. This is indeed the case when the producer readily collects more than the volume required to meet EPR ($s < s_0(\delta, \alpha, c)$) or adopts a Mixed or End-of-life Recycling strategy ($s > s_1(\delta, \alpha, c, k)$); see Appendix A §A2). However, the next result shows that when the producer utilizes a Used Product Recycling strategy, a higher collection target may have the opposite effect.

**Proposition 7** *Let $s_0(\delta, \alpha, c) \leq s \leq s_1(\delta, \alpha, c)$, i.e., Used Product Recycling strategy ($0 < q_u = \alpha q_n$ and $q_{eol} = 0$) is optimal. Then, a higher collection target leads to a lower reuse level. It also leads to a higher level of new production if $\alpha < \alpha_1(\delta, c, s)$.*

Proposition 7 identifies two counter-intuitive results as illustrated by Figure 4. It states that (i) an increased collection target results in a lower reuse level as long as the producer utilizes the Used Product Recycling strategy, and (ii) a higher collection target may lead to a higher production level under the Used Product Recycling strategy when the collection target is below a certain threshold. These results are driven by the balance (or lack thereof) between two contrasting effects of

**Figure 4:** Levels of production $q_n$ (panel a) and reuse $(q_n - q_u)/q_n = 1 - \alpha$ (panel b) as a function of collection target $\alpha$, for a Used Product Recycling strategy.




*Note:* In the above figure, $k = 0.3$, $c = 0.2$, $s = 0.4$ and $\delta = 0.6$.

the collection target on the new production volume: As the collection target increases, the producer effectively incurs a higher effective cost to comply with EPR, implying reduced margins and leading to a negative effect on the new production volume. In contrast, to make recovering used products more cost effective, the producer may also need to increase new production to increase used product availability and reduce the price of used products on the secondary market.

In sum, these observations suggest that increasing collection targets do not necessarily imply environmental benefits in a durable goods setting (as demonstrated in §4.3). These results also highlight a trade-off involved with setting a collection target for an efficient EPR implementation: Higher collection targets may lower levels of new production for durable goods, but this may happen at the expense of lower reuse levels.

## 2.6 Extensions

We now provide three extensions that capture additional considerations and relax some of the assumptions used in our main analysis.

### 2.6.1 Refurbishing.

In our main analysis, we assumed that the producer does not refurbish recovered used products and sell them back to consumers. We now generalize our model to allow the producer to refurbish recovered used products. Therefore, we consider two different used goods markets in our model, viz., a secondary market where consumers can purchase used products from other consumers, and one where the producer sells refurbished products to consumers (in a similar vein to [150]). We assume that the gross utility of a consumer with valuation $\theta$ from using a refurbished product is given by $U_r(\theta) = \delta_r \theta$, where $\delta_r \in (\delta, 1)$. This captures that the consumers' valuation for a refurbished product will be lower than that for a new product, but higher than that for a used product (see [110] for a similar formulation). In other words, refurbishing improves the quality of the used product from $\delta$ to $\delta_r$. Let the per-unit refurbishing cost be denoted by $c_r > 0$, where $c_r < \delta_r - \delta$. If this condition does not hold, then refurbishing would trivially never be profitable for the producer.

The detailed derivation of the inverse demand functions for this scenario is relegated to the Appendix A §A7. There are at most four undominated consumer strategies in this case: Consumers of type $\theta \in (\theta_1^r(p_n, p_u, p_r), 1]$ purchase a new product and sell their used product on the secondary market in every period, consumers of type $\theta \in (\theta_2^r(p_u, p_r), \theta_1^r(p_n, p_u, p_r)]$ purchase a remanufactured product from the producer in every period, consumers of type $\theta \in (\theta_3^r(p_u), \theta_2^r(p_u, p_r)]$ purchase a used product from the secondary market in every period, and the rest remain inactive, where $\theta_1^r(p_n, p_u, p_r) \doteq \frac{p_n - p_r - \rho p_u}{1-\delta_r}$, $\theta_2^r(p_u, p_r) \doteq \frac{p_r - p_u}{\delta_r - \delta}$ and $\theta_3^r(p_u) = \frac{p_u}{\delta}$. Accordingly, the demand for new, refurbished and used products from consumers is given by $q_n = 1 - \theta_1^r(p_n, p_u, p_r)$, $q_r = \theta_1^r(p_n, p_u, p_r) - \theta_2^r(p_u, p_r)$ and $q_{ud} = \theta_2^r(p_u, p_r) - \theta_3^r(p_u)$. The market-clearing price of used products can be found by solving $q_n = q_{ud} + q_u$. Solving for the market-clearing price and inverse demand functions yields $p_u(q_n, q_u, q_r) = \delta(1 - 2q_n - q_r + q_u)$, $p_n(q_n, q_u, q_r) = 1 + \delta + 2\delta q_u - q_n(1 + 3\delta) - q_r(\delta_r + \delta)$

and $p_r(q_n, q_u, q_r) = \delta_r(1 - q_r) + \delta q_u - q_n(\delta + \delta_r)$.

#### *2.6.1.1 No EPR.*

We begin by focusing on the setting without EPR by assuming $\alpha = 0$. Similar to our main analysis, the producer will have no incentive to recover end-of-life products in the absence of EPR. The producer's problem is then given by $\max_{q_n,q_u,q_r}(p_n(q_n, q_u, q_r) - c)q_n - p_u(q_n, q_u, q_r)q_u + (p_r(q_n, q_u, q_r) - c_r)q_r$ such that $0 \leq q_r \leq q_u \leq q_n$.

**Lemma 2** *In the absence of EPR, the producer undertakes refurbishing of recovered used products ($q_r > 0$) if and only if $c_r < r_1(c, \delta_r, \delta)$. Otherwise, the producer does not refurbish ($q_r = 0$) and still interferes with the secondary market ($q_u > 0$) if $\delta < 1-2c$.*

Lemma 2 shows that if the refurbishing cost is low ($c_r < r_1(\cdot)$), the producer will find refurbishing profitable, which requires the producer to recover used products by interfering with the secondary market. Note that if the refurbishing cost is high ($c_r \geq r_1(\cdot)$), then the producer does not refurbish and the results are identical to those in Lemma 1.

**Lemma 3** *When $c_r < r_1(\cdot)$, there exists a threshold $r_2(c, \delta_r, \delta)$ such that when $\delta < 1 - 2c$ and $c_r > r_2(\cdot)$, the producer does not refurbish all recovered used products, i.e., $q_u > q_r$. Otherwise, the producer refurbishes all recovered used products ($q_u = q_r$).*

When refurbishing is profitable, the producer may recover used products that it does not intend to refurbish, i.e., $q_u > q_r$. In other words, the producer recovers some of the used products simply to interfere with the secondary market. This happens for products with low durability ($\delta < 1 - 2c$) when the refurbishing cost is sufficiently high ($c_r > r_2(\cdot)$).

#### *2.6.1.2 Refurbishing under EPR.*

In the presence of EPR, when the producer recovers $q_u$ used products and refurbishes $q_r$ to sell back to consumers, only $q_u - q_r$ used products are available for recycling to meet the EPR obligations (in addition to end-of-life products). Therefore, the producer's problem is given by the following steady-state formulation:

$$\max_{q_n,q_u,q_{eol},q_r} (p_n(q_n,q_u,q_r)-c)q_n - p_u(q_n,q_u,q_r)q_u + (p_r(q_n,q_u,q_r)-c_r)q_r - kq_{eol} - s\alpha q_n$$

such that $q_{eol} \leq q_n - (q_u - q_r), \alpha q_n \leq (q_u - q_r) + q_{eol}, q_r \leq q_u \leq q_n, q_n, q_u, q_{eol}, q_r \geq 0.$

In this setting, the quantity of end-of-life products that the producer can recover is larger due to refurbishing, $q_{eol} \leq q_n - q_u + q_r$. However, the quantity of used products that can be recycled to meet the collection target is lower, $\alpha q_n \leq (q_u - q_r) + q_{eol}$.[6] Finally, the quantity of products that can be refurbished is constrained by the quantity of used products recovered by the producer ($q_r \leq q_n$) and the quantity of used products that can be recovered by the producer is constrained by the quantity of new products sold ($q_u \leq q_n$).

**Lemma 4** *In the presence of EPR, the producer undertakes refurbishing ($q_r > 0$) if and only if $c_r < r_3(c, \delta_r, \delta, k, s, \alpha)$.*

As in the absence of EPR, the producer undertakes refurbishing of recovered used products only if the refurbishing cost is sufficiently low. An important implication of this result is that when $c_r \geq r_3(\cdot)$, then it is optimal for the producer to not refurbish, and all our results from the main analysis (Lemma 1, Propositions 1-7) hold exactly. For the rest of this analysis, we focus on $c_r < \min(r_1(\cdot), r_3(\cdot))$ to analyze the case where the producer undertakes refurbishing.

Recall that in our main analysis without refurbishing, greater secondary market interference due to EPR implied a larger quantity of used products recycled to meet EPR obligations. However, with refurbishing, the producer may have two different reasons to interfere with the secondary market, which have contrasting effects on the

[6] Note that this formulation assumes that refurbishing does not count towards collection and recycling obligations under EPR, as in the majority of EPR implementations in the US [43]. It can be shown that the results presented in this section will be moderated but continue to structurally hold if refurbishing counts towards recycling obligations.

reuse level. First, the producer may recover used products for refurbishing, which maintains the reuse level as these products are sold back to consumers. Second, it may recover used products for recycling to meet EPR obligations, which reduces the number of used products available to consumers and effectively reduces the reuse level. Hence, the reduction in the reuse level is now measured only by the level of secondary market interference for recycling, i.e., the quantity of used products recovered and recycled. Accordingly, for the rest of this discussion, to understand the effect of EPR in a context with refurbishing, we focus on the producer's *secondary market interference for recycling*, measured by $q_u - q_r$.

We next investigate how EPR influences secondary market interference for recycling in the presence of refurbishing. We begin by focusing on the setting with $\delta \geq 1-2c$, where the producer refurbishes all recovered used products in the absence of EPR (see Lemma 3). We analyze whether EPR induces secondary market interference for recycling.

**Proposition 8** *Let $\delta \geq 1 - 2c$. If $k \geq \delta_r - c_r$, EPR leads the producer to interfere with the secondary market for recycling (i.e., $q_u - q_r > 0$) and only used products are recycled to meet the EPR obligations (i.e., $q_{eol} = 0$).*

The above result shows that the producer recovers used products for recycling to meet EPR obligations if refurbishing is not very attractive (i.e., $\delta_r - c_r < k$, implying that the maximum additional benefit from refurbishing a used product is smaller than $k$). Otherwise, the producer will find it profitable to refurbish more of the recovered products, requiring recycling end-of-life products to meet the target. Note that the result in the above proposition is structurally similar to that in the no refurbishing case (see Proposition 1), except that it requires a more restrictive condition $k > \delta_r - c_r$ (as $\delta_r - c_r > \delta$). That is, when the collection cost for end-of-life products is high, recovering used products for recycling to meet EPR obligations is less attractive in the presence of refurbishing.

**Proposition 9** *Let* $\delta \geq 1 - 2c$ *and* $k < \delta_r - c_r$. *There exists thresholds* $s_1^r(\delta, \alpha, c, k, c_r) \leq s_2^r(\delta, \alpha, c, k, c_r)$ *such that the producer utilizes a Used Product Recycling strategy for* $s \leq s_1^r(\delta_r, \delta, \alpha, c, k, c_r)$, *a Mixed Recycling strategy for* $s_1^r(\delta_r, \delta, \alpha, c, k, c_r) < s < s_2^r(\delta_r, \delta, \alpha, c, k, c_r)$, *and End-of-life Recycling strategy otherwise. The thresholds* $s_1^r(\cdot)$ *and* $s_2^r(\cdot)$ *are increasing in* $c_r$.

The above result shows that the producer's recycling strategy is similar to that obtained in our main analysis (see Proposition 2). That is, the producer recycles recovered used products to meet EPR obligations even with refurbishing. As the thresholds are increasing in $c_r$, we have that when refurbishing is more attractive (i.e., low $c_r$), the producer will recycle fewer used products for EPR compliance. Overall, Propositions 8-9 show that EPR induces secondary market interference for recycling for high durability products, i.e., the results are aligned with those from our main model.

We next focus on the setting with $\delta < 1-2c$, where the producer may not refurbish all recovered used products in the absence of EPR (see Lemma 3). In this case, it can be shown that the producer's recycling strategy to meet EPR when it refurbishes is almost identical to that identified in Proposition 9. The only difference is that when $\delta < 1 - 2c$, the producer may recycle more used products than the volume required to meet EPR obligations if $s < s_0^r(\delta_r, \delta, \alpha, c, c_r)$, where $s_0^r(\cdot) < s_1^r(\cdot)$. This, however, does not change the structure of the producer's EPR compliance strategy: the producer recycles used products to meet EPR obligations for $s < s_1^r(\cdot)$, both used and end-of-life products for $s_1^r(\cdot) \leq s \leq s_2^r(\cdot)$, and only end-of-life products otherwise. In order to investigate whether EPR leads to greater secondary market interference for recycling when the producer refurbishes, we compare $q_u - q_r$ in the absence and presence of EPR. Let $\widehat{\alpha}^r(c, \delta_r, c_r) \doteq \frac{q_u - q_r}{q_n}$, which denotes the fraction of used products recovered but not refurbished in the absence of EPR.

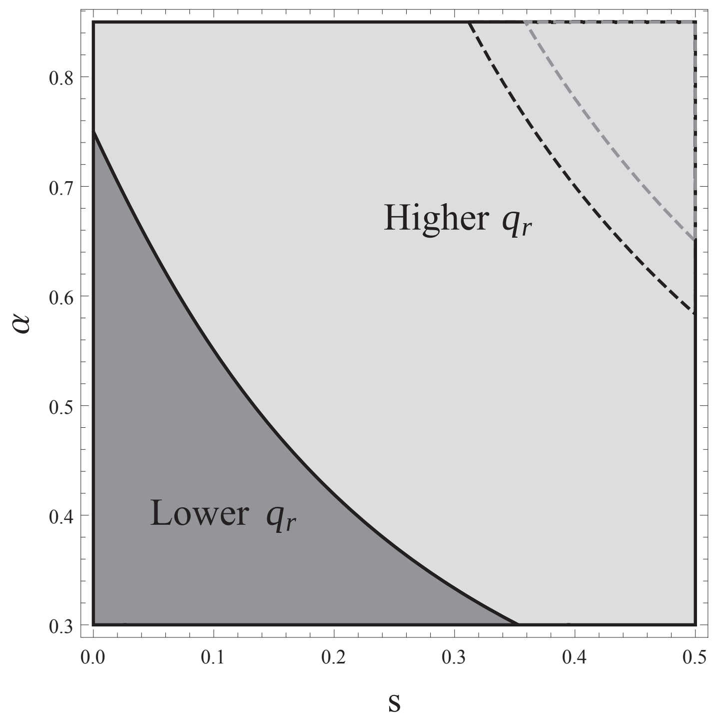
**Proposition 10** *Let $\delta < 1 - 2c$. EPR increases secondary market interference for recycling if $\alpha > \widehat{\alpha}^r(\cdot)$ and $s < \widehat{s}^r(\delta, \alpha, c, k, c_r)$, where $\widehat{s}^r(\delta, \alpha, c, k, c_r) < s_2^r(\cdot)$. Otherwise, EPR reduces interference.*

Proposition 10 shows that EPR may increase the volume of used products recovered and recycled for EPR compliance even when a producer refurbishes. Note that the above result identifies similar conditions for increased interference as in our main model without refurbishing as summarized in Proposition 3. In particular, EPR increases secondary market interference when the collection target set by EPR is high and the recycling standard is low. As such, our conclusion in §4 that EPR may lead to greater new production and lower reuse continues to hold in the context of refurbishing.

We next investigate whether our insights from §2.5 regarding the effect of EPR parameters on the level of production, reuse and recycling also hold under refurbishing. In the presence of refurbishing, the reuse level is given by $r_u = \frac{q_n - q_u + q_r}{q_n}$. We find that our results in Propositions 5-7 hold in the presence of refurbishing (see proofs of Propositions 8-10 for details): A more stringent recycling standard leads to a higher reuse level and lower new production. A more stringent collection infrastructure requirement may lead to a higher new production and a lower level of reuse. Finally, under the Used Product Recycling strategy, a higher collection target leads to a lower reuse level, and it may also lead to a higher level of new production.

A natural follow-up question is how EPR affects the refurbishing level for durable goods. We find that there are two contrasting effects that determine the answer to this question: On one hand, refurbishing may become less attractive under EPR because the producer may recycle used products to meet its EPR obligations. On the other hand, EPR increases the effective production cost faced by the firm (due to the recycling and collection costs), making reusing products through refurbishing more attractive. Overall, we find that EPR may increase or decrease the refurbishing

**Figure 5:** Effect of EPR on refurbishing level $q_r$.




*Note:* In the above figure, $\delta = 0.5$, $\delta_r = 0.6$, $c = 0.1$, $k = 0.1$ and $c_r = 0.05$. EPR leads to a higher refurbishing level in the light gray region and a (weakly) lower refurbishing level in the gray region. The producer utilizes a Used Product Recycling strategy below the black dashed line, a Mixed Recycling strategy between the dashed lines, and an End-of-life Recycling strategy above the gray dashed line.

level. This can be observed by the numerical example illustrated in Figure 5. When the collection target and the recycling costs are both low (the dark grey area in the figure), refurbishing is not as attractive and the producer utilizes a Used Product Recycling strategy. Under this setting, EPR reduces the refurbishing level as the producer has to divert recovered products from refurbishing to recycling. However, when either the collection target or the recycling cost are high (the light grey area in the figure), the effective cost faced by the firm is higher, making refurbishing more attractive under EPR.

### 2.6.2 Limited Access to Used and End-of-life Products.

We made an implicit assumption in our main analysis that the producer can access all used and end-of-life products in the market. However, in practice, some consumers may simply hold onto their used or end-of-life products even though they have purchased a new or a used product. Therefore, the producer may not have access to the entire supply of used and end-of-life products in the market. We can consider this case by making the following modification to our model: Let $\gamma \in (0, 1]$ denote the fraction of consumers who do not hold onto a used (end-of-life) product when they purchase a new (used) product, i.e., $\gamma$ denotes the recovery yield for used and end-of-life products.

Generalizing our model for $\gamma < 1$ has two important effects (see §A8 in the Appendix A for details): First, the supply of used products on the secondary market is now lower, resulting in a higher price for used products ($p_u$). Second, the quantity of used and end-of-life products that the producer can recover is lower, i.e., $q_u \leq \gamma q_n$ and $q_{eol} \leq \gamma(\gamma q_n - q_u)$. Accordingly, when some consumers hold onto their used or end-of-life products, it becomes more difficult for the producer to meet the collection target. Also note that the reduction in the supply of end-of-life products is much larger than that for the used products. In addition, it can be seen from the constraints on the supply of used and end-of-life products that if the collection target is higher than the recovery yield, i.e., $\alpha \geq \gamma$, the producer will not be able to meet the target. Therefore, we assume $\alpha < \gamma$ hereafter.

We begin by focusing on the situation where $\alpha < \gamma^2$, i.e., the collection target is low. Under this setting, we find that our structural results in Lemma 1 and Propositions 1-7 remain unchanged (see Appendix A §A8 for details). Qualitatively, a lower recovery yield makes recovering used products more costly, making it less attractive for the firm to utilize them to meet EPR obligations. However, EPR may still increase secondary market interference. We next consider the situation where

$\alpha \geq \gamma^2$, i.e., the collection target is high. Under this setting, again our structural results in Lemma 1, Propositions 1, 3-5 and 7 remain unchanged (see Appendix A §A8 for details). However, Proposition 2 changes in the following manner: The producer always utilizes a Used Product or Mixed Recycling strategy (i.e., $q_u > 0$). This is because the supply of end-of-life products ($\gamma(\gamma q_n - q_u) < \gamma^2$) is not sufficient to meet the collection target, requiring utilizing used products to meet the target. Therefore, the producer never utilizes the End-of-Life Recycling strategy. This implies that under this setting, a lower recovery yield may necessitate secondary market interference by the producer to meet EPR obligations.

### 2.6.3 EPR Implementations with Recycling Fees.

Our main model assumes that the producer can independently determine how it fulfills EPR obligations. While this is allowed under most EPR implementations (e.g., in Wisconsin, Minnesota and European Member States after the WEEE Directive Recast), some implementations may limit the producer's EPR compliance role. This may be the case especially when a state authority (which is often a not-for profit entity) manages or operates the recycling system (i.e., collecting and recycling end-of-life products through an existing state infrastructure) and charges producers (or consumers) a unit recycling fee.

For example, consider the two well-known models of state-operated systems in California [116] and Washington State [65]. In California, the state-level electronics recycling system is based on an Advance Recovery Fee (ARF) model [29], where consumers pay the ARF at the moment of purchase. A set of registered consolidators then manage the collection and recycling of electronics, the costs of which are covered by the funds generated by the ARF. In Washington state, a state-authority (WMMFA) manages the collection and recycling of electronics on behalf of the producers participating in the state's standard EPR plan. WMMFA coordinates a system of registered collectors and recyclers and funds the system by charging the participating producers a unit fee for the recycling of the products they are responsible for. It is nevertheless important to note that while a producer may not manage its own recycling operations in these EPR compliance systems, it may still contribute to these state systems as a collector. For example, Apple is a registered collector in California [30]. In this case, the producer can divert used products recovered from the secondary market to the organization in charge of the system and get paid as a collector.

To analyze the implications of such EPR implementations, we modify our model as follows: The not-for-profit authority incurs collection and recycling costs and passes them to the producer or consumers in the form of a per-unit recycling fee $\sigma$. Let the collection fee paid to the producer for bringing in recovered used products to the EPR system be denoted by $\kappa$. The producer's problem is then given by the following[7]:

$$\max_{0 \leq q_u \leq q_n} \Pi(q_n, q_u) = (p_n(q_n, q_u) - c)q_n - (p_u(q_n, q_u) - \kappa)q_u - \sigma q_n.$$

The producer's problem in this setting is structurally similar to the producer's problem in our main analysis with $\kappa \equiv k$ and $\sigma \equiv \alpha(k + s)$ (see Appendix A §A9 for details). Therefore, while the interpretation of these EPR-related parameters are different than our main analysis, the qualitative insights regarding the effect of EPR remains unchanged: EPR may increase secondary market interference (similar to the results in Propositions 2-3). Increasing the unit fee charged to the producer ($\sigma$) may help achieve greater reuse and lower production (similar to the effect of $s$ in Proposition 5). A higher collection fee ($\kappa$) paid to the producer may lead to higher level of new production and lower reuse (similar to the effect of $k$ in Proposition 6).

[7]Note that this formulation assumes that the unit fee is charged to the producer. It can be shown that an ARF charged to the consumer affects the producer the same way (see Appendix A §A10; also see [116]).

## 2.7 Conclusion

In this essay, we analyze the effect of EPR on the markets for durable goods. We find that a producer's response to EPR may involve secondary market interference and this involvement depends on product durability. For products with high durability, the producer does not interfere with the secondary market in the absence of EPR. However, EPR may directly induce such interference, leading to premature recycling of used products with remaining useful lives to meet the obligations. We find that this unintended effect will occur when: (i) recycling standards do not lead to sufficiently high recycling costs, (ii) collection infrastructure requirements significantly inflate collection costs for end-of-life products, and (iii) stringent collection targets are imposed on producers. For products with low durability, the producer may readily interfere with the secondary market even in the absence of EPR and the effect of EPR differs substantially for such products. In this case, EPR with high (low) collection targets and low (high) recycling stringency increases (reduces) the producer's secondary market interference. In turn, these results suggest that such increased secondary market interference may be attenuated by increased recycling standards and non-stringent collection targets.

Collectively, these results suggest that EPR implementations for durable goods may require different approaches because of the inherent interactions between producers' recovery strategies and secondary markets. Implementation approaches that may be considered successful for non-durables, i.e., for packaging or end-of-life batteries, may backfire for certain durable goods such as electronics. Along these lines, our results imply that recent calls in the U.S. for a unifying model of EPR that applies across several different waste categories [106, 77], may need to be cautiously evaluated, should they target durable goods.

# CHAPTER III

# A MARKET-BASED EXTENDED PRODUCER RESPONSIBILITY IMPLEMENTATION - THE CASE OF MINNESOTA ELECTRONICS RECYCLING ACT

## 3.1 Introduction

Extended Producer Responsibility (EPR) employs a market-based approach to waste management if it provides producers implementation flexibility in organizing their compliance efforts in a competitive market. EPR in this form is favored because it promotes cost efficiency [83, 28]. A market-based approach can be expected to better manage the tension between landfill diversion and economic objectives in a regulated system by setting desirable targets for collection, and then providing operational flexibility to manufacturers to achieve these targets. This perspective on EPR has been supported by industry and some NGOs. For instance, HP, a company with strong interest in forming and implementing e-waste policies, announced its support for market-based solutions [74]. Recycling Reinvented, a non-profit organization focusing on EPR implementation, indicates several projected benefits of a market-based approach such as improved efficiency, decreased cost, increased recovery rates and ultimately better environmental and economical outcomes [60]. These arguments follow from the assumption that allowing flexibility to the private sector enhances the effectiveness of operations relative to the case where government dictates specific operational choices for implementation and pursues a centralized coordination approach such as the Washington State implementation [65].

In this article, we consider the Minnesota Electronics Recycling Act [101] as an example of a market-based EPR implementation and use it as a benchmark to explore efficiency conditions for market-based EPR implementations. To do so, we use publicly available data/reports and stakeholder interviews we conducted in Minnesota, as well as information on the Washington E-Waste Recycling Law implementation, which we interpret as a representative example of a centralized coordination approach. We find that the Minnesota Act achieves a significantly higher collection rate than most other states in the U.S. and has high cost efficiency. This however appears to happen at the expense of other environmental or economic efficiency measures, which include selective collection and recycling, increased economic burden on local governments, and an uneven competitive landscape for certain stakeholders. We nevertheless posit that these unexpected drawbacks are not necessarily driven by the market-based approach itself. They are rather outcomes of certain operational flexibility provisions in implementation that aim to increase the efficiency of the working system. Accordingly, we suggest that the effectiveness of an EPR implementation; be it market-based or centrally coordinated, will depend significantly on the operational rules chosen for its implementation.

We begin our discussion by summarizing implementation details and outcomes of the Minnesota Electronics Recycling Act along with different stakeholder perspectives in §2. In §3, we provide a critical discussion of the Minnesota Act, and contrast it with Washington State Law. We conclude with a summary of insights in §4.

## 3.2 An Overview of the Minnesota Electronics Recycling Act

The Minnesota Electronics Recycling Act was enacted in 2007 to administer the increasing amounts of e-waste and the rising costs of its proper management in the state of Minnesota. This act imposes stringent obligations on brand-owners, hereafter referred to as manufacturers, in terms of collection and recycling targets, but does not intervene in operational decisions and price dynamics in the market (see Manufacturers in subsection below). The underlying motive is to allow manufacturers to create a collection and recycling infrastructure as economically as possible, i.e., to achieve high cost efficiency for collection and recycling. Such characteristics make the Minnesota Act a prevailing example of a market-based EPR implementation in practice. In this section, we present how the market-based approach was translated into operational rules determining its implementation in Minnesota (e.g., product scope, covered entities, assigned responsibilities, extent of operational flexibilities, etc.) along with resulting perspectives of stakeholders.

**Covered Products and Entities:** The act defines manufacturer obligations based on two product classifications: Video Display Devices (VDDs) and Covered Electronics Devices (CED). VDDs are televisions (including TV-DVD/VCR combinations, monitors for home security/CCTV systems, etc.) and computer monitors (including laptop computers, tablet PCs, eBook readers, digital picture frames, etc.) that contain a cathode-ray tube (CRT) or a flat-panel screen with a screen size diagonally greater than 9 inches, excluding refurbished or used products. CEDs are computers, peripherals (i.e., external input or output devices of computers such as keyboards and printers), facsimile machines, DVD players, and VCRs in addition to the VDDs [105]. Covered entities, i.e., entities that can utilize the collection and recycling system at no cost, are households in the state of Minnesota. More specifically, the Minnesota Act covers the CEDs marketed to households and excludes devices sold to schools, businesses and non-profit/charity organizations [49].

**Stakeholders:** In line with the EPR concept, the Minnesota Act places collection and recycling obligations on manufacturers. In order to ensure a transparent working system, the act also specifies obligations for other parties including collectors, recyclers, retailers, and local governments. These obligations clearly affect key operational decisions of the stakeholders, which in turn determine the economics of collection and recycling in the state. Therefore, a thorough understanding of the stakeholder obligations and perspectives is essential for a critical overview of the act.

**a) Manufacturers**

Obligations: The act mandates manufacturers of VDDs that market their products to households in Minnesota to annually register with the Minnesota Pollution Control Agency (MPCA) and to pay a registration fee to the Minnesota Department of Revenue based on their sales of VDDs in the previous year ($2500 for companies with sales of 100 or more in the previous program year, $1250 for companies with sales fewer than 100) (see the Oversight Entities subsection below for duties of the MPCA and Minnesota Department of Revenue). Additionally, the act requires manufacturers of VDDs to collect and recycle CEDs at a level at least equal to 80% of the weight of VDDs they sell in Minnesota in the concurrent program year. Note that the act uses only the market share of manufacturers to determine their obligations, i.e., the act does not take into account their return share, which utilizes information on the type and volume of returned devices sold by each manufacturer. This is to eliminate sampling and brand counting in the collection or recycling stages and the associated administrative cost. Note also that the act bases manufacturer obligations on their sales of VDDs, however, it counts CEDs, which include a much wider scope of products, towards compliance. The goal behind this differentiation is to target the manufacturers of VDDs, (as these products pose an imminent threat to the environment due to CRT and leaded glasses contained within) while providing them with a broad scope of products with which they can fulfill their obligations. Within the scope of this flexibility, the act allows manufacturers to use any combination of the following four options: (i) Obtain pounds of Recycled CEDs: Manufacturers can directly undertake collection and recycling operations to obtain pounds of recycled CEDs. (ii) Buy pounds of Recycled CEDs: Manufacturers can contract with recyclers (see the Recyclers subsection below) to buy the pounds of recycled CEDs. Under both of these options, CEDs should be collected and recycled during the current program year in order to be eligible. (iii) Use Recycling Credits: Manufacturers can maintain recycled or purchased pounds that exceed recycling obligations of the program year as recycling credits. These credits can be used to meet at most 25% of the recycling obligations in the subsequent years or sold to other manufacturers. This can be interpreted as flexibility for manufacturers on the timing of the recycling. (iv) Pay Recycling Fees: If a manufacturer fails to or does not prefer to satisfy its collection and recycling obligations by using any of the options above, then it pays a recycling fee. This corresponds to a penalty fee charged per pound of the shortfall depending on the percentage of the shortfall ($0.3/lb if it is 10% or less, $0.4/lb if it is between 11% and 50%, $0.5/lb if it is 51% or more).

To ensure uniform collection (i.e., collection evenly from urban, suburban and rural locations), several EPR implementations for e-waste in the U.S. impose convenience standards, defined in terms of the minimum number of required locations by geography or by other similar measures (e.g., Washington, Oregon, Texas) [51]. Given this definition, the Minnesota Electronics Recycling Act does not introduce any convenience standard for CED collection. Instead, the act offers incentives for rural collection to encourage uniformity in collection by assigning additional recycling pounds to collection from areas where collection is expensive due to diseconomies of scale (e.g., low population or insufficient infrastructure). Accordingly, each pound of CEDs collected in Greater Minnesota, outside the 11-county metropolitan area surrounding the cities of Minneapolis and St. Paul, earns an additional 0.5 pound towards the producers obligation. To reflect the multiplier established for the weight of collected CEDs from the 11-county and the Greater Minnesota areas, we refer to this rule as the 1:1.5 ratio. In addition to the 1:1.5 ratio, to further boost collection from the Greater Minnesota area, the MPCA has formed a competitive grant program funded from recycling fees paid by manufacturers.

Another manufacturer obligation under the Minnesota Act is to submit annual reports to the Minnesota Department of Revenue including the total weight of VDDs sold to Minnesota households, the total weight of CEDs recycled from the 11-county and the Greater Minnesota areas, documentation of contracts with recyclers and collectors, total recycling weights from each recycler contracted, and transactions of recycling credits.

Perspectives: Our stakeholder interactions suggest that manufacturers in Minnesota are generally supportive of the components of the Minnesota Electronics Recycling Act. The majority of manufacturers consider the proper disposal of e-waste as an inevitable trend, hence they prefer to actively engage in the legislative process. In this way, they have the opportunity to cooperate with other stakeholders and increase their competence to shape the act towards their interest, i.e., to minimize any negative impact on their operations and profitability.

Manufacturers selling their VDDs in Minnesota appear to enjoy the market-based approach and its flexibility provision, which is reflected by the high volume of collection and recycling credits in the state. More specifically, manufacturers of the VDDs recycle beyond their obligations and hold an abundant amount of recycling credits in every program year: The total recycling obligation is almost half (54%) of the total pounds recycled, therefore the number of accumulated recycling credits held has increased significantly (22.7 million pounds in 2009, 33.2 million pounds in 2010, and 43.4 million pounds in 2011)[1].

The total credits available are approximately equivalent to requirements of all manufacturers for two years. Despite the abundance of recycling credits, statistics indicate that manufacturers of the VDDs generally rely on purchasing eligible pounds of recycled CEDs (approximately 90% of the total pounds) to comply with their obligation, while using fewer credits (around 8%) than the legislative limit (25%), and rarely paying recycling fees (1-3% of the total pounds on the average) as a penalty

[1]MPCA 2011a, op. cit., p.12

for the short-fall[2].

On the other hand, manufacturers of VDDs express some concerns regarding the assignment of obligations based on market share. First, the time lag between production and recycling of products causes manufacturers in the current market to recycle devices produced by other manufacturers a long time ago. Second, manufacturers of electronics such as TVs and monitors that have low market share but high return share have an advantage over other manufacturers.

An analysis of sales by manufacturers demonstrates that although the number of VDDs sold increased, the overall weight has dropped for the second consecutive year in 2011 (31.2 million in 2009, 29.2 million in 2010, 26.9 million in 2011)[3]. As the majority of e-waste legislation in the U.S. (including the Minnesota Act) determines the recycling obligations of manufacturers based on the weight of their sales, manufacturers have the incentive to design lighter products to decrease their obligations, in addition to other factors such as minimizing material costs or exploiting new opportunities for miniaturization.

**b) Collectors**

Obligations: Collectors in the Minnesota Act refer to private (e.g., retailers, independent collectors) or public entities (e.g., local governments) that receive the CEDs from households and deliver them to recyclers (see also the Retailer and Local Governments subsections). The act requires collectors to annually register with the MPCA (at no cost) and to submit annual reports at the end of each program year on collection sources, amounts and names of the recyclers they contracted with.

Perspectives: The act does not set any registration fee or permanent location requirement on collectors, resulting in low start-up costs for collection businesses. Consequently, many private entities have entered the market to undertake collection

[2] MPCA 2011a, op. cit., p.11-12
[3] ibid., p.4

operations. An evaluation report of the MPCA illustrates an increase in the number of registered collectors (207 in 2010, 229 in 2011, 204 in 2012)[4] with a growing presence of retailers. This translated to a high collection rate per capita (6.5 pounds in 2010, 6.2 pounds in 2011, 6.6 pounds in 2012)[5].

Our discussions with Minnesota stakeholders suggest that the competition between collectors has increased together with the number of collectors and the volume of collection, leading to a low margin and a high volatility for collection businesses, especially for independent collectors. The majority of collectors in the state stay in the market for approximately 3 years and this appears to limit the negotiation power of collectors in their contracts with manufacturers, which potentially further decreases their margins.

An analysis of current collection options in Minnesota demonstrates that permanent locations take up about 75% of the total collection amount, while curbside (4%), collection events (12%) and pick-up services (8%) complete the rest[6]. A similar analysis in terms of collection areas highlights that the total weight of collection from the 11-country area is twice that of the collection from the Greater Minnesota Area (22.2 vs. 11.1 million pounds in 2011), which has stayed nearly same throughout all the program years for which data is available[7]. Although the ratio of pounds between these areas reflects the respective population ratio, collection entities in these areas differ significantly: Local governments offer nearly half of the collection services in the Greater Minnesota Area, whereas independent collectors, i.e., profit-oriented collectors, concentrate their collection efforts in urban areas (e.g., densely populated areas with a developed collection infrastructure) such as the 11-county metropolitan area (See Table 2). Discussions with stakeholders in the state indicate that this

[4]MPCA 2011a, p. 4.
[5]ERCC 2014c, op. cit.
[6]MPCA 2011a, op.cit., p. 2-3.
[7]ibid.

is particularly because the act does not assign any additional pounds to collectors (unlike the case for manufacturers) for the CEDs they obtain from the Greater Minnesota area. This puts independent collectors in the Greater Minnesota at a significant disadvantage (the effective payment they get for their collection is lower). Despite being subject to the same disadvantage, local governments in the area provide collection services to residents as part of their public service role (see the Local Governments subsection for further details).

**c) Recyclers**

Obligations: Recyclers covered by the Minnesota Act include private or public entities that receive CEDs from registered collectors, or directly provide collection services to households and dismantle collected CEDs for further processing. The act mandates recyclers to annually register (at no cost) and to file an annual report with the MPCA to disclose information on weights of CEDs bought from each collector or collected from households, and sold to manufacturers. The act further requires them to specify pounds from the 11-county and the Greater Minnesota area separately. Under the act, recyclers are the boundary of the collection and recycling system, because the act considers the CEDs as recycled upon their arrival to the recycling facilities. This role brings additional legislative requirements to registered recyclers such as having a permanent site for recycling operations, obtaining a (free) license from the county or state to establish their compliance with hazardous waste processing requirements, and having a certain level of insurance coverage (e.g., having $1 million liability insurance).

Perspectives: As in the case of the collection market, the enactment of the act and the large volume of e-waste attracted entry into the recycling market in Minnesota, reflected by a growth in the number of registered recyclers (59 in 2010, 77 in 2011) and some increase in the weight of the CEDs recycled (34.7 million pounds in 2010, 33 million pounds in 2011, 35.1 pounds in 2012). This increased the competition in the recycling industry while potentially decreasing the contractual power of recyclers vis-a-vis manufacturers. Moreover, the larger e-waste volume attracted higher-end recyclers who now dominate the market. Anecdotally, one leading recycling company in Minnesota expanded its capacity fourfold, while one third of the companies (mostly smaller mom and pop operations) that once existed went out of business shortly after the enactment of the act. Furthermore, in 2011, the top ten recyclers owned 95% of the total recycled pounds, and the top three recyclers processed 72% of the total pounds[8]. Therefore, the recycling industry in Minnesota can be considered to be highly concentrated.

From the perspective of the recycling industry as a whole, involvement with the act has brought a stable collection volume and a wide product mix. However, due to intense competition and the volatility in commodity markets for recycled materials, it remains a challenging business environment, creating the incentive to export the collected e-waste to developing countries to maintain low cost levels. This does not appear to be a major issue in Minnesota. Two recycling facilities in Minnesota are certified with the e-Stewards program established by the Basel Action Network and four are qualified for Responsible Recycling (R2), which is a standard released by the Environmental Protection Agency (EPA) [76].

**d) Retailers**

Obligations: Retailers in the Minnesota Act refer to retail stores as well as catalog and online sellers of VDDs, but exclude third party resellers, businesses, or institutional sales. The act requires retailers to ensure that they sell only products of registered manufacturers and provide consumers with information of where and how the CEDs are collected for recycling. In addition, the act allows retailers to participate in collection on a voluntary basis, in which case they are subject to collector obligations.

[8] MPCA 2011a, op.cit., p. 9.

**Table 1:** Program year comparison of Minnesota Electronics Recycling Act.

| **Year** | **2008** | **2009** | **2010** | **2011** |
|---|---|---|---|---|
| **VDD Sales** | 25.6M | 31.2M | 29.2M | 26.9M |
| **Manufacturer Obligations** | 15.3M | 25M | 23.4M | 21.5M |
| **Recycled Amount** | 33.6 | 30.3M | 34.7M | 33M |
| **Accumulated Recycling Credits** | 17.6M | 5.1M | 10.5M | 10.2M |
| **Registered Collectors** | 177 | 181 | 207 | 229 |
| **Registered Recyclers** | 55 | 52 | 59 | 77 |
| **Collection Rate per Capita** | 6.5 | 5.7 | 6.5 | 6.2 |

*Note:* See [104].

Perspectives: Retailers appear to evaluate the Minnesota Act very favorably as suggested by their broad participation in collection activities. In particular, retailers including Best Buy, Staples and Radio Shack collect approximately 20% of the volume, significantly contributing to the collection infrastructure in the state [75]. This is presumably because the requirements coming along with the act fit the business models of retailers well. In particular, offering take-back programs (where they offer gift cards for some product returns) allow them collect items that have recycling volume and simultaneously help retailers improve their consumer relations, increase shopping occasions and improved their brand image (e.g., Best Buy E-Cycle) [102, 27]. As retailers are politically very powerful in the state of Minnesota, it is a common stakeholder expectation that their involvement as collectors will continue to contribute to achieving high collection volumes.

**e) Local Governments**

Obligations: The act requires local governments that participate in collection activities of the CEDs (e.g., provide curbside collection and pick-ups, set up permanent collection points, and organize collection events for households) to comply with collector obligations (See Collectors section above).

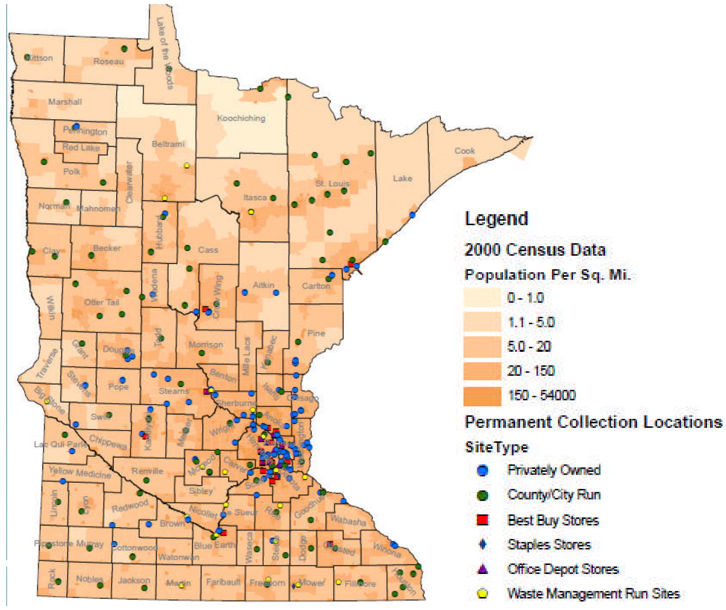
Perspectives: A key observation from our discussions with Minnesotan stakeholders is that local governments in a collector role appear to shoulder more of the cost compared to independent collectors. The data on collection illustrates that local governments provide the majority of collection opportunities in the Greater Minnesota Area, where the collection cost is high and variable [127], and local governments collect a large portion of the products that are difficult and expensive to handle in the 11-Country Area. This suggests that local governments undertake collection services even when collection is very costly so as to ensure the proper management of e-waste. As a result, they may end up with a net cost burden. For example, in the 11-county area, local governments cover approximately 50% of their collection costs via contracting with recyclers, while they fund less than 20% by subsidies, leaving them with a 30% of shortfall. In the Greater Minnesota Area, local governments cannot recover costs from recyclers (e.g., the percentage is approximately zero for Becker, Crow Wing and St. Louis)[9]. They (partially) handle these challenges by utilizing free recycling pounds offered by recyclers at the beginning of each program year. The growing e-waste volume under the Minnesota Act further increases the gap in the economies of collection between local governments and other collectors, who have the flexibility of offering collection services only in profitable locations and to be more selective in the type of products they accept. In sum, part of the systems cost is subsidized by local governments and inherently, the Minnesotan taxpayers.

**f) Oversight Entities**

The Minnesota Pollution Control Agency (MPCA) and the Minnesota Department of Revenue hold oversight duties for the implementation of the Minnesota Act. Based on the act, registration and recycling fees collected from manufacturers are used to cover costs associated with the duties of the MPCA and the Minnesota Department of Revenue.

[9] MPCA 2011a., op. cit., p. 4.

**Figure 6:** Permanent collection locations in Minnesota in 2010.




The main duties of the MPCA are (i) gathering and analyzing collection and recycling data from all the related stakeholders (e.g., reviewing reports submitted by collectors and recyclers on total weights of the CEDs collected and recycled, estimating sales of the VDDs to households during the preceding program year); (ii) publishing an annual report to the public to illustrate outcomes of the act and suggesting recommendations for possible future improvements; (iii) maintaining a website containing guidance and fact sheets about the act (e.g., a list of registered manufacturers of VDDs, collectors and recyclers of CEDs); (iv) managing an e-waste account that maintains the registration and recycling fees of manufacturers; (v) arranging meetings with different stakeholders to discuss and examine the current status of the act; (vi) organizing various outreach programs to educate the public about available collection and recycling programs[10].

The main duties of the Minnesota Department of Revenue are (i) compiling and

[10]Minnesota Legislature, op. cit., p. 8-10.

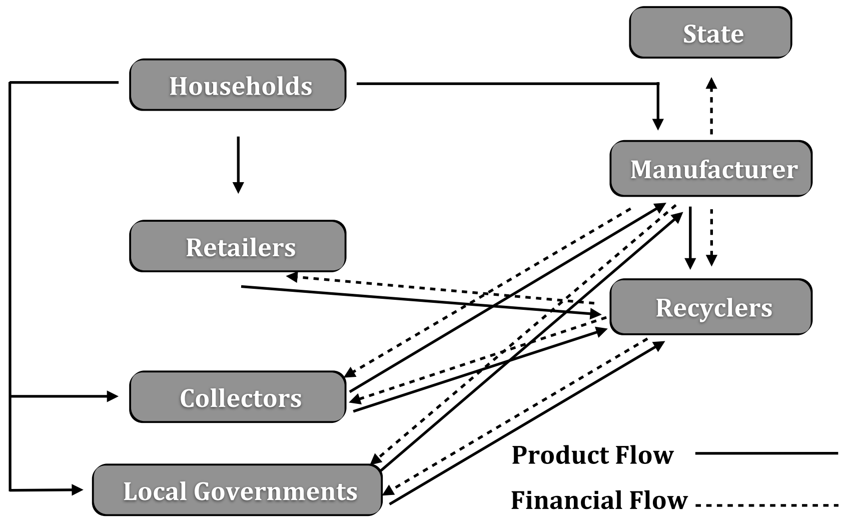
review-ing reports submitted by manufacturers on total weight of the VDDs sold to households; (ii) analyzing how manufacturers meet their recycling obligations and calculating recycling credits[11].

**Contracts between Stakeholders:** At the beginning of each program year, recyclers provide manufacturers with their price offers. Manufacturers then estimate their collection and recycling obligations, decide on how many pounds to buy from each recycler, and accordingly contract with recyclers. Based on forecasts in these contracts, recyclers form their collection plans (e.g., determine the number and location of collection sites) and/or contract with collectors. Recyclers periodically calculate the volume they have collected and/or purchased from collectors, and report to manufacturers on how many pounds are available. At the end of the year, if a recycler has obtained a volume exceeding the obligation of a manufacturer, the manufacturer can purchase the extra pounds from the recycler and bank them up as recycling credits. However, if the manufacturer has already fulfilled its obligations, the manufacturer has a strong bargaining position, so the contract will often be at a lower unit price. Conversely, when a recycler fails to provide enough volume, a manufacturer can purchase extra pounds from other manufacturers (i.e., purchase recycling credits of other manufacturers) or from other recyclers, usually at a higher price, or use his banked-up recycling credits. Since this will reflect poorly on that recycler, recyclers make efforts to be above the contracted volume and sometimes offer to take recycling pounds for free from collectors to shore up their volumes.

**Product Flow:** The product flow under the Minnesota Act starts from households discarding their CEDs. For such households, several options are available: (i) collection programs established by manufacturers, which allow consumers to drop off the CEDs in a store or to mail the CEDs back; (ii) collection services offered by retailers, which in turn can offer discounts or gift cards for future purchases, such as

[11]Minnesota Legislature, op. cit., p. 10.

**Figure 7:** Product and financial flow under the Minnesota Electronics Recycling Act.




Best Buy, Office Depot, and Staples [104]; and (iii) collection opportunities provided by other registered collectors such as independent collectors or local governments (e.g., permanent collection sites, curbside collection, direct pick-up services, or collection events). The attractive offers by retailers for some high value items allow them to do some amount of cherry picking, with local governments shouldering more of the cost burden. The CEDs collected through one of these options are then passed to registered recyclers, where they are considered as recycled upon their arrival. Usually, at recycler facilities, the CEDs are first dismantled or shredded into smaller parts, and then sorted based on their characteristics. Valuable components and materials such as circuit boards and metal parts are sold to brokers and smelters, and the remaining materials are delivered to special recyclers for further recycling or landfilling.

**Financial Flow:** CED collection from households usually occurs at no charge with some exceptions. The exceptions include the cases where collectors charge a per item fee for products that exceed a certain size or need a home pick-up service, and manufacturers/retailers offer gift cards or discounts toward new purchases for the return of certain CEDs. Collectors, retailers, and manufacturers sell the collected CEDs to recyclers, and recyclers charge manufacturers per recycled pound based on the contractual agreement they have. From CED processing, depending on product type and vintage, recyclers can either obtain a net profit by selling valuable materials as commodities or incur a net cost due to paying other recyclers or smelters for further treatment or landfilling. The cost of monitoring and inspecting these operations is the responsibility of over-sight entities, and is covered by annual registration fees of manufacturers. As authorized by the act, all stakeholders are responsible for their own profits and losses except local governments that are funded by environmental taxes or sponsored by private businesses.

## *3.3 An Implementation Perspective on the Minnesota Act*

In this section, we analyze the Minnesota Act from an implementation perspective and provide a discussion with respect to its effectiveness in terms of cost efficiency, incentives for environmentally benign design, collection infrastructure choices, economic burden imposed on local governments, and the resulting competitive landscape. We also contrast it with the Washington E-Waste Law implementation, which adopts a central coordination approach, to assess the relative effectiveness of what we refer to as the market-based approach used in Minnesota. We then provide a discussion regarding the design and implementation of effective market-based EPR[12].

We start with a brief overview of our benchmark: the Washington Law (see [65] for a detailed overview). The Washington State implementation defines covered products as TVs, monitors and computers that have screen size of 4 inch and more (excluding peripherals). It covers collection and recycling from covered entities such as households, small businesses, charities/non-profit organizations, schools and

[12] MPCA 2011a, op. cit., p. 5.

governmental entities. It requires at least one collection site in every county and every city with population more than 10,000. The Washington implementation utilizes a centralized coordinating body called the Washington Materials Management and Financing Authority, which operates the standard plan, the default plan any manufacturer can sign up with (Manufacturers are also allowed to develop independent plans that meet the same criteria as the standard plan, but none have emerged to date). No manufacturer-to-recycler or recycler-to collector contracts exist in Washington; it is the WMMFA that contracts with collectors, transporters and recyclers, determines (in real time) to which recycler to send the e-waste from each collection site and with which transporter, and pays these service providers based on the contracted per pound prices. Every quarter, the WMMFA then apportions the total operational and administrative cost to manufacturers based on a cost allocation method that is a function of return share and market share [65].

The key differences between the Washington and Minnesota implementations are with respect to their coverage, manufacturer obligations, convenience standards, the financing of collection and recycling, and the form of competitive marketplace they induce. In terms of coverage, the Minnesota implementation focuses on TVs, monitors and computers (9 inch) from only households, while the Washington implementation focuses on TVs, monitors and computers (4 inch) from households, small businesses and organizations. In terms of manufacturer obligations, the Minnesota implementation imposes producer operational responsibility and requires manufacturers to collect and recycle 80% of their sales volumes in the previous year. In contrast, the Washington implementation has producers participate in the state level standard plan, and re-quires processing of all returns available in the state for collection and recycling. With respect to convenience standards, the Minnesota implementation has none; it only provides a rural collection incentive using the 1:1.5 ratio. In Washington, on the other hand, at least one collection point has to be set-up in every city and county with population above 10, 000. In terms of financing, the Minnesota implementation has producers directly contract with chosen recyclers, while the Washington state body WMMFA contracts with all service providers and allocates the corresponding realized costs to manufacturers based on a combination of market and return shares by weight. Finally, in terms of the competition in the market place, the Minnesota implementation appears to encourage competition, while the Washington implementation appears to favor local entities more to stimulate local business.

### 3.3.1 Key Observations:

*The Minnesota Act achieves one of the highest collection rates in the country:* The Minnesota and Washington programs have achieved the highest collection rates (defined as the weight of products recycled per capita) in the U.S. In the 2012-2013 and 2013-2014 program years, the collection rate was 6.01 lb and 6.52 lb per capita in Minnesota[13]. The associated numbers in Washington were 6.48 lb and 6.28 lb per capita[14]. For a more informative comparison, we note that the Washington Law covers desktop computers, laptops, monitors, TVs that are 4 inch or larger from households, small businesses, government entities, schools and nonprofit/charity organizations, whereas the Minnesota Act applies to the same product categories that are 9 inch or larger and only from households [50]. This suggests that were the Minnesota Act to have broader scope, the state would lead in collection volume. A high collection rate implies a lower impact on the environment, but for a comprehensive evaluation, we need to take a closer look at other dimensions such as the mix of products collected and recycled, incentives for environmentally benign designs, and characteristics of the resulting collection infrastructure as discussed below.

*Collection and recycling levels in Minnesota vary across product categories:* The

[13]ERCC 2014c, op.cit.
[14]ibid.

Minnesota Act defines manufacturer obligations based on the VDDs, but counts the CEDs, which include a wider range of products, towards meeting the obligations. That is, while the recycling obligations are in terms of TVs containing CRT, which potentially form the majority of e-waste in the state and are costly to recycle, manufacturers have the flexibility to use the recycling of personal computers or laptops, some of which generate recycling profits, to meet their obligations. Under this flexibility, manufacturers and recyclers prefer to obtain and process products with low recycling costs or products carrying high-value materials. Such selective recycling behavior naturally encourages selectivity in the collection market in the state as well. In particular, stakeholder interviews we conducted indicate that independent collectors and recyclers in Minnesota limit their collection of TVs with CRT and/or monitors brought by households. For example, some retailers accept monitors but not TVs thus imposing a limit on CRTs collected. Several recyclers are no longer accepting consumer-generated material in part due to the costs of managing CRTs. These observations suggest that collectors and recyclers handling products with high processing costs or low material value may need to be compensated to alleviate incentives for selectivity in collection and recycling; this is easier to accomplish in a centrally coordinated system such as the Washington program. Alternatively, the targets should be set more aggressively, or they could be set based on CED sales.

*Design changes of manufacturers tend to be towards lighter products with limited change in their toxicity and recyclability levels:* One of the main goals of EPR implementations is to encourage manufacturers to design environmentally benign products, i.e., products with less toxicity and high recyclability. However, the trend in the electronics industry appears to be designing smaller and lighter products [76] rather than less toxic or more recyclable products. In light of our stakeholder interviews, we saw two potential reasons that may explain this. First, both states base manufacturer obligations on weight, not toxicity or recyclability level. Hence, there is no mechanism that directly reflects the benefit of environmentally benign design improvements; the effect indirectly occurs through processing cost. Second, there exists no direct linkage between design improvements by manufacturers to their cost obligation because there is no brand separation in recycling operations in the state. That is, all covered products are recycled collectively in a mix, and an average per lb. recycling cost is charged to contracted manufacturers. Nevertheless, the market-based approach in Minnesota appears a step ahead from this perspective: A manufacturer with the capability to independently operate its own recycling infra-structure for its own products only is empowered to do so in this state and can thus find improved incentives for design.

*The Minnesota Act achieves cost efficiency:* Our interviews with Minnesota stakeholders indicate that the cost of handling e-waste (including collection, transportation, processing) can be as low as 8 cent per pound for some collector-retailer dyads. This number, should it be representative of the state-wide average cost, is significantly below the same reported in Washington at 24 cents per lb.

*The collection infrastructure emerging under the Minnesota Act is non-uniform in the state:* As one of the EPR implementations with a convenience standard, the Washington program requires at least one collection site in every county and in each population center with more than 10,000 residents. Additionally, the WMMFAs obligation to contract with all collectors induces it to pay higher collection prices to collectors in rural areas who do not benefit from scale economies. The convenience standard and the compensation structure in Washington guarantee some level of stability in revenue streams of collectors and recyclers, but also raise the average cost of handling e-waste. On the other hand, the Washington collection infrastructure reaches 90% of the population (estimate obtained through Census Data 2010), leading to a uniform collection infrastructure throughout the state.

The Minnesota Act does not set convenience standards; instead it provides credit for collection from rural areas in the form of extra recycling pounds for manufacturers (extra 0.5 pound for each pound collected). Despite these extra pounds, the resulting collection infrastructure in the state is not even: independent collectors concentrate their collection efforts in the 11-county area, whereas mainly local governments provide collection opportunities in the Greater Minnesota area. This presumably arises from how additional pounds are assigned to the stakeholders in the state. Only manufacturers are allowed to obtain additional recycling pounds, whereas recyclers or collectors do not get credit for collection from rural areas. In a competitive supply environment with an abundance of returns (relative to the target), this translates to lower profitability for collection from rural areas. The 1:1.5 ratio applied to manufacturers appears to not be sufficient to achieve uniform collection by independent retailers. In sum, geographical characteristics (e.g., transportation infrastructure, dispersion of settlements), market dynamics (e.g., competition level between the collectors, resulting collection cost), and incentives provided by the act (e.g., 1:1.5 ratio) determine the number and type of collectors and accordingly the availability of collection in Minnesota.

*Some local governments in Minnesota face a substantially high economic burden for VDD recycling:* One of the fundamental premises associated with the EPR concept is to decrease the financial and operational burden on local governments and translate it to manufacturers, as in the Washington implementation case. However, this may not necessarily be the case for local governments in Minnesota due to selective collection and recycling taking place in the state. As discussed above, independent collectors do not have sufficient incentives to offer collection services in the Greater Minnesota area. Accordingly, local governments in this area provide the largest portion of collection efforts. In a similar manner, some local governments in the urban areas, i.e., the 11-county area of Minnesota, receive large volumes of products that are difficult to handle or costly to recycle (e.g., TVs with CRTs, monitors), because independent collectors and recyclers may decline to accept these products. These local governments will continue to face growing volumes of products at their collection sites, which in turn brings them additional financial and operational responsibilities.

*The Minnesota Act provides incentives for recycling technology investments and creates some stimulation in the local economy:* Our stakeholder interviews in Minnesota indicate that the effect of recycling competition on recycling technology investments is highly favorable. Recyclers, given the high business volume in the state, have the incentive to adopt more efficient technologies to gain advantage against competitors and possible entrants to the market. On the economic development side, the act initially motivated entry into collection and recycling but then further growth in this market is expected to be limited, given the existing concentration level and low cost margins, unless significant scope expansion occurs. If more emphasis on stimulating the local economy is desired, incentives for manufacturers to contract locally could be created, paralleling the stipulation in Washington that the WMMFA give preference to processors operating in the state.

*Flexibility provisions in the Minnesotan implementation create a non-level playing field across different stakeholders:* Manufacturers can accrue recycling credits and benefit from the 1:1.5 ratio, but recyclers and collectors cannot. The first implies pressures to sell overstock pounds to manufacturers more cheaply and the second implies a lower effective margin for a portion of the collection volume, eroding the bargaining power of collectors and recyclers vis-a-vis manufacturers and creating cash flow challenges for these entities. These could - in the long run - prove detrimental to investments in more efficient technologies.

### 3.3.2 Towards Effective Market-Based EPR Implementation

In summary, the Minnesota Act implementation achieves a high collection rate and provides high cost efficiency. This nevertheless appears to happen at the expense of selective collection and recycling, an uneven competitive landscape, increased responsibility for local governments, and limited design incentives for manufacturers. These could be overcome in the following manner:

*Developing end-use markets for the recycling industry:* Material costs in commodity markets shape recycler operations and accordingly their product preferences. Hence, developing more robust markets for materials contained in the targeted electronic products (e.g., CRT, leaded glass, etc.,) would be valuable in providing sufficient incentives for recyclers to reduce selective recycling, i.e., recycling primarily products with low recycling cost or those containing high-value materials.

*Maintaining a better balance among the flexibilities provided to the stakeholders:* Following the tenets of the market-based approach, the Minnesota Act provides flexibilities to manufacturers in terms of the ability to directly contract with recyclers to fulfill their obligations, the scope of products that can be recycled, incentives to recycle products collected from rural areas, and the timing of their recycling (via recycling credits). In contrast, collectors and recyclers experience fewer flexibility benefits and are in some instances disadvantaged by benefits offered to manufacturers. Moreover, collection and recycling are low-margin businesses with strong price competition. These factors decrease their contractual power vis-a-vis manufacturers and create an uncertain business environment for them. Consequently, it may be difficult for recyclers to invest in costly, but efficiency-enhancing technologies, limiting the long-term cost-effectiveness of operations. Therefore, it would be valuable to set up some mechanisms that increase operational flexibilities of collectors and recyclers. These flexibilities may take the form of subsidies in return for their contributions to the accumulation of recycling credits or differentiated compensation as discussed below.

*Strengthening the compensation mechanism for collection from rural areas and the recycling of certain products:* The experience with the Minnesota Act indicates that to encourage collection from areas with disperse settlements and more costly access, higher compensation is necessary. This compensation can be in the form of higher additional recycling pounds, i.e., a higher ratio than 1:1.5, or a requirement to meet a certain percentage of recycling obligations from rural areas. Furthermore, the Minnesota experience suggests that mechanisms such as extra credit for recycling high-cost products or the facilitation of commodity markets (as discussed above) are critical to achieve uniform recycling of all product types covered by the act. These implementation tools would help create higher coverage by independent collectors across the state, reduce the burden on local governments and further stimulate the local economy.

*Decreasing the differentiation between targeted and covered products;* Distinguishing targeted and covered products is a key flexibility provision to manufacturers under the Minnesota act. This means there is ample return product volume to choose from in meeting recycling obligations. However, this differentiation also appears to be one of the leading reasons for selective collection and recycling. Therefore, decreasing this differentiation through introducing certain targets for the recycling of targeted products, or expanding the scope of targeted products may help improve the environmental benefits gained through the act.

*Developing mechanisms to reflect design improvements of manufacturers in their obligations:* Experience with the Washington and Minnesota programs highlights the as-yet-unrealized potential of implementation rules that reward manufacturers design improvements in toxicity and recyclability. Possible approaches include individualizing manufacturer obligations based on the recycling cost or value differential of their products and subsidizing better design choices. All of these naturally add to the complexity of EPR implementations. Furthermore, EPR implementations also need to expand their focus beyond recycling obligations by considering other important elements of proper waste management and design incentives such as design for reuse and refurbishing.

## *3.4 Conclusion*

In this essay, we explore the on-the-ground benefits of the market-based approach by focusing on the Minnesota Electronics Recycling Act, which we consider a prevailing example of the market-based approach. To this end, we analyze the act, including its implementation rules, its environmental and economic outcomes, and the associated stakeholder perspectives. Our key observation is that the Minnesota act, which boasts of a market-based foundation, achieves a high collection rate and appears to exhibit higher cost efficiency relative to more centrally operated systems. Another benefit of the market-based approach is that it can provide the basis for achieving Individual Producer Responsibility (IPR). IPR refers to the principle that each producer should only be responsible for the processing cost of its own products [96, 100, 84]. Several stakeholders (including some manufacturers) have advocated for IPR by arguing that it promotes environmental benign design by allowing the manufacturers to recoup the benefit from their design investments. In putting the IPR concept into operation, the market-based approach holds some potential. This is because the market-based approach allows for independent manufacturer decisions and contracts (e.g., determining their collection strategies, contracting directly with collectors and/or recyclers) and puts no operational constraints that could increase the cost of achieving IPR. In particular, although the Minnesota act does not focus on individual responsibility, the broad operational flexibilities of the act give manufactures the opportunity to collect only their own products and to reap the greatest benefit from their design improvements.

However, the operational freedoms of this approach may result in unintended outcomes that detract from the environmental and local economic benefits. For example, (i) a non-uniform collection infrastructure may emerge and selective collection may occur; (ii) selective recycling may take place, i.e., mainly products with low recycling cost may be collected and recycled; (iii) local governments may be effectively the ones who undertake collection for products with high collection and recycling costs, increasing their operational and economic burden; (iv) low margins in the highly competitive recycling industry may preclude recycling technology investments that improve on environmental outcomes; and (v) incentives for designing smaller and lighter products may be more dominant than those for designing less toxic and more recyclable products. Moreover, despite the opportunity for manufacturers to develop a set of contracts that simulate IPR, this has not happened yet in Minnesota to the best of our knowledge.

Our findings suggest that these outcomes are driven by the complexity associated with translating the market-based approach into operational specifications that balance economic and environmental considerations. These complexities are mainly related to strategic interactions between stakeholders and evolving market dynamics at the execution stage. Our analysis highlights the value of understanding the economics driving the decisions of each stakeholder and looking ahead to possible stakeholder interactions and market dynamics in the design phase of EPR legislation so as to attain the intended goals. In particular, our observations can help provide policy recommendations along several dimensions: (i) to diminish incentives for selective collection and recycling; (ii) to allocate costs in a way that rewards design improvements that reduce the products environmental burden; and (iii) to create a level competitive field for all stakeholders.

In sum, our analysis indicates the important role of program choices in determining the effectiveness of EPR implementations. In particular, if the translation of the high-level policy approach into (operational) program choices fails to consider possible interactions at the implementation (execution) stage, even the ideal policy approach can result in unintended economic and environmental outcomes. What this means in the context of a market-based approach to EPR is that operational choices need to be carefully made to most effectively exploit the free-market premise underpinning this approach.

## *3.5 About Stakeholder Interviews*

We express our sincere thanks to Garth Hickle, Executive Member Product Stewardship Team Leader of the Minnesota Pollution Control Agency, who made this research possible by sharing his expertise and facilitating stakeholder interviews. We are deeply grateful to stakeholders who accepted to meet with us and share their perspectives, including Paul Gardner and Recycling Reinvented, Universal Recycling Technologies LLC (in Wisconsin), Hennepin County Environmental Services, Minnesota Pollution Control Agency, Conservation Minnesota, Recycling Association of Minnesota, Dakota County Environmental Management Department, and Materials Processing Corporation. The opinions expressed in this article and any associated mistakes are the authors' own.

# CHAPTER IV

# EXTENDED PRODUCER RESPONSIBILITY FOR PHARMACEUTICALS

## *4.1 Introduction*

Nearly half of the prescription medicines dispensed in the U.S. go unused every year [138], corresponding to more than ten billion dollars of medicine wasted [61]. In addition to the economic loss, unused pharmaceuticals accumulate at households and create serious public health and safety concerns by increasing the risk of unintentional poisonings, medicine diversion and abuse [137, 64]. The Centers for Disease Control and Prevention (CDC) has classified the abuse of prescription medicines as an epidemic, because medicine-induced deaths have been the second leading cause of unintentional deaths in the U.S. for the last decade [31]. Furthermore, unused pharmaceuticals that are thrown away end up in nature with potential adverse effects. Pharmaceutical residuals are found in surface, ground, and even in drinking water and pose a considerable ecological risk [92]. Consequently, preventing the accumulation of pharmaceuticals at households and in nature has become a serious public safety and environmental concern. In response to this concern, some voluntary pharmaceutical collection programs have emerged in the U.S., primarily run by local and other government entities, while calls to adopt a concept called Extended Producer Responsibility (EPR) for pharmaceuticals have been increasing [37].

In 2005, the E.U. passed a mandate that requires pharmaceutical producers to contribute to the collection system for unused pharmaceuticals [133]. In the U.S., Alameda County, CA enacted the first EPR-based legislation for pharmaceuticals in 2012, which mandates producers to submit compliance plans [5], followed by King

County, WA in 2013 [87]. At the national level, the Pharmaceutical Stewardship Act of 2011 was the first related bill introduced in Congress, which aimed to require producers to establish a national collection and disposal program for unused pharmaceuticals [78].

As its adoption in the E.U. and U.S. suggests, EPR appears to be the emerging policy concept for managing unused pharmaceuticals. However, very little is known regarding the effectiveness of different forms of EPR implementations in the context of pharmaceuticals. This is because pharmaceuticals have very different product and demand characteristics as compared to other product categories for which EPR has been prevalent for decades. In particular: (i) pharmaceuticals are consumable and perishable, (ii) the demand for pharmaceuticals and the associated consumption patterns are not completely consumer-driven (i.e., patient-driven) as doctors' prescribing behavior is a major determinant of the demand for pharmaceuticals, and (iii) incineration (rather than value recovery) appears to be the primary post-consumption disposal option for unused pharmaceuticals.

Given these significantly different characteristics, a natural question is whether and how EPR can be effectively operationalized for pharmaceuticals. Because EPR aims to minimize the environmental externalities associated with post-consumption waste, an ideal place to look for appropriate EPR implementation policies is the Waste Management Hierachy (WMH) of the EPA [142]. The WMH lists (i) reducing consumption and production, (ii) reusing products, (iii) recycling materials, and (iv) recovery and environmentally friendly disposal of post consumption products as possible waste management options, in order of preference from an environmental perspective. Due to the perishable and consumable nature of pharmaceuticals, their potential for reuse and recycling is very limited, if any. Accordingly, an EPR implementation for pharmaceuticals needs to focus on the "reduce" and "recovery for environmentally friendly disposal" options. EPR implementation models in practice use two types of policies to operationalize these options, respectively: Source Reduction and End-of-Pipe Control (see Atasu et al. 2009 for a similar discussion).

With the source reduction ($SR$) policy, a social planner typically imposes a cost on a producer so that the producer internalizes the environmental externalities associated with production and consumption. This cost is often in the form of a unit fee associated with sales, which is then used to cover the costs of the collection and treatment of post-consumer products. For instance, the pharmaceutical producers in British Columbia fund the collection system by paying a cost per sale of their products [69]. In Portugal, producers are subject to a collection-system levy that determines a fee for each producer based on the number of his products in the market [68]. The End-of-Pipe Control ($EC$) policy, on the other hand, typically imposes a post-consumer product collection requirement on producers (e.g., the collection targets imposed by the WEEE Directive and the Minnesota electronics take-back legislation [103]). In the context of pharmaceuticals, this corresponds to the collection of unused pharmaceuticals by producer-operated systems as is the case with many implementations to date, including the models in Hungary and Belgium in Europe [68], Alameda County, CA and King County, WA in the U.S. As such, the critical difference between these policies for pharmaceuticals is the stage of direct financial impact: $SR$ aims to impose a cost for the dispensed medicine quantity, whereas $EC$ aims to impose a cost for the unused medicine quantity.

An important observation is that comparison between the effectiveness of these two EPR-based policies is straightforward for non-consumable products such as electronics: The $SR$ policy appears more favorable. This is because the volume of post-consumer waste is theoretically equal to the volume of production for non-consumables (e.g., all used durables will eventually become obsolete). Hence, any collection cost induced by a collection target imposed under $EC$ can be equivalently presented as a unit fee on the producers under $SR$ [11]. This critical observation, however, does not apply to pharmaceuticals because of their consumable nature and the doctor-patient interface. The same comparison for pharmaceuticals needs to take into account the stakeholder interactions leading to a gap between volume of dispensed and used pharmaceuticals. In this essay, we particularly focus on (i) producers' promotions to doctors, (ii) producers' pricing choice, and (iii) doctors' over-prescribing behavior, and (iv) patients' usage choice. Capturing these factors, our objective is to analyze how the $SR$ and $EC$ policies compare for an EPR implementation for pharmaceuticals.

To address this question, we develop a game-theoretic model that involves a social planner, a producer, a doctor, and a heterogeneous patient population. In our model, the sequential decisions are as follows: The social planner sets the EPR-based policy (i.e., $EC$ vs. $SR$); the pharmaceutical producer makes pricing and promotional decisions; the doctor determines the prescription quantity; and the patient decides on the consumption level. To the best of our knowledge, we propose the first synthesized model to analyze the interactions in the pharmaceutical supply chain with respect to pharmaceutical overage and its management with EPR-based policies. Our analysis shows that effective EPR-based policies for pharmaceuticals presents a departure from the conventional wisdom obtained from non-consumables. In particular, $EC$ becomes more effective when for pharmaceuticals when compared to $SR$, particularly if the medicines of concern (i) pose high environmental risks and social concerns (e.g., addiction and abuse issues); (ii) require high collection costs (e.g. stringent collection requirements or standards); and (iii) have moderate healthcare impact. These results draw from consumable nature and mediated demand of pharmaceuticals and suggest that there is no one-size-fits-all EPR-based policy for pharmaceuticals. Hence, characteristics and dynamics unique to pharmaceuticals should be carefully evaluated before EPR-based policy implementation. Finally, we extend our base model to include a certain insurance coverage, different consumer usage behavior and alternative effects of promotions on the doctor's prescription. We find that our structural results and associated insights remain valid in all of these extensions.

EPR-based policy naturally affects the key operational decisions of the pharmaceutical stakeholders, whose interactions then determine the effectiveness of the policy. Given different interests and goals, the stakeholders preferences toward the effective policy may differ significantly, possibly resulting in tensions among stakeholders and implementation challenges. To understand these challenges, we compare the $EC$ and $SR$ policies with respect to their impact on the producer, environment and public health. We find that there are several interrelated factors including the collection cost and healthcare impact of the medicine that influence the stakeholders' perspectives in different ways. This suggests that the pharmaceutical stakeholders need to identify the effect of different EPR-based policies on their businesses in a careful manner and engage with other stakeholders to shape their lobbying efforts. Moreover, our analysis indicates that the aligning the policy preferences of different pharmaceutical stakeholders may be challenging due to the complexity of interactions.

We start our discussion by providing an overview of related literature streams and our contributions in §4.2. We then describe our base model in §4.3 and analyze its solution in the pharmaceutical supply chain along with stakeholder perspectives in §4.4. We conclude with a summary of our results and their policy implications in §4.6.

## 4.2 Related Literature

The environmental economics literature has long analyzed EPR-based policies, mainly producer take-back programs. The existing work in this literature uses stylized models to determine the optimal policy structure. Walls (2003) presents a broad overview of adopted models and associated results. Recent operations management literature has also analyzed EPR-based policies, with a particular focus on operational decisions subject to these policies such as collection network design [148], new product introductions [116], product design [123, 135, 14], as well as their implications for stakeholder preferences [141, 11]. These streams of literature mainly investigate the policies for non-consumable products (e.g., electronics). The novelty of our work lies in being the first to make a similar policy analysis for pharmaceuticals by explicitly modeling their unique product characteristics (such as health benefit, consumable nature) and demand complexities (such as mediated structure due to the intermediary role of doctors). We show that the basic intuitions regarding the effectiveness of EPR-based policies for non-consumables may not necessarily apply to in the context of pharmaceuticals. Accordingly, we contribute to the existing literature by introducing new perspectives on EPR-based policies.

Our work closely relates to the health economics literature, which uses highly stylized game-theoretic models with utility maximization assumption to reflect the doctor-patient interaction. In these models, key factors are the nature of the illness, price of the treatment and diagnostic skills of the doctor. The well-established assumption is that doctors recommend a treatment by balancing the gains and losses from the treatment and patients consent by combining the information provided by the doctor and their own values [47, 117]. We extend this stream of research by including (i) the "ideal" doctor and patient roles from the medical sociology literature such as the paternalistic treatment behavior of the doctor and passive involvement of the patient [48]; and (ii) the "actual" roles, on which the pharmaceutical promotions have a significant effect, such as increased prescription by the doctor [21] and non-adherence of the patient due to his health-related preferences [121, 134]. In the inclusion of these roles, we focus on the pharmaceutical overage due to over-prescription and usage of the patients. Accordingly, our contribution to the health economics literature is to incorporate factors relevant to the provision and usage of pharmaceuticals into the analysis of doctor-patient interaction and analyze their effect on the effectiveness of EPR-based policies.

## *4.3 Model Description*

We build a game-theoretic model involving a social planner, a producer, a doctor, and patients from a heterogeneous patient base. In our model, the social planner determines the EPR-based policy ($EC$ vs. $SR$); the pharmaceutical producer sets the medicine price and level of promotional efforts targeting the doctor and patient base; the doctor decides on a prescription quantity, and the patient determines the consumption level, which may or may not lead to a volume of unused medicine. In what follows, we develop the model by explaining the rationale behind stakeholder decisions. For better exposition, we use bold characters when we first introduce the notation and regular ones afterwards.

### 4.3.1 Doctor-Patient Interaction

The doctor-patient interaction brings a unique demand structure for pharmaceuticals, mainly due to the intermediary role of the doctor. In essence, the doctor's prescribing behavior can be primarily affected by the pricing and promotional decisions of the producer and the potential benefits for health of the patient, and may differ from the patient's preferences [98]. As such, we first model the interaction between the doctor and the patient.

**Patient Types and Behavior:** We focus on patients from a heterogeneous patient base that suffer from a particular type of illness (e.g. hypercholesterolemia, depression, allergies) that require a particular type of medicine (e.g. statins, antidepressants, antihistamines). We describe the heterogeneity in the patient base by a two dimensional patient type: the prescription medicine quantity that a patient (i) needs to recover from the illness (as diagnosed by doctor) and (ii) prefers to use (private information).

We denote the medicine quantity that the patient needs to recover by $\theta_n$, which reflects the severity of the patient's illness. For instance, when the illness is hypercholesterolemia, depending on his or her cholesterol level, a patient needs different doses of statins [36]. Similarly, a patient needs different dosages of antidepressants in a depression treatment based on the depression intensity assessment [20]. To capture this heterogeneity in a simple way, we assume that the illness severity $\theta_n$ in the patient base is uniformly distributed on $[0, 1]$, where 0 corresponds to having no illness and 1 is the maximum possible need level. We also assume that the doctor knows the exact value of $\theta_n$; however, other stakeholders, i.e., the patient, producer and social planner, know only its distribution in the patient base. This allows the doctor to provide prescription quantity $q_p$ that may exceed $\theta_n$, which we call over-prescription.

The patient with severity level $\theta_n$ sees the doctor to get a prescription medicine treatment. Following the literature describing typical patient behavior [22, 48], we assume that the patient accepts $q_p$ at the time of their encounter. However, the patient may prefer to use a different quantity than $q_p$.

We represent the medicine quantity that the patient prefers to use by $\theta_u$. We assume that the patient realizes the value of $\theta_u$ after his encounter with the doctor under the effect of a number of influential factors. For example, side effects, difficulty with sticking to the dosing schedules, and lack of outward symptoms affect the statin usage of patients significantly [131, 140]. Associated factors for antidepressants are bothersome side effects, lack of immediate recovery, complicated regimens, and opinion of the society [118]. Although there is a rich body of studies on the effect of these factors on usage, it is still not possible to capture all the underlying dynamics [32, 111, 114]. Due to the difficulty in capturing this complex usage behavior, we do not make any assumptions on how $\theta_u$ may depend on $q_p$ and $\theta_n$. Instead, we assume it is uniformly distributed on [0,1] in the patient base, and only this distribution information is known by the doctor, producer, and policy maker.

Consequently, the patient uses $\theta_u$ amount of medicine if the prescription is at least as much as $\theta_u$, and $q_p$ otherwise, such that used medicine quantity $q_u$ becomes $\min(\theta_u, q_p)$, leading to an unused medicine quantity equal to $(q_p - q_u)^+$.

**Doctor's Prescribing Behavior:** The medical sociology literature typically assumes that doctors exhibit paternalistic behavior, in which a doctor provides the best medical treatment to a patient [48, 112]. However, the empirical medical literature indicates that promotional efforts of pharmaceutical producers affect doctors' behavior in practice [117], hence doctors also consider their financial and personal interests while treating patients [80, 67, 97, 136]. We combine these aspects into a self-serving paternalistic prescribing behavior by the doctor and adopt the utility maximization approach from the health economics literature to model it. As such, we assume that the doctor chooses a prescription quantity that maximizes his utility $U_d$, where $U_d$ includes both patient wellbeing and his personal benefit [42, 26, 113]. We describe how we account for the paternalistic and self-serving aspects in more detail below.

*Paternalistic Behavior:* The paternalistic portion of the doctor's utility includes two patient-relevant factors: the prescription treatment benefit and cost to the patient, $u_p\theta_n - p\ q_p$. In our model, the treatment benefit corresponds to the health improvement provided to the patient. We assume that the doctor provides prescription medicine at least equal to the patient's need $\theta_n$ and less than 1, which is the maximum possible need level, i.e., $\theta_n \leq q_p \leq 1$. We further assume that the patient gets unit health benefit $u_p$ from using the prescribed medicine up to his need level $\theta_n$ (and none from exceeding that level). In this context, $u_p$ represents the decreased health risks as a result of taking the prescription medicine. For example, the value of $u_p$ is associated with decreased risk for asthma, insomnia, fatigue, and decreased productivity for allergy treatment [23], whereas it is associated with

decreased risk for heart diseases and death for hypercholesterolemia treatments [36]. The doctor calculates the treatment benefit of meeting the patient's need, i.e., the health improvement provided to the patient from his perspective, as $u_p\theta_n$. The patient incurs the cost of the medicine treatment and this becomes the second patient-relevant factor for the doctor. In the base model, we assume that the patient does not have any insurance coverage for the medicine treatment[1], hence the patient pays the whole unit price $p$ of the medicine, making the treatment cost for the patient equal to $p\ q_p$.
*Self-Serving Behavior:* As part of his self-serving behavior, the doctor takes into account his personal gains from the pharmaceutical promotions and his reputation in the following way. Doctors are subject to different types of promotions by pharmaceutical producers such as personal detailing, free samples, travel subsidies, and sponsored symposia. Such promotions are known to influence doctor prescribing practices and increase prescription rates [94, 126, 145, 24]. We incorporate these effects into our model by assuming that the doctor derives positive utility from the promotional effort level targeting the doctor, denoted by $\eta_d$. We further assume his utility increases as the prescription quantity $q_p$ increases since a higher $q_p$ implies continuation of the promotional benefits offered by the producer. Without loss of generality, in our model, $\eta_d$ determines the unit promotional benefit that the doctor obtains from prescribing the medicine, hence the total direct promotional benefit for the doctor is $\eta_d\ q_p$. In addition to this benefit, the doctor also considers his reputation as part of his utility. When the doctor provides a prescription quantity beyond the need of the patient ($q_p > \theta_n$), i.e., when he over-prescribes, he may develop a bad reputation. Accordingly, we denote the unit over-prescription disutility to the doctor by $o_d$ and calculate the absolute bad reputation effect on his utility as $o_d(q_p - \theta_n)^+$.

Promotions targeting the patient base (known as direct-to-consumer (DTC) advertising) also affects the doctor's personal benefits. According to the DTC

[1]We discuss the insurance extension of the base model and related implications in Conclusion.

advertising model of Kravitz (2005), these promotions affect prescribing behavior of doctors through changing the perception of patients. In particular, as a patient is exposed to more promotions, he increases his medical care requests, which in turn leads to an increase in prescription levels. Parallel to this, statins, antidepressants and antihistamines, three medicine categories with high prescription rates, are also among the most promoted medicines to patients in the U.S [91, 35]. We include this effect in our model by assuming that an increase in the DTC advertising attenuates the bad reputation associated with a doctor's over-prescription. We represent promotional effort level targeting the patient (DTC advertising) by $\eta_p$. To capture its fundamental effect on the doctor reputation without losing tractability, we set the doctor's net bad reputation from over-prescribing to be $o_d(1-\eta_p)(q_p-\theta_n)^+$, where $0 \leq \eta_p \leq 1$. For consistency, we assume $0 \leq \eta_d \leq 1$. These constraints on the promotional efforts are also in line with the legislative limitations and budget constraints for the producers.

In sum, given the pricing and promotional decisions of the producer, i.e., given $p$, $\eta_d$, and $\eta_p$, the doctor determines his utility maximizing prescription medicine quantity $q_p^*[p, \eta_d, \eta_p]$ by solving the following problem:

$$\max_{q_p} U_d(q_p) = \underbrace{\underbrace{u_p\,\theta_n}_{\text{Health Benefit}} - \underbrace{p\,q_p}_{\text{Prescription Cost}}}_{\text{Patient-Relevant Utility}} + \underbrace{\underbrace{\eta_d\,q_p}_{\text{Promotional Benefit}} - \underbrace{o_d\,(1-\eta_p)(q_p-\theta_n)^+}_{\text{Reputational Cost}}}_{\text{Personal Utility}}$$

such that $\theta_n \leq q_p \leq 1$.

Anticipating how the doctor-patient interaction occurs, the pharmaceutical producer maximizes expected profit $\Pi_m$ while maintaining a non-negative utility level for the doctor, i.e., $U_d \geq 0$. He sets the unit price of the medicine $p$ and the level of promotional efforts targeting the doctor and patient, $\eta_d$ and $\eta_p$, respectively. We assume that he incurs quadratic promotional costs in the form of $\alpha\,\eta_d^2$ and $\beta\,\eta_p^2$ where $\alpha$

and $\beta$ are promotional cost constants [128][2], in addition to expected EPR compliance cost $C_P[p, \eta_d, \eta_p]$ (defined in the next subsection), whose structure depends on the policy choice of the social planner. As such, given the policy and its parameters, the producer makes pricing and promotional decisions, i.e., determines $p[x_P], \eta_d[x_P]$ and $\eta_p[x_P]$, by solving the following expected profit maximization problem:

$$\max_{p,\eta_d,\eta_p} \Pi_m(p, \eta_d, \eta_p) = E_{\theta_n,\theta_u}[p\ q_p^*[p, \eta_d, \eta_p] - \alpha\ \eta_d^2 - \beta\ \eta_p^2] - C_P[p, \eta_d, \eta_p]$$

$$\text{such that } \ 0 \leq \eta_d \leq 1, \ \ 0 \leq \eta_p \leq 1.$$

The usage behavior of the patient results in the following used and unused medicine volumes: $q_u^*[p, \eta_d, \eta_p] = \min(\theta_u, q_p^*[p, \eta_d, \eta_p])$ and $(q_p^*[p, \eta_d, \eta_p] - q_u^*[p, \eta_d, \eta_p])^+$.

### 4.3.2 Policy Choice of the Social Planner

The social planner makes the choice of EPR-based policy to manage the collection of unused prescription medicine. If the choice is End-of-pipe Control ($EC$), then the planner mandates the producer to comply with a collection rate requirement $r_{EC}$. In this case, the producer collects $r_{EC}$ fraction of the unused medicine by incurring collection cost $k$ per unit. If the choice is Source Reduction ($SR$), then the planner mandates the producer to pay a unit fee $t$ for every unit he produces and uses the funds generated through fees to collect $r_{SR}$ fraction of unused medicine. In this case, the planner may have surplus or deficit $\Pi_{sp}$, arising from a potential mismatch between the costs of collecting pharmaceuticals and producer fees, which equals $\Pi_{sp}[r_{SR}, t] \doteq t\ q_p - k\ r_{SR}(q_p - q_u)^+$. Accordingly, given the pricing and promotional decisions of the producer, his expected EPR compliance cost is:

[2]In our model, we do not consider the effect of R&D investments and any patent protection and we assume that unit production cost for the producer as 0 in our model without loss of generality.

$$C_P[p, \eta_d, \eta_p] = \begin{cases} E_{\theta_n,\theta_u}[k\ r_{EC}(q_p^*[p, \eta_d, \eta_p] - q_u^*[p, \eta_d, \eta_p])^+] & : \quad P = EC \\ \\ E_{\theta_n}[t\ q_p^*[p, \eta_d, \eta_p]] & : \quad P = SR \end{cases}$$

Note that under $SR$, the producer pays the unit fee $t$ for all the dispensed quantity, whereas under $EC$ he pays the unit collection cost $k$ for only the uncollected unused medicine quantity. As the unused quantity is always less than the prescribed (dispensed) quantity (as a result of the consumable nature of pharmaceuticals), the producer pays the EPR-related cost for only a fraction of the dispensed quantity under $EC$, whereas, he pays fee even for medicine that do not go unused under $SR$. This represents an important difference between the policies and will be critical in comparing their effectiveness.

Anticipating the interactions between the producer, doctor and patient based on the distributions of $\theta_n$ and $\theta_u$, the social planner maximizes the total expected welfare, $W$. She calculates $W$ through an additive formulation that includes (i) the doctor utility $U_d$ (which also includes the patient utility implicitly), (ii) the producer profit $\Pi_m$, (iii) any social planner surplus $\Pi_{sp}$, (iv) environmental disutility $DU_e$ (explained below), (v) social disutility $DU_s$ (explained below).

*Environmental disutility:* Medicine residuals present in the environment pose high risks with respect to ecological balance. For example, antihistamine residuals in streams harm aquatic communities that have vital roles for the ecosystem [125]. Similarly, organisms exposed to antidepressant residuals in the environment exhibit behavioral changes such as reduced reaction times and reproduction rates, which in turn can result in unbalanced changes in the population of many species [124, 34]. To reflect these risks in our model, we define a *unit environmental disutility* measure $\epsilon_e$, which represents the economic impact of the associated environmental harm (See [11] for detailed discussion). The total environmental disutility stems from the total prescription medicine quantity that eventually ends up in the environment. This quantity is equal to the sum of the prescription medicine used and metabolized by the patient, $q_u$, and uncollected (disposed improperly such as flushing down the drain) unused prescription medicine quantity, $(1-r_P)\ (q_p-q_u)^+$ where $P \in EC/SR$. There is no known difference between metabolized or disposed medicine in terms of their environmental impact, hence we assume that they exhibit same environmental disutility. As such, the environmental disutility $DU_e[r_P] \doteq \epsilon_e\ (q_u+(1-r_P)\ (q_p-q_u)^+)$.

*Social disutility:* Potential misuse, abuse and illegal diversion of unused medicine together with related unintentional poisonings pose significant public health and safety risks. For instance, antidepressants are one of the most abused prescription medicines [31], and their abuse may result in heart diseases and death [129]. Additionally, certain type of antihistamines are commonly abused for their hallucination and sensation effects [66] with risks including kidney failure and pancreatitis [33]. We represent the economic impact of these risks by a *unit social disutility* $\epsilon_s$ and calculate the social disutility related to the uncollected unused prescription medicines as $DU_s[r_P] \doteq \epsilon_s\ (1-r_P)\ (q_p-q_u)^+$.

In sum, the social planner maximizes total expected welfare $W$ under each policy by setting the associated policy parameter set $x_P$ as below. She then compares the total welfare of policies, $EC$ vs $SR$, and chooses the one that gives higher total welfare. Note that at the equilibrium, $\Pi^*_{sp}[r_{SR}, t] \doteq t\ q^*_p(p^*(x_P), \eta^*_d(x_P), \eta^*_p(x_P)) - k\ r_{SR}(q^*_p(p^*(x_P), \eta^*_d(x_P), \eta^*_p(x_P)) - q^*_u(p^*(x_P), \eta^*_d(x_P), \eta^*_p(x_P)))^+$, $DU^*_e[r_P] \doteq \epsilon_e(q^*_u(p^*(x_P), \eta^*_d(x_P), \eta^*_p(x_P)) + (1 - r_P)(q^*_p(p^*(x_P), \eta^*_d(x_P), \eta^*_p(x_P)) - q^*_u(p^*(x_P), \eta^*_d(x_P), \eta^*_p(x_P)))^+)$, and $DU^*_s[r_P] \doteq \epsilon_s(1 - r_P)(q^*_p(p^*(x_P), \eta^*_d(x_P), \eta^*_p(x_P)) - q^*_u(p^*(x_P), \eta^*_d(x_P), \eta^*_p(x_P)))^+$.

$$\max_{x_P} W(x_P) \doteq E[U_d[q_p^*[p^*[x_P], \eta_d^*[x_P], \eta_p^*[x_P]]] + \Pi_m[p^*[x_P], \eta_d^*[x_P], \eta_p^*[x_P]] + \Pi_{sp}^*[x_P]$$
$$- DU_e^*[r_P] - DU_s^*[r_P]]$$

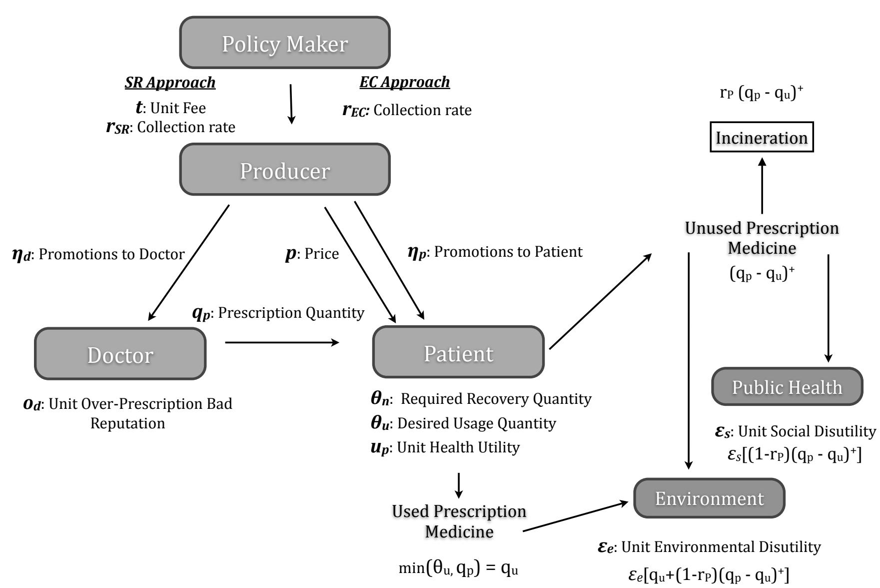
such that $0 \leq r_P \leq 1$

where

$$x_p = \begin{cases} r_{EC} & : \text{ if } P = EC \\ r_{SR}, t & : \text{ if } P = SR \end{cases}$$

Let $P^*$ and $x_P^*$ denote the policy and its parameters at the Stakelberg equilibrium. We derive full equilibrium characterization with backwards induction by calculating $(p^*, \eta_d^*, \eta_p^*)$ under $(P^*, x_P^*)$ and subsequently evaluating $q^*(p^*, \eta_d^*, \eta_p^*)$. Figure 4.3.2 illustrates these sequential decisions in the pharmaceutical chain.

**Figure 8:** Sequential decisions in the pharmaceutical chain and associated variables and parameters.



## 4.4 Analysis of Decisions in the Pharmaceutical Chain

Our analysis focuses on the management of pharmaceutical overage and related externalities associated with the over-prescription of the doctor and the usage of the patient. In our model, patient usage behavior is invariant with respect to the choice of $EC$ or $SR$. Therefore, the policy choice depends on how it affects over-prescription and its externalities via its impact on producer and social planner decisions. Accordingly, we first explore key drivers of the doctor's over-prescription and analyze how these drivers relate to characteristics specific to pharmaceuticals (such as their consumable nature, their health benefit and intermediary role of the doctor). Next, we investigate differences between the policies in relation to these drivers and analyze how these differences shape the preferred policy from the welfare perspective. For brevity, we relegate all the proofs and closed-form expressions to the Appendix B.

### 4.4.1 Key Drivers of Over-Prescription

As a first step, we analyze the doctor's prescription behavior given the decisions of the producer and the social planner. Recall that the doctor provides prescription medicine at least equal to the need of the patient and the producer guarantees the non-negativity of the doctor utility. Hence, the promotional and patient-relevant benefits need to exceed the cost of the treatment, imposing the condition $p \leq \eta_d + u_p$. Paralleling the practice, this condition captures the following: the health benefit of the medicine restricts the unit price that the producer can charge and the producer needs to increase his promotional efforts in order to set higher price. More specifically, the market price of the medicine reflects the health benefits of the medicine and the extent of its promotions. Given this condition, we find under what conditions the doctor's decision is to over-prescribe, i.e., to provide prescription medicine beyond the patient's need.

**Lemma 5** *The doctor provides prescription medicine equal to the patient's need if* $\eta_d < o_d(1-\eta_p)+p$ *and beyond the patient's need if* $\eta_d \geq o_d(1-\eta_p)+p$.

Lemma 5 demonstrates that the doctor decides on the prescription quantity based on its marginal benefit and cost. In particular, the doctor's marginal utility is $U_d'(q_p) = \eta_d - (p + o_d(1-\eta_p))$. This consists of marginal promotional benefit $\eta_d$ and marginal cost $p + o_d(1-\eta_p)$, the sum of the unit price of the medicine and the unit bad reputation to the doctor due to over-prescription (moderated by the effect of promotions targeting the patient). When the marginal cost exceeds the marginal benefit, the doctor prescribes medicine equal to the need of the patient; otherwise, he over-prescribes. This suggests that the doctor over-prescribes when pharmaceutical promotions are high and the price of the medicine is affordable.

Anticipating doctor's behavior as above, given the EPR-based policy and the obligations it imposes (collection rate $r^{EC}$ under $EC$ and fee $t$ under $SR$), the producer makes his pricing and promotional decisions. We next analyze these decisions by focusing on factors that drive the producer to set high pharmaceutical promotions and a low price for the medicine, i.e., factors that induce over-prescription by the doctor in equilibrium. For ease of discussion, we suppress the arguments in the thresholds presented in the results below.

**Proposition 11** *There exists a medicine health benefit threshold* $\bar{u}_p^{EC}(o_d,\alpha,\beta,c) \doteq \bar{u}_p^{EC}$ *under EC* ($\bar{u}_p^{SR}(o_d,\alpha,\beta,c) \doteq \bar{u}_p^{SR}$ *under SR) such that when* $u_p < \bar{u}_p^{EC}$ ($u_p < \bar{u}_p^{SR}$) *for any* $r^{EC} \in [0,1]$ *(for any* $t > 0$*) the producer gains a higher profit by inducing over-prescription. Moreover,* $\frac{\partial \bar{u}_p^{EC/SR}}{\partial o_d} \leq 0$ *and* $\bar{u}_p^{EC} < \bar{u}_p^{SR}$.

Proposition 11 illustrates how the medicine health benefit affects the producer's profit and inducement of over-prescription. In particular, when the health benefit is below a threshold value for the given policy, i.e.,$u_p < \bar{u}_p^{EC/SR}$ under $EC/SR$, the producer's profit is always higher with inducing over-prescription. The intuition behind this result is as follows: The pharmaceutical producer has two fundamental levers to increase his revenue level; increase the unit price or increase the dispensed (prescription) quantity. Recall that the health benefit of the medicine restricts the unit price that the producer can charge for the medicine. Hence, when the health impact is low, the producer cannot set high prices. In those cases, to achieve a higher revenue, the producer is particularly motivated to increase his promotional efforts to increase the prescription quantity dispensed, i.e., to induce over-prescription. Furthermore, the health benefit threshold increases as the over-prescription bad reputation to the doctor $o_d$ decreases. This is because when the effect of over-prescription on the reputation of the doctor gets low, the producer has more flexibility to set higher prices. This decreases the effective cost of inducing over-prescription and it becomes more feasible for the producer.

The results above highlight the effect of the mediated demand structure on the effectiveness of the EPR-based policies in limiting over-prescription. In essence, the doctor, as the intermediary between the producer and the patient, considers the trade-off between patient-relevant and promotional benefits together with his reputation. This, in turn, makes the unique feature of reputational consideration of the doctor and health benefit aspect as key factors for the decisions of the producer.

Proposition 11 further illustrates that the medicine health benefit threshold under $SR$ is always higher than the threshold under $EC$, implying that the producer has higher incentives to induce over-prescription under $SR$. This result follows the fact that $EC$ and $SR$ policies impose producer responsibility obligations on different volumes of medicine due to the consumable nature of pharmaceuticals. In particular, $SR$ charges the unit fee $t$ for the total quantity dispensed ($q_p$) whereas $EC$ mandates the collection rate $r^{EC}$ for the unused quantity ($(q_p - q_u)^+$). Given this difference, the producer increases his obligations and related cost at larger extent by inducing over-prescription under $EC$ policy as compared to $SR$. In other words, avoiding to over-prescription creates more dramatic decrease in the obligation of the producer under $EC$, decreasing incentives for him to induce over-prescription. Consequently, EC policy becomes more effective in eliminating over-prescription for the medicine with high health utility level. This is an important difference between the EPR-based policies in terms of their effectiveness in the management of pharmaceutical overage.

**Proposition 12** *Under the EC policy, there exists a unit collection cost threshold* $\bar{k}(u_p, o_d, \alpha, \beta, c) \doteq \bar{k}$ *such that when* $k < \bar{k}$ *for any* $r^{EC} \in [0, 1]$ *the producer gains a higher profit by inducing over-prescription.*

The $SR$ and $EC$ policies have inherent differences in the context of managing the collection of pharmaceutical overage. Under $SR$, the social planner operates the collection system and incurs the associated collection costs; on the other hand, under $EC$, the producer undertakes collection and incurs the unit collection cost $k$. Hence, the collection cost becomes a direct driver of the producer decisions only under $EC$. In particular, as Proposition 12 states, the producer subject to $EC$ always induces over-prescription when the unit collection cost is below a threshold value, i.e., $k < \bar{k}$. In those cases, the gains from dispensing a larger quantity of medicine dominate the collection-related costs for the producer. As a result, the producer obtains a higher profit with inducing over-prescription and has no incentive to limit the quantity of pharmaceutical overage. This suggests that when the collection standards of pharmaceutical collection programs are not stringent, the $EC$ policy cannot create sufficient incentives for the producer to avoid over-prescription.

We now analyze the inducement of over-prescription from the perspective of the social planner under each EPR-based policy. In this part, to compare different prescription outcomes, we only consider the cases where the policies can avoid pharmaceutical overage due to over-prescription (i.e. $k \geq \bar{k}$ and $u_p \geq \bar{u}_p^{EC}$ under $EC$; $u_p \geq \bar{u}_p^{SR}$ under $SR$).

**Proposition 13** *There exists an environmental externality threshold* $\bar{\epsilon}_e^{EC}(\epsilon_s, u_p, o_d, k, \alpha, \beta, c) \doteq \bar{\epsilon}_e^{EC}$ *under EC* ($\bar{\epsilon}_e^{SR}(\epsilon_s, u_p, o_d, k, \alpha, \beta, c) \doteq \bar{\epsilon}_e^{SR}$ *under SR) such that when* $\epsilon_e < \bar{\epsilon}_e^{EC}$ ($\epsilon_e < \bar{\epsilon}_e^{SR}$) *total welfare is higher with over-prescription. Furthermore,* $\frac{\partial \bar{\epsilon}_e^{EC/SR}}{\partial \epsilon_s} < 0$.

Proposition 13 states that when the environmental impact of the medicine is below a certain threshold, it may be too costly to eliminate over-prescription via EPR tools. This means that the losses of other pharmaceutical stakeholders (producers and doctors) from eliminating over-prescription dominate the environmental gains. In those cases, the planner can impose higher collection rate imposing higher collection rate to decrease the externality associated with the pharmaceutical overage. Additionally, the threshold increases as the unit social disutility $\epsilon_s$ decreases, meaning that as the public health externality decreases over-prescription becomes acceptable for a large range of environmental impact. Similar result can be obtained for the social disutility $\epsilon_s$.

### 4.4.2 Preferred EPR-Based Policy for Pharmaceuticals

Building on the insights from the previous subsection, we compare the EPR-based policies, $EC$ vs. $SR$, from the total welfare perspective. For ease of disposition, we focus on the cases where $u_p < \bar{u}_p^{SR}$, i.e., the medicines with moderate health and reputational impact. This assumption is in line with the practice as majority of the collection programs based on the EPR concept exclude controlled substances, whose treatment-related impact is substantial, i.e., $u_p \gg 0$ and $o_d \gg 0$, (e.g. Morphine, Xanax) [56]. This is mainly because of the regulatory complications in handling these substances[3]. We provide brief discussion of the analysis for $u_p \geq \bar{u}_p^{SR}$ (See Appendix B §A2 for details) and associated implications for the adoption of the EPR

[3]FDA in the U.S. has recently revised it requirements on the collection of controlled substances to increase options for disposal by third parties.

concept for the controlled substances in the conclusion.

**Proposition 14** *There exist a unit collection cost, a medicine health benefit and an environmental disutility threshold (denoted by* $\bar{k}$*,* $\bar{u}_p \doteq \bar{u}_p^{EC}$ *and* $\tilde{\epsilon}_e(\epsilon_s, u_p, o_d, k, \alpha, \beta, c) \doteq \tilde{\epsilon}_e$*, respectively) that determine the preferred EPR-based approach as in Table 2.*

**Table 2:** Total welfare maximizing EPR-based policy for pharmaceuticals.

| | $\boldsymbol{u_p < \bar{u}_p}$ | $\boldsymbol{u_p \geq \bar{u}_p}$ |
|---|---|---|
| $\boldsymbol{k < \bar{k}}$ | $EC^* = SR^*$ | |
| $\boldsymbol{k \geq \bar{k}}$ | $SR\ ^*$ | $EC$ when $\epsilon_e \geq \tilde{\epsilon}_e$<br>$SR\ ^*$ otherwise |

*Note:* The equilibrium outcomes with $^*$ exhibits over-prescription.

Proposition 14 presents how the choice of EPR-based policy changes with the health benefit (together with over-prescription bad reputation effect) and collection cost of the medicine along with its environmental and public health externality. To better understand how these factors determine the preferred policy, we first discuss the levers of EPR-based policies, $EC$ vs. $SR$, to manage the total welfare through controlling the collected pharmaceutical overage. In this context, the social planner has two main levers: affecting the pharmaceutical overage and setting collection rates. Under $SR$, the planner uses two independent tools, unit fee $t$ and collection rate $r^{SR}$. He has complete flexibility in setting $r^{SR}$ and directs the producer decisions, which eventually determines the overage, via unit fee $t$. As $t$ applies to all units produced, $SR$ does not directly target the pharmaceutical overage, meaning that its impact on the overage is indirect. On the other hand, under $EC$, the planner uses a single tool, collection rate $r^{SR}$, for both affecting the pharmaceutical overage and directing the producer decisions. This may create limitations in terms of the collection rate that the planner can set, while making $EC$ more focused on the pharmaceutical overage. Under the effect of these dynamics, there exist certain conditions where the $EC$ policy dominates $SR$ as explained in detail below.

Recall that we restrict our analysis to the case where $u_p < \bar{u}_p^{SR}$. Following Proposition 11, this means that the $SR$ policy results in inducement of over-prescription. Given this, we first consider the case where the unit collection cost is low ($k < \bar{k}$). From Proposition 12, we know that both policies induce over-prescription. In this case, the policy that can set collection rate flexibly manages the externalities associated with pharmaceutical overage better and provides higher total welfare. As discussed above, under $SR$, the planner can set any collection rate ($r^{SR} \in [0, 1]$, corresponding to flexibility to achieve lowest or highest collection rate possible) to manage the externalities. Similarly, the low collection cost ($k < \bar{k}$) allows $EC$ to induce over-prescription for any collection rate ($r^{EC} \in [0, 1]$), providing it with the same flexibility as $SR$. Hence, both policies give same welfare results.

We next consider the high unit collection cost case ($k \geq \bar{k}$). In this case, the unit collection cost is sufficiently high that flexibility of $EC$ in setting collection rate decreases (while there is no change for the $SR$ policy). This is because the planner may now use collection rate as the tool to affect the amount of pharmaceutical overage depending on the health benefit of the medicine. For a medicine with low health impact ($u_p < \bar{u}_p$), due to the restricted pricing power, the producer has incentives to leverage dispensed quantity to increase his revenue level, i.e., to induce over-prescription. As both policies induce over-prescription, as before, the policy that is flexible in setting higher or lower collection rates gives higher total welfare. In this case, this policy is the $SR$. However, for a medicine with high health impact ($u_p \geq \bar{u}_p$), the producer subject to the $EC$ can set sufficiently high price for the medicine and the planner can utilize the collection rate in a way to avoid over-prescription. Hence, in this case, the preferred policy depends on the balance between the flexibility in setting collection rates and amount of pharmaceutical overage. At the low levels of environmental disutility, over-prescription outcome is bearable because the flexibility of the $SR$ policy for the collection rate can alleviate the externalities associated with over-prescription, making it the preferred policy. When the disutility reaches a certain threshold ($\epsilon_e \geq \tilde{\epsilon}_e$ where $\frac{\partial \bar{\epsilon}_e^{EC/SR}}{\partial \epsilon_s} < 0$), limiting environmental externalities requires avoiding the over-prescription, hence the $EC$ policy becomes the welfare-maximizing policy.

To sum up, treatment-related impact, collection standards and externalities associated with the medicine determine the effective EPR implementation policy for managing pharmaceuticals (summarized by Table 2). In particular, $EC$ is the effective policy when the medicine under consideration has (i) high treatment-related impact; (ii) stringent collection standards; and (iii) high environmental and social risks. Otherwise, the $SR$ policy gives equally good or better welfare outcomes. This result is one of the key results related to EPR implementations in the pharmaceutical context and has important implications for practice. First, it suggests that the $EC$ policy appears to be effective for antidepressants and pharmaceuticals with similar characteristics. Due to their effects on the nervous system, antidepressants pose high public health and environmental risks: They are commonly abused medicines and they may lead to significant behavioral changes on aquatic species, endangering the ecological balance. Moreover, their collection and handling require a high level of security standards, leading to high collection-related costs. This further suggests that one-size-fits-all type of EPR-based collection programs are not suitable for managing the pharmaceutical overage and associated externalities from environmental and public health perspectives.

Second, this result presents a critical departure from the existing EPR literature for non-consumable products (e.g. electronics). For these products, a welfare comparison of $EC$ and $SR$ policies favors the $SR$ policy. The reason is that the quantity at the end-of-pipe, i.e. volume of waste, is theoretically equal to the volume of production for non-consumables, hence any collection cost induced by a collection target under the $EC$ can be equivalently presented under the $SR$ as a unit fee on the producers [11]. This critical result, however, is not valid for pharmaceuticals due to the consumable nature of pharmaceuticals and mediated demand structure in the pharmaceutical supply chain. These results collectively show that the policy choice in the pharmaceutical context depends on the characteristics specific to pharmaceuticals, indicating the importance of analysis of these characteristics in the context of EPR implementations.

## 4.5 Pharmaceutical Stakeholder Perspectives

In the previous section, we addressed the question which EPR-based policy needs to be chosen for the management of pharmaceutical overage from a total welfare perspective. However, the policy chosen may not be necessarily preferred by all pharmaceutical stakeholders. More specifically, a particular EPR-based policy may favor a certain group of stakeholders over others, leading to possible tensions among them and challenges related to implementation. To shed light on these challenges, we next compare the $EC$ and $SR$ policies with respect to their impact on the producer, environment and public health. For brevity, we focus on more relevant case where the externality of medicine is sufficiently high that the planner aims to prevent over-prescription if possible (see Proposition 14 for detailed discussion).

**Proposition 15** *Preference of the producer for EC vs. SR policies vary as a function of unit collection cost threshold $\bar{k}$, health benefit threshold $\bar{u}_p$ and a unit fee threshold $\bar{t}(u_p, o_d, k, \alpha, \beta, c) \doteq \bar{t}$ as illustrated by Table 3.*

Proposition 15 states that unit collection cost, medicine health benefit, and unit fee under $SR$ are key factors that determine the preference of the producer for the

**Table 3:** Producer preferences for the EPR-based policies.

<table>
<tr><th></th><th></th><th>$\boldsymbol{u_p < \bar{u}_p}$</th><th>$\boldsymbol{u_p \geq \bar{u}_p}$</th></tr>
<tr><td rowspan="2">$\boldsymbol{k < \bar{k}}$</td><td>$\boldsymbol{k < \epsilon_e + \epsilon_s}$</td><td colspan="2">$EC$ if $t > \bar{t}$; $SR$ otherwise</td></tr>
<tr><td>$\boldsymbol{k \geq \epsilon_e + \epsilon_s}$</td><td colspan="2">$EC$</td></tr>
<tr><td rowspan="2">$\boldsymbol{\bar{k} \leq k < \bar{\bar{k}}}$</td><td>$\boldsymbol{k < \epsilon_e + \epsilon_s}$</td><td>$SR$</td><td rowspan="2">$EC$ if $t > \bar{t}$; $SR$ otherwise</td></tr>
<tr><td>$\boldsymbol{k \geq \epsilon_e + \epsilon_s}$</td><td>$EC$</td></tr>
<tr><td rowspan="2">$\boldsymbol{k \geq \bar{\bar{k}}}$</td><td>$\boldsymbol{k < \epsilon_e + \epsilon_s}$</td><td colspan="2">$SR$</td></tr>
<tr><td>$\boldsymbol{k \geq \epsilon_e + \epsilon_s}$</td><td>$EC$</td><td>$EC$ if $t > \bar{t}$; $SR$ otherwise</td></tr>
</table>

EPR-based policies. Table 3 indicates that the effect of unit collection cost on the profit of producer are two fold: (i) the direct effect on the profit (represented by thresholds $\bar{k}$ and $\tilde{k}$), and (ii) the indirect effect in comparison with the externality (demonstrated by the value of $k$ with respect to $\epsilon_e + \epsilon_s$), which, in turn, determines the collection rate imposed. The direct effect of the unit collection cost occurs only under $EC$ and changes the policy preference of the producer in the expected way: As the unit collection cost decreases, it directly decreases the collection-related cost for the producer, hence the producer's preference shifts towards the $EC$ policy.

However, the indirect effect of the unit collection cost is in the opposite direction: The producer benefits from the $EC$ policy more as the unit collection cost of the medicine with respect to the associated externality increases. The social planner sets the collection rate based on its marginal benefit and cost. In particular, increasing collection rate creates the marginal benefit of $\epsilon_e + \epsilon_s$ by decreasing environmental and public health risks and has the marginal cost of $k$. If the unit collection cost of the medicine is higher (lower) than unit externality, i.e., $\epsilon_e + \epsilon_s \leq (>) k$, then the planner sets the minimum (maximum) possible collection rate. In those cases, the collection rate imposed on the producer under the $EC$ policy is so low that the producer incurs low collection-related cost. As a result, the producer tends to gain higher profit under $EC$ than $SR$ as the value of unit collection increases with respect to the externality of the medicine. The preference of the producer in this case depends on the unit fee imposed by the planner. As the planner charges a higher fee, the producer naturally favors $EC$. This is parallel to the practice. For instance, in the industries in which collection and recycling programs run through fees (e.g. electronics and beverage industry), producers (e.g. HP, American Beverage Association) oppose high fees [6, 11]. These result suggests that, contrary to the common expectation, the producer may favor $EC$ even at high collection cost levels when the externality of the medicine is relatively low.

The above result has important implications for the pharmaceutical supply chain in practice. First, pharmaceutical producers need to shape their lobbying efforts on the EPR-based policy choices by taking into account the health aspects of the medicine together with the existing collection infrastructure. This means that producers may not benefit from unified collection programs set for the pharmaceuticals. This is because the benefits of these collection programs may disappear with the inclusion of medicine with different characteristics. Moreover, producers may need to support different policies even for the same medicine in different states. This arises from the fact that efficiency of collection infrastructure may change considerably from one state to another due to several factors such as geographical conditions and dispersion of the population. As a result, the operational landscape for producers may differ substantially, possibly changing their perspectives. Second, the preferences of the producer toward the $EC$ policy does not exhibit the same structure as the welfare maximizing policy. This suggests that the policy makers introducing EPR-based policies need to expect significant resistance from pharmaceutical producers.

**Proposition 16** *Environmental and public health externality under the $EC$ vs. $SR$ policies vary as a function of unit collection threshold $\bar{k}$ and unit health benefit threshold $\bar{u}_p$ as illustrated by Table 4.*

**Table 4:** Environmental and public health preferences for the EPR-based policies.

| | | $\boldsymbol{u_p < \bar{u}_p}$ | $\boldsymbol{u_p \geq \bar{u}_p}$ |
|---|---|---|---|
| $\boldsymbol{k < \bar{k}}$ | $\boldsymbol{k < \epsilon_e + \epsilon_s}$ | $EC = SR$ | |
| | $\boldsymbol{\epsilon_e + \epsilon_s \leq k}$ | | |
| $\boldsymbol{\bar{k} \leq k < \bar{\bar{k}}}$ | $\boldsymbol{k < \epsilon_e + \epsilon_s}$ | $SR$ | $EC = SR$ |
| | $\boldsymbol{\epsilon_e + \epsilon_s \leq k}$ | $EC = SR$ | $EC$ |
| $\boldsymbol{k \geq \bar{\bar{k}}}$ | $\boldsymbol{k < \epsilon_e + \epsilon_s}$ | $SR$ | $SR$ if $\epsilon_s \geq \bar{\epsilon}_s$; $EC$ otherwise |
| | $\boldsymbol{\epsilon_e + \epsilon_s \leq k}$ | $EC = SR$ | $EC$ |

Environment and public health always benefit from lower volumes of uncollected unused pharmaceuticals, and in turn, from the policy that restricts the amount of dispensed pharmaceuticals and/or establishes higher collection rates. Accordingly, factors affecting the prescription level and collection rate shape the preferred policy from environmental and social perspectives. Proposition 16 expresses that these factors are the unit collection cost and medicine health benefit. As in the case of producers, the effect of unit collection cost is two fold: the effect on the prescription level through influencing the decisions of the producer (represented by threshold $\bar{k}$) and the effect on the collection rate imposed (demonstrated by the value of $k$ with respect to $\epsilon_e + \epsilon_s$). Proposition 16 further indicates that the $EC$ policy may be favorable from environmental and social perspectives except the cases where the health benefit of the medicine is low and its collection cost is relatively lower than the associated externality.

The underlying dynamics in Table 4 can be explained as follows: Recall from our earlier discussion that the $SR$ policy is flexible in setting the collection rate ($r_{SR} \in [0, 1]$) and $EC$ has the same flexibility when the unit collection cost is low. As both policies result in same pharmaceutical overage at low levels of the collection cost, environmental and public health perspectives favor both policies equally. As the collection cost increases, the flexibility of $EC$ in terms of setting collection rate decreases. This means that $SR$ now has the ability to impose lower or higher collection rates than $EC$. Recall also that the planner determines the collection rate based on the value of unit collection cost of the medicine with respect to its environmental and public health externality, i.e., $k$ vs. $\epsilon_e + \epsilon_s$. For a medicine with low health benefit levels ($u_p < \bar{u}_p$), the pharmaceutical overage is same under both policies. Hence, $SR$ becomes more favorable from the environmental and public health perspectives when $k < \epsilon_e + \epsilon_s$, by setting higher collection rate.

Moreover, as Table 2 illustrates, the ability of $EC$ in avoiding over-prescription increases as the health benefit of the medicine increases. Hence, the environmental and public health preferences shift toward the $EC$ policy with an increase in health benefit. Accordingly, for a medicine with high health benefit ($u_p \geq \bar{u}_p$), when the unit collection cost of the medicine is higher as compared its externality, $EC$ becomes the sole preferred policy by both resulting in lower overage and setting higher collection rate. Furthermore, when the unit collection cost of the medicine is lower, it becomes the preferred policy except the case when the public health disutility of the medicine is above a threshold ($\epsilon_s \geq \bar{\epsilon}_s$). This is because although the $SR$ policy results in over-prescription, it can effectively prevent public health risks through high collection rate ($r^*_{SR} = 1$) and can only lead to some environmental externality due to consumption. On the other hand, the $EC$ policy can avoid the over-prescription in this case, it sets lower collection rate, which in turn results in some environmental and public health externality. Therefore, when the public health disutility of the medicine is significantly high, $SR$ policy leads to lower environmental and public health impact.

The above result implies that, similar to the case of producers, environmental and social advocacy groups need to coordinate their political efforts differently for different medicine categories or even for same categories in different operating conditions. Furthermore, they need to analyze the unifying collection models that apply to multiple categories of pharmaceuticals cautiously. All of these collectively suggest that pharmaceutical NGOs need to consider several interrelated factors (e.g. factors that drive the volume of pharmaceuticals dispensed and collected, including treatment-related aspects of the medicine, collection-related requirements in place, and infrastructural conditions) to ensure better environmental and public health outcomes. Consideration of such factors requires anticipating the response of producers to different policy choices and impact of the medicine on the environment and public health before the implementation stage. Hence, our work indicates the importance of NGOs' engagement with the industry (e.g. gathering relevant information and eliciting the potential responses) and involvement in research regarding harmful reflections on the environment and public health.

**Proposition 17** *The preferred policy from a welfare perspective aligns the perspectives of producer and environmental/public health advocacy groups based on threshold $\bar{k}$ and $\bar{t}$ as given by Table 5.*

**Table 5:** Alignment of pharmaceutical stakeholder preferences.

<table>
<tr><th colspan="2"></th><th>$\boldsymbol{u_p < \bar{u}_p}$</th><th>$\boldsymbol{u_p \geq \bar{u}_p}$</th></tr>
<tr><td rowspan="2">$\boldsymbol{k < \bar{k}}$</td><td>$\boldsymbol{k < \epsilon_e + \epsilon_s}$</td><td colspan="2">$EC$ if $t > \bar{t}$; $SR$ otherwise</td></tr>
<tr><td>$\boldsymbol{\epsilon_e + \epsilon_s \leq k}$</td><td colspan="2">$EC$</td></tr>
<tr><td rowspan="2">$\boldsymbol{\bar{k} \leq k < \bar{\bar{k}}}$</td><td>$\boldsymbol{k < \epsilon_e + \epsilon_s}$</td><td>$SR$</td><td rowspan="2">$EC$ if $t > \bar{t}$</td></tr>
<tr><td>$\boldsymbol{\epsilon_e + \epsilon_s \leq k}$</td><td>–</td></tr>
<tr><td rowspan="2">$\boldsymbol{k \geq \bar{\bar{k}}}$</td><td>$\boldsymbol{k < \epsilon_e + \epsilon_s}$</td><td>$SR$</td><td>–</td></tr>
<tr><td>$\boldsymbol{\epsilon_e + \epsilon_s \leq k}$</td><td>–</td><td>$EC$ if $t > \bar{t}$</td></tr>
</table>

Based on Propositions 14-16, Proposition 17 presents the conditions under which EPR-based policies, $EC$ vs. $SR$, can align the preferences of the pharmaceutical producer and advocacy groups along with the choice of the planner. This result demonstrates that welfare maximizing policy can give higher welfare for all the pharmaceutical stakeholders than the alternative policy. However, this may occur only under limited conditions. This indicates that alignment of pharmaceutical stakeholder perspectives may be challenging even under ideal conditions. While two counties in the U.S. (Alameda in CA and King in WA) passed some form of EPR-based legislation for the collection of unused pharmaceuticals, many more counties and states are considering to pass similar type of legislation (e.g. San Francisco [130], Oregon, Maine, New York, Florida [120]). Given this potential growth, legislators need to be prepared for an unending objections from pharmaceutical stakeholders.

## 4.6 Conclusion

Our objective in this essay is to investigate the effective implementation of EPR for pharmaceuticals, a product category with unique characteristics. In particular, we evaluate the effectiveness of two common EPR-based policies that are suitable for pharmaceuticals, End-of-Pipe Collection ($EC$) and Source Reduction ($SR$). The critical difference between these two policies arises from the different mechanisms they use to manage the pharmaceuticals and associated adverse environmental and public health effects. Specifically, $SR$ aims to decrease the dispensed pharmaceuticals with a potential decrease in the unused pharmaceuticals and associated externalities. On the other hand, $EC$ aims to reduce the quantity of unused pharmaceuticals and associated externalities with a potential decrease in the quantity of dispensed pharmaceuticals. To compare these policies, we focus on the unique characteristics of pharmaceuticals by bringing a large body of literature from diverse fields. Accordingly, we document the major roles and interactions of pharmaceutical stakeholders and combine all the relevant factors with a game-theoretic interaction model in the EPR context. To the best of our knowledge, our work is the first to analyze the provision and consumption of the pharmaceuticals with respect to EPR. Based on our analysis, we provide insights to inform the policy makers, producers, and environmental and public health groups about their roles in the pharmaceutical context as summarized below.

*Effective implementation of EPR for pharmaceuticals:* Our work uncovers the conditions for the effectiveness of $EC$ and $SR$ policies for pharmaceuticals. Our analysis demonstrates that $EC$ may work better for pharmaceuticals than $SR$. More specifically, $EC$ gives better welfare results when the medicine has (i) high environmental and public health risks; (ii) moderate/high treatment impact; and (iii) high collection cost. This result has important implications for both literature and practice. First, well-established assumptions regarding the effectiveness of EPR implementations for non-consumable products may fail in the context of pharmaceuticals. In particular, due to the consumable nature of pharmaceuticals and mediated demand structure due to the intermediary role of the doctor in the pharmaceutical chain, the seemingly more flexible $SR$ may be suboptimal. Second, a unified collection program approach applying to many categories of pharmaceuticals may not work effectively from the welfare perspective. For instance, control at the end-of-pipe approach can effectively manage pharmaceuticals with high health impact and high collection-related requirements such as antidepressants, whereas reduction at the source approach can work better for managing the pharmaceuticals with low health impact such as common pain killers and over the counter antihistamines. This suggests that the benefits of collection programs may disappear as they expand to include pharmaceuticals that exhibit different characteristics. Additionally, our analysis predicts that limited treatment impact and low collection-related requirements give high incentives for producers to maintain higher sales of pharmaceuticals. In those cases, even the most stringent EPR implementations may not effectively reduce such incentives. Consequently, end-of-pipe control and source reduction policies may not achieve large reductions in the amount of dispensed pharmaceuticals. Furthermore, given the exogenous patient usage behavior, there always exist an overage in the pharmaceutical supply chain, which may not be completely eliminated though the collection programs. This indicates that EPR implementations need to be complemented by some other arrangements such as restricting promotional activities of the pharmaceutical industry and providing extensive education for patients to create changes in their usage behavior.

*Stakeholder perspectives on EPR-based policies for pharmaceuticals:* Our work demonstrates that collection-related requirements, medicine characteristics, and fee mechanisms of the collection programs determine preferred EPR-based policies from the perspectives of pharmaceutical stakeholders. In particular, producers and environmental/public health advocacy groups should consider collection standards (e.g. highly secure boxes, strict handling requirements, presence of security enforcement at the collection sites, requirement to have collection cites in every city), collection cost efficiency (e.g. diseconomies of scale), medicine treatment aspects (e.g. health aspects associated with the medicine, strength of doctor reputation in the society), and fees that are set by the programs (e.g. disposal fees, point of sale fees) while evaluating different policies. Moreover, our analysis shows that the producer perspectives may favor end-of-pipe collection policies as the collection-related requirements as compared to externality of pharmaceuticals increase and their treatment-related impact decreases. The preferences of environmental and public health advocacy groups move in the opposite direction with a decrease in the treatment impact. As such, aligning the perspectives of stakeholders in the pharmaceutical chain may only happen under limited conditions. This suggests that the pharmaceutical stakeholders need to identify the effects of the different policy implementations on their and other stakeholders' businesses while forming lobbying strategies to avoid disadvantageous situations (e.g. decreased competitiveness for producers and broader environmental and public health problems for NGOs). However, as the pharmaceutical stakeholders use appropriate lobbying strategies, aligning the preferences in the pharmaceutical chain may become more challenging. As the significant growth of EPR-based legislation suggests, EPR legislation will find more place in the state agendas sooner or later for management of pharmaceuticals, particularly in the E.U. and U.S. where the environmental and public health advocacy is getting stronger. Therefore, it is crucial for the pharmaceutical stakeholders to be part of the legislation process by bringing their perspectives clearly into the attention of the legislators and society and to increase their engagement within the pharmaceutical chain to smooth the legislation process.

In closing, we provide a brief discussion on extensions of our analysis with insurance coverage, different DTC advertising effects, and different patient consumption behavior, which are omitted for brevity. See Appendix B §A3 for a detailed analysis. In the insurance extension, we consider a normalized patient population with certain percentage of insured patients whose insurance coverage pays a certain portion of the treatment cost. In the DTC advertising extension, we consider increasing doctor welfare with promotions targeting the patient. In the different patient behavior extension, we make the assumption that the patient stops using the medicine only when he recovers, i.e., the only source of unused pharmaceuticals is the over-prescription of the doctor. We show that our structural results (e.g. the critical factors affecting decisions of the pharmaceutical producer, effectiveness conditions of $EC$ policy as compared to $SR$) continue to hold under these extensions. The possible directions to expand our work in future include incorporating competition dynamics in the pharmaceutical industry and different types of insurance contracts together with their effects on doctor-patient interaction.

# CHAPTER V

# CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

The primary focus of this thesis is Extended Producer Responsibility, which mandates producer responsibility to finance or operate collection and recycling of discarded post-consumer products. In the last two decades, EPR has been employed prevalently for durable products (e.g. electronics) and has recently gained momentum for consumable products (e.g. pharmaceuticals). Three essays in this thesis provide operational perspectives on EPR for durable and consumable products by focusing on electronics and pharmaceuticals, respectively.

In the first essay, we study the environmental effectiveness of EPR in a durable product setting. The existing analysis and current implementations for durable products ignore the durable nature of products and related dynamics in the market, which may have a significant effect on the environmental outcomes. We focus on these ignored aspects and identify the interaction between durability and EPR-based policies by explicitly modeling the durable nature of products. We find that this interaction may result in unintended adverse environmental outcomes by characterizing secondary market strategies of producers to EPR obligations. We demonstrate the validity of our results by using real life data and extending our analysis in several directions to cover different operational settings. Our work in this essay makes contributions by (i) being the first to identify the interaction between EPR and secondary market strategies based on the durable nature of the products; (ii) showing that established assumptions regarding the environmental effectiveness of EPR may not hold in the context of durable products; and (iii) generating policy insights on how to achieve better environmental outcomes for durable products via EPR. These results have brought new perspectives and opened up future research directions with a significant impact on practice:

*Counting refurbishing and remanufacturing operations toward EPR obligations:* The first research direction is regarding whether and how EPR implementations should factor refurbishing and remanufacturing operations towards compliance. There have been recent legislative efforts towards the inclusion of related targets [109], hence whether these operations should count toward recycling targets is an important policy question.

*Incorporating product design aspects:* Another research direction in this context regards product design strategies of durable good producers. The work in the first essay can be extended to include the design decisions of the producer in terms of durability and recyclability and to investigate whether/when environmental obligations lead to superior design (e.g. higher durability, increased recyclability) under different operational configurations.

*Analyzing export practices of developed countries:* Another research direction is related to the trend in export practices and associated restriction policies [147], where prominent examples are full restrictions suggested by Basel Convention [139] and partial restrictions that only allow the export of products with remaining useful life introduced by the US and the EU (The Responsible Recycling Act in the US and the WEEE Directive in EC) [1, 62]. Given the variations across export restrictions in different parts of the world, analyzing the effect of these restrictions on the environmental effectiveness of EPR together with the secondary market strategies of the producer is an interesting question in the international policy arena.

In the second essay, we analyze the adoption of a market-based approach in the implementation of the EPR concept, which has been advocated to have several benefits. We focus on the operational implementation details of the Minnesota

Electronics Recycling Act as it represents the prevailing example of EPR-based policy adopting a marked-based approach. We explore the experience with the Minnesota act along the dimensions of underlying motivations behind its implementation rules, associated stakeholder perspectives and resulting effectiveness. Our analysis suggests that the Minnesota act achieves the advocated benefits of the market-based approach, but this happens at the expense of several unintended outcomes due to the complexity arising from translating the approach into operational specifications. Accordingly, the second essay provides insights into EPR implementations on the ground by showing how operational rules at the implementation stage significantly determine the effectiveness of the market-based approach in practice. The insights presented can be extended by future research that analyzes the implementation of alternative approaches (e.g. central coordination approach with advanced disposal fee and disposal program in CA [43], disposal ban with no producer responsibility requirements in New Hampshire [44], etc.) along with their opportunities and challenges.

In the third essay, we investigate the management of pharmaceutical overage via EPR-based policies, which have gained significant traction in practice in recent years. In particular, we analyze how to effectively operationalize prevalent EPR-based policies in the pharmaceutical context by incorporating the unique characteristics of pharmaceutical supply chain. We mainly focus on the major pharmaceutical stakeholders and the fundamental dynamics in their interactions as they relate to EPR. Our analysis uncovers the effectiveness conditions for EPR-based policies from both a total welfare perspective and the perspectives of pharmaceutical stakeholders. The main contributions of our analysis are three-fold: (i) building the first analytical model that focuses on interactions in the pharmaceutical chain as they relate to EPR; (ii) showing how the complexity of interactions in the pharmaceutical chain affects the preferred EPR-based policy from the welfare perspective and imposes a challenge towards aligning EPR-based implementation choices among the stakeholders; (iii) demonstrating that the characteristics unique to pharmaceuticals may require a completely different perspective in implementation of EPR-based policy when compared to other product categories for which EPR is prevalent. These results have lead to several paths for future research:

*Including competition and insurance dynamics in the policy analysis:* The first possible research direction relates to exploring the effect of competition and different insurance dynamics on EPR-based policy choices in the management of pharmaceutical overage. The underlying motivation is that the presence of competition among pharmaceutical producers may bring interesting pricing and cost dynamics that may affect promotional decisions of the producers. Moreover, different insurance plans as cost-sharing tools are shown to have different effects on the doctor practices [67] and access of the patients to the medicine [97]. The research in this context has the potential to enrich perspectives on EPR-based policies by increasing the influential dynamics analyzed.

*Investigating the design of pharmaceutical collection networks:* Another future research direction concerns the design of collection networks for pharmaceuticals under EPR-related obligations. It would be valuable to incorporate the real-world challenges and opportunities associated with pharmaceutical take-back programs (e.g. requirements to undertake collection at law enforcement offices or pharmacies, to have security personnel at the collection sites, to impose strict handling specifications; and economies of scale opportunities in incineration treatment) and to explore the establishment of efficient collection infrastructure.

*Analyzing the implementation details on the ground:* As the second essay in this thesis suggests, stakeholder responses and operational outcomes can vary significantly in response to the specifics of the chosen policy and associated implementation details. Given the unique characteristics of the pharmaceutical supply chain and the complexity of interactions among pharmaceutical stakeholders, analyzing the implementation choices of the current EPR-based policies with respect to expected outcomes is an interesting research path.

In sum, the three essays in this thesis bring new perspectives on environmental policies and their effect on business practices in electronics and pharmaceutical industries by (i) challenging established assumptions and (ii) providing insights on the prevalent policy questions contingent on the nature of products and market dynamics. Accordingly, this thesis contributes to the generation of responsible policies for industries with prominent environmental and social impacts by focusing on the management of operational challenges at the intersection of business practices and sustainability.

# APPENDIX A

# EXTENDED PRODUCER RESPONSIBILITY AND SECONDARY MARKETS

**A1. Derivation of inverse demand functions.** The action vector of consumer with type $\theta$ in period $t$ is denoted by $C^t(\theta) = (N^t(\theta), U^t(\theta), I^t(\theta))$ where indicator variables $N^t, U^t$ and $I^t$ correspond to buying a new product (N), buying an used product (U), and remaining inactive (I), respectively. The net utility per period is denoted by $\pi^t_\theta[C^t(\theta), C^{t-1}(\theta), p^t, p^{t+1}]$ where $p^t = [p^t_n, p^t_u]$. A consumer's utility-maximization problem is given by $V^t_\theta[C^{t-1}(\theta), p^t, p^{t+1}] = \max_{C^t(\theta)}\{\pi^t_\theta[C^{t-1}(\theta), C^t(\theta), p^t, p^{t+1}] + \rho V^{t+1}_\theta[C^t(\theta), p^{t+1}, p^{t+2}]\}$, where $V^t_\theta[C^{t-1}(\theta), p^t, p^{t+1}]$ is the net present value function in period $t$. This decision is subject to $C^t(\theta)1' = 1$, i.e., the consumer can obtain at most one product at each time period. Let $R^t_\theta[C^{t-1}(\theta), p^t, p^{t+1}]$ be the reaction function of the consumer type $\theta$ in period $t$. Since we focus on Markov perfect equilibria where all decisions stay constant in time, i.e., the focal point, the net present value maximization problem can be written as $V_\theta[C(\theta), p] = \max_{C(\theta)}\{\pi_\theta[C(\theta), R_\theta[C(\theta), p], p] + \rho V_\theta[R_\theta[C(\theta), p], p]\}$ s.t. $C(\theta)1' = 1$.

Under stationarity, the per-period net utility from $N$ is $\theta - p_n + \rho p_u$, from $U$ is $\delta\theta - p_u$, and 0 from $I$. There are nine possible strategies for the consumer which can be shown as $NN$, $NI$, $IN$, $NU$, $UN$, $UU$, $UI$, $IU$, and $II$. Due to the periodicity of two for all consumer strategies at the focal point, permutations of the same pattern are not distinct. Hence there exist only six distinct strategies: $NN$, $NU$, $NI$, $UU$, $UI$, and $II$. Moreover, as the net utility from any of the actions is independent of the action in the previous period, any strategy where a consumer chooses an action which is different than the action in the previous period is dominated (see [70] and [4]). This implies that $NU$, $NI$, and $UI$ strategies are ruled out.

The present value of the remaining strategies can be calculated using the Bellman equation. For consumers playing the $NN$ strategy, solving $V_\theta[N,p] = \theta - p_n + \rho p_u + \rho V_\theta[N,p]$, we get $V_\theta[N,p] = \frac{\theta - p_n + \rho p_u}{1-\rho}$. For consumers playing the $UU$ strategy, solving $V_\theta[U,p] = \delta\theta - p_u + \rho V_\theta[U,p]$, we get $V_\theta[U,p] = \frac{\delta\theta - p_u}{1-\rho}$. Finally, for consumers who play the $II$ strategy, $V_\theta[I,p] = 0$. It is straightforward to show that $\frac{d(V_\theta(N,p) - V_\theta(U,p))}{d\theta} > 0$ and $\frac{d(V_\theta(U,p) - V_\theta(I,p))}{d\theta} > 0$. This implies that the consumers who play $NN$ have higher valuation $\theta$ than the ones who play $UU$, who in turn have higher $\theta$ than the consumers who play $II$. Let $\theta_1$ and $\theta_2$ represent the indifferent consumer types between $NN$ and $UU$ strategies, and between $UU$ and $II$ strategies, respectively. The consumers with valuations $\theta \in (0, \theta_2]$ play the $II$ strategy, the consumers with valuations $\theta \in (\theta_2, \theta_1]$ play the $UU$ strategy, and the consumers with valuations $\theta \in (\theta_1, 1]$ play the $NN$ strategy, where we obtain $\theta_2 \doteq \frac{p_u}{\delta}$ by solving $V_\theta[U,p] = V_\theta[I,p]$, and $\theta_1 \doteq \frac{p_n - (1+\rho)p_u}{1-\delta}$ by solving $V_\theta[N,p] = V_\theta[U,p]$.

In the secondary market, the supply of used products is given by $1 - \theta_1$. Demand for the used products is given by $\theta_1 - \theta_2 + q_u$. The market-clearing price for the used products on the secondary market is obtained by solving $1 - \theta_1 = \theta_1 - \theta_2 + q_u$, and is given by $p_u = \frac{\delta(-1+\delta+2p_n+(1-\delta)q_u)}{1+\delta+2\delta\rho}$. The demand for new products is given by $q_n = 1-\theta_1$, which yields $p_n = 1+(1+\rho)p_u - \delta(1-q_n) - q_n$. Solving these simultaneously, the inverse demand functions are given by $p_n(q_n, q_u) = 1 - q_n + \delta(-q_n + q_u + \rho(1 - 2q_n + q_u))$ and $p_u(q_n, q_u) = \delta(1 - 2q_n + q_u)$. Note that for $0 \leq q_u \leq q_n$, we have that the maximum value of $p_u$ is $\delta$ and is attained at $q_n = q_u = 0$. Therefore, $p_u(q_n, q_u) \leq \delta$. $\square$

**A2. Proofs.** We assume $\rho = 1$ for the proofs.

**Proof of Lemma 1**. Assume that there is no EPR legislation ($\alpha = 0$). The producer's problem is given by $\max_{q_n, q_u} \Pi(q_n, q_u, 0) = (p_n(q_n, q_u) - c)q_n - p_u(q_n, q_u)q_u$, such that $q_u \leq q_n$ and $q_u, q_n \geq 0$. The Hessian of the per-period profit function is given by $\begin{pmatrix} -2(1+3\delta) & 4\delta \\ 4\delta & -2\delta \end{pmatrix}$, which is negative definite for $\delta \in (0,1)$. Therefore, the profit function is jointly concave in $q_n$ and $q_u$. The Lagrangian of the problem is given by $L(q_n, q_u, \lambda, \mu_1, \mu_2) = \pi(q_n, q_u, 0) - \lambda(q_u - q_n) + \mu_1 q_n + \mu_2 q_u$. The first-order conditions are given by $\Psi_1(q_n, q_u, \lambda, \mu_1) \doteq \frac{\partial L}{\partial q_n} = 1 - c + \delta + \lambda + \mu_1 - 2(1+3\delta)q_n + 4\delta q_u = 0$ and $\Psi_2(q_n, q_u, \lambda, \mu_2) \doteq \frac{\partial L}{\partial q_u} = -\lambda + \mu_2 - \delta(1 - 4q_n + 2q_u) = 0$. There are four candidate solutions.

**Case 1.** $q_u = q_n = 0$, which implies $\lambda, \mu_1, \mu_2 \geq 0$. Solving $\Psi_1(0, 0, \lambda, \mu_1) = 0$ gives $\lambda + \mu_1 = c - 1 - \delta$. $\lambda, \mu_1 \geq 0$ requires $c \geq 1 + \delta$. To restrict our analysis to parameters for the producer to have non-negative profit, we assume $c < 1 + \delta$, and this case is ruled out.

**Case 2.** $0 = q_u < q_n$, which implies $\lambda = \mu_1 = 0$, and $\mu_2 \geq 0$. Solving $\Psi_1(q_n, 0, 0, 0) = 0$ and $\Psi_2(q_n, 0, 0, \mu_2) = 0$ gives $q_n = \frac{1+\delta-c}{2(1+3\delta)}$ and $\mu_2 = \frac{\delta(\delta+2c-1)}{1+3\delta}$. $q_n > 0$ due to the assumption $c < 1 + \delta$. $\mu_2 \geq 0$ if and only if $\delta \geq 1 - 2c$. The new and used prices are $p_n = \frac{1+c+\delta}{2}$ and $p_u = \frac{\delta(c+2\delta)}{1+3\delta}$, respectively.

**Case 3.** $0 < q_u = q_n$, which implies $\lambda \geq 0$ and $\mu_1 = \mu_2 = 0$. Solving $\Psi_1(q_n, q_n, \lambda, 0) = 0$ and $\Psi_2(q_n, q_n, \lambda, 0) = 0$ gives $\lambda = -\delta c < 0$, hence this case is ruled out.

**Case 4.** $0 < q_u < q_n$, which implies $\lambda = \mu_1 = \mu_2 = 0$. Solving $\Psi_1(q_n, q_u, 0, 0) = 0$ and $\Psi_2(q_n, q_u, 0, 0) = 0$ gives $q_n = \frac{1-\delta-c}{2(1-\delta)}$ and $q_u = \frac{1-\delta-2c}{2(1-\delta)}$, where $q_n > q_u$ holds. $q_u > 0$ if and only if $\delta < 1 - 2c$. The new and used prices are $p_n = \frac{1+c+\delta}{2}$ and $p_u = \frac{\delta}{2}$, respectively. Let $\widehat{\alpha}(\delta, c) \doteq \frac{q_u}{q_n} = \frac{1-\delta-2c}{1-\delta-c}$ denote the fraction of used products collected by the producer.

Summarizing the above: if $\delta < 1 - 2c$, then $0 < q_u < q_n$, otherwise, $q_u = 0$, proving Lemma 1. □

**Proof of Propositions 1-4.** The producer's problem is given by $\max_{q_n, q_u, q_{eol}} \Pi(q_n, q_u, q_{eol}) = (p_n(q_n, q_u) - c)q_n - p_u(q_n, q_u)q_u - s\alpha q_n - kq_{eol}$, such that $q_{eol} \leq q_n - q_u$, $\alpha q_n \leq q_u + q_{eol}$, and $q_n, q_u, q_{eol} \geq 0$. The Hessian of the per-period profit function is given by $\begin{pmatrix} -2(1+3\delta) & 4\delta & 0 \\ 4\delta & -2\delta & 0 \\ 0 & 0 & 0 \end{pmatrix}$, which is negative definite for $\delta \in (0,1)$.

Therefore, the profit function is jointly concave in $q_n$, $q_u$, and $q_{eol}$. The Lagrangian of the problem is given by $L(q_n, q_u, q_{eol}, \lambda, \mu, \beta_1, \beta_2, \beta_3) = \pi(q_n, q_u, q_{eol}) - \lambda(q_{eol} + q_u - q_n) - \mu(\alpha q_n - q_u - q_{eol}) + \beta_1 q_n + \beta_2 q_u + \beta_3 q_{eol}$. The first-order conditions are $\Psi_1(q_n, q_u, \lambda, \mu, \beta_1) \doteq \frac{\partial L}{\partial q_n} = 1 - c + \delta + \lambda + \beta_1 - 2(1+3\delta)q_n - \alpha(s+\mu) + 4\delta q_u = 0$, $\Psi_2(q_n, q_u, \lambda, \mu, \beta_2) \doteq \frac{\partial L}{\partial q_u} = \beta_2 + \mu - \lambda - \delta(1 - 4q_n + 2q_u) = 0$, and $\Psi_3(\lambda, \mu, \beta_3) \doteq \frac{\partial L}{\partial q_{eol}} = \mu + \beta_3 - \lambda - k = 0$. There are seven candidate solutions (summarized below).

**Case 1.** $q_u = q_{eol} = 0$, which implies $q_n = 0$ and $\lambda, \mu, \beta_1, \beta_2, \beta_3 \geq 0$. It is straightforward to show that the required condition for this case is $s \geq \max\{\frac{1+\delta-c-\alpha k}{\alpha} \doteq s_*^1(\delta, \alpha, c, k), \frac{1+\delta-c-\alpha\delta}{\alpha} \doteq s_*^2(\delta, \alpha, c)\}$, or $c \geq 1 + \delta - \alpha(s + \min(\delta, k))$ (details available on request). To ensure non-negativity of the producer's profit, we hereafter assume $c < 1 + \delta - \alpha(s + \min(\delta, k))$ holds, which rules out this case.

**Case 2.** $q_u > 0$, $q_{eol} = 0$, $\alpha q_n = q_u < q_n$, which implies $\lambda = \beta_1 = \beta_2 = 0$ and $\mu, \beta_3 \geq 0$. Solving $\Psi_1(q_n, \alpha q_n, 0, \mu, 0) = 0$, $\Psi_2(q_n, \alpha q_n, 0, \mu, 0) = 0$ and $\Psi_3(0, \mu, \beta_3) = 0$ gives $q_n = \frac{1-c+(1-\alpha)\delta-\alpha s}{2+2(3-\alpha)(1-\alpha)\delta}$, $\mu = \frac{\delta(-1+2c+\delta-\alpha(-1+c+\delta-(2-\alpha)s))}{1+(3-\alpha)(1-\alpha)\delta}$, and $\beta_3 = \frac{k(1+(3-\alpha)(1-\alpha)\delta)-\delta(-1+2c+\delta-\alpha(-1+c+\delta-(2-\alpha)s))}{1+(3-\alpha)(1-\alpha)\delta}$. For $q_u > 0$, $\mu \geq 0$ and $\beta_3 \geq 0$, the required conditions are $s < s_*^2(\cdot)$, $s \leq \frac{k-\delta(-1+2c+\delta-3k-\alpha(-1+c+\delta-(4-\alpha)k))}{\alpha\delta(2-\alpha)} \doteq s_1(\delta, \alpha, c, k)$ and $s \geq \frac{1-2c-\delta+\alpha(-1+c+\delta)}{\alpha(2-\alpha)} \doteq s_0(\delta, \alpha, c)$. As $s_0(\cdot) < s_1(\cdot)$, $s_0(\cdot) < s_2^*(\cdot)$, and $s_1(\cdot) \leq s_2^*(\cdot)$ only for $\delta > k$, the required conditions are $s_0(\cdot) \leq s < s_2^*(\cdot)$ for $\delta \leq k$, and $s_0(\cdot) \leq s \leq s_1(\cdot)$ for $k < \delta$.

**Case 3.** $q_u > 0$, $q_{eol} = 0$ and $\alpha q_n < q_u < q_n$, which implies $\lambda = \mu = \beta_1 = \beta_2 = 0$ and $\beta_3 \geq 0$. Solving $\Psi_1(q_n, q_u, 0, 0, 0) = 0$, $\Psi_2(q_n, q_u, 0, 0, 0) = 0$ and $\Psi_3(0, 0, \beta_3) = 0$ gives $q_n = \frac{1-\delta-c-\alpha s}{2(1-\delta)}$, $q_u = \frac{1-\delta-2c-2s\alpha}{2(1-\delta)}$, and $\beta_3 = k$. For $0 < \alpha q_n < q_u$, the required condition is $s < s_0(\cdot)$, where $s_0(\cdot) > 0$ only if $\delta < 1 - 2c$.

**Case 4.** $q_u > 0$, $q_{eol} = 0$ and $\alpha q_n < q_u = q_n$, which implies $\beta_1 = \beta_2 = \mu = 0$ and $\lambda, \beta_3 \geq 0$. Solving $\Psi_1(q_n, q_n, \lambda, 0, 0) = 0$ and $\Psi_2(q_n, q_n, \lambda, 0, 0) = 0$ gives $\lambda = -\delta(c + \alpha s) < 0$, and this case is ruled out.

**Case 5.** $q_u = 0$, $q_{eol} > 0$ and $\alpha q_n = q_{eol} < q_n$, which implies $\lambda = \beta_1 = \beta_3 = 0$ and

$\mu, \beta_2 \geq 0$. Solving $\Psi_1(q_n, 0, 0, \mu, 0) = 0$ and $\Psi_2(q_n, 0, 0, \mu, \beta_2) = 0$, and $\Psi_3(0, \mu, 0) = 0$ gives $q_n = \frac{1+\delta-c-\alpha(s+k)}{2(1+3\delta)}$, $\mu = k$, and $\beta_2 = \frac{\delta(-1+\delta+2c+2\alpha(s+k))}{1+3\delta} - k$. For $q_{eol} > 0$ and $\beta_2 \geq 0$, the required conditions are $\frac{k(1+3\delta)+\delta(1-2c-\delta-2\alpha k)}{2\alpha\delta} \doteq s_2(\delta, \alpha, c, k) \leq s < s_*^1(\cdot)$, where $s_2(\cdot) < s_*^1(\cdot)$ holds only for $k < \delta$.

**Case 6.** $q_u \geq 0$, $q_{eol} > 0$ and $\alpha q_n < q_{eol} \leq q_n$, which gives $\mu = \beta_1 = \beta_3 = 0$ and $\lambda \geq 0$. In this case, $\Psi_3(0, 0, 0) = -\lambda - k < 0$, hence this case is ruled out.

**Case 7.** $q_u > 0$, $q_{eol} > 0$ and $\alpha q_n = q_u + q_{eol} < q_n$, which gives $\lambda = \beta_1 = \beta_2 = \beta_3 = 0$ and $\mu \geq 0$. Solving $\Psi_1(q_n, q_u, 0, \mu, 0) = 0$, $\Psi_2(q_n, q_u, 0, \mu, 0) = 0$ and $\Psi_3(0, \mu, 0) = 0$ gives $q_n = \frac{1-c-\delta-\alpha s+(2-\alpha)k}{2(1-\delta)}$, $q_u = \frac{k+\delta(1-2c-\delta+3k-2\alpha(s+k))}{2(1-\delta)\delta}$, $q_{eol} = \frac{-k-\delta(1-2c-\delta+3k+\alpha(-1+c+\delta-(2-\alpha)s-(4-\alpha)k))}{2\delta(1-\delta)}$, and $\mu = k$. For $q_u > 0$ and $q_{eol} > 0$, the required conditions are $s_1(\cdot) < s < s_2(\cdot)$, where $s_1(\cdot) < s_2(\cdot)$ holds only for $k < \delta$. In this case, $p_u = \frac{\delta+k}{2}$, where $p_u > k$ for $\delta > k$.

It is straightforward to show that the above cases can be summarized as follows: (i) $\delta \leq k$: if $s < s_0(\cdot)$, $\alpha q_n < q_u < q_n$, $q_{eol} = 0$; if $s \geq s_0(\cdot)$, $q_u = \alpha q_n$, $q_{eol} = 0$. (ii) $k < \delta$: if $s < s_0(\cdot)$, $\alpha q_n < q_u < q_n$, $q_{eol} = 0$; if $s_0(\cdot) \leq s \leq s_1(\cdot)$, $q_u = \alpha q_n$, $q_{eol} = 0$; if $s_1(\cdot) < s < s_2(\cdot)$, $q_u, q_{eol} > 0$, $q_u + q_{eol} = \alpha q_n$, and if $s \geq s_2(\cdot)$, $q_u = 0$, $q_{eol} = \alpha q_n$. As $s_0(\cdot) \leq 0$ for $\delta \geq 1 - 2c$, the above proves Propositions 1 and 2.

To prove Proposition 3, assume $\delta < 1-2c$. We need to compare the $q_u = \frac{1-\delta-2c}{2(1-\delta)} (> 0)$ in the absence of EPR with the cases above that hold for $\delta < 1-2c$, viz., Cases 2, 3, 5, and 7. If $s < s_0(\cdot)$, then comparing with Case 3, $\frac{1-\delta-2c}{2(1-\delta)} - \frac{1-\delta-2c-2s\alpha}{2(1-\delta)} = \frac{\alpha s}{1-\delta} > 0$. Note that the condition $s_0(\cdot) > 0$ can be written as $\alpha < \frac{1-2c-\delta}{1-c-\delta} \doteq \widehat{\alpha}(\delta, c)$. If $s_0(\cdot) \leq s \leq s_1(\cdot)$, then comparing with Case 2 gives that $\frac{1-\delta-2c}{2(1-\delta)} - \alpha\left(\frac{1-c+(1-\alpha)\delta-\alpha s}{2+2(3-\alpha)(1-\alpha)\delta}\right) < 0$ only if $s < \frac{(c(2-\alpha)-(1-\alpha)(1-\delta))(1+(3-2\alpha)\delta)}{\alpha^2(1-\delta)} \doteq \widehat{s}_1(\delta, \alpha, c)$ and $\alpha \geq \widehat{\alpha}(\cdot)$. Comparison with Case 7 (where $s_1(\cdot) < s < s_2(\cdot)$) gives that $\frac{1-\delta-2c}{2(1-\delta)} - \frac{k+\delta(1-2c-\delta+3k-2\alpha(s+k))}{2(1-\delta)\delta} = \frac{k+3\delta k-2\alpha\delta k-2\alpha\delta s}{2\delta(1-\delta)} < 0$ for $s < \frac{k(1+(3-2\alpha)\delta)}{2\alpha\delta} \doteq \widehat{s}_2(\delta, \alpha, k)$ and $\alpha \geq \widehat{\alpha}(\cdot)$. Comparing with Case 5 (where $s \geq s_2(\cdot)$), $\frac{1-\delta-2c}{2(1-\delta)} - 0 > 0$. Therefore, EPR leads to higher $q_u$ for $\alpha \geq \widehat{\alpha}(\delta, c)$ and $s < \widehat{s}(\delta, \alpha, c, k)$ where $\widehat{s}(\cdot) = \widehat{s}_1(\cdot)$ for $s < s_1(\cdot)$ and $\widehat{s}(\cdot) = \widehat{s}_2(\cdot)$ for $s_1(\cdot) \leq s \leq s_2(\cdot)$, where

$\widehat{s}_2(\cdot) - s_2(\cdot) = \frac{\delta+2c-1}{2\alpha} < 0$, which implies that $\widehat{s}(\cdot) < s_2(\cdot)$. This proves Proposition 3. $\frac{d\widehat{\alpha}(\delta,c)}{d\delta} = \frac{-c}{(1-c-\delta)^2} < 0$, $\frac{ds_0(\delta,\alpha,c)}{d\delta} = -(\frac{1-\alpha}{\alpha(2-\alpha)}) < 0$, $\frac{ds_1(\delta,\alpha,c,k)}{d\delta} = -(\frac{(1-\alpha)\delta^2+k}{(2-\alpha)\alpha\delta^2}) < 0$ and $\frac{ds_2(\delta,\alpha,c,k)}{d\delta} = -(\frac{\delta^2+k}{2\alpha\delta^2}) < 0$, proving Proposition 4. □

**Proof of Propositions 5-7.** Let $ru = \frac{q_n-q_u}{q_n}$ denote the reuse level. When $s < s_0(\cdot)$, $\frac{dru}{ds} = \frac{\alpha(1-\delta)}{(1-c-s\alpha-\delta)^2} > 0$ and $\frac{dq_n}{ds} = -(\frac{\alpha}{2(1-\delta)}) < 0$. When $\delta \leq k$ and $s \geq s_0(\cdot)$ or when $k < \delta$ and $s_0(\cdot) \leq s \leq s_1(\cdot)$, $ru = 1-\alpha$ and $\frac{dq_n}{ds} = -(\frac{\alpha}{2+2(3-\alpha)(1-\alpha)\delta}) < 0$. When $k < \delta$, if $s_1(\cdot) < s < s_2(\cdot)$, $\frac{dru}{ds} = \frac{\alpha(1-\delta)(\delta-k)}{\delta(c+\delta-1+\alpha s-(2-\alpha)k)^2} > 0$ and $\frac{dq_n}{ds} = -(\frac{\alpha}{1-\delta}) < 0$; and if $s \geq s_2(\cdot)$, $ru = 1$ and $\frac{dq_n}{ds} = -(\frac{\alpha}{2(1+3\delta)}) < 0$. This proves Proposition 5. Under the End-of-life Recycling strategy, $\frac{dq_n}{dk} = -(\frac{\alpha}{2(1+3\delta)}) < 0$. Under the Mixed Recycling strategy, $\frac{dq_n}{dk} = \frac{2-\alpha}{2(1-\delta)} > 0$ and $\frac{dru}{dk} = -(\frac{(1-\delta)(1-c+(1-\alpha)\delta-\alpha s)}{\delta(c+\delta-1+\alpha s-(2-\alpha)k)^2}) < 0$. This proves Proposition 6. When the producer adopts the Mixed Recycling strategy, $\frac{dq_n}{d\alpha} = -(\frac{k+s}{2(1-\delta)}) < 0$ and $\frac{dru}{d\alpha} = \frac{(k+s)(\delta-k)(1-\delta)}{\delta(1-c+k(2-\alpha)-s\alpha-\delta)^2} > 0$. When the producer adopts a End-of-Life Recycling strategy, $\frac{dq_n}{d\alpha} = -(\frac{k+s}{2(1+3\delta)}) < 0$ and $ru = 1$. When the producer adopts an Used Product Recycling strategy and $s < s_0(\cdot)$, $\frac{dq_n}{d\alpha} = -(\frac{s}{2(1-\delta)}) < 0$ and $\frac{dru}{d\alpha} = \frac{s(1-\delta)}{(1-c-s\alpha-\delta)^2} > 0$. Finally, when the producer adopts the Used Product Recycling strategy and $s \geq s_0(\cdot)$, there is a unique value of $\alpha \in (0,1)$, given by $\alpha_1(\delta,c,s) \doteq \frac{\delta-c\delta+\delta^2-\sqrt{\delta(\delta((c-1)^2+(-1+2c)\delta)+2\delta(-1+2c+\delta)s+(1+3\delta)s^2)}}{\delta(\delta+s)}$, that solves $\frac{dq_n}{d\alpha} = 0$. It is straightforward to show that $\frac{d^2q_n}{d\alpha^2}|_{\alpha_1(\cdot)} < 0$. This implies that $\frac{dq_n}{d\alpha} > 0$ when $\alpha < \alpha_1(\cdot)$ and $\frac{dq_n}{d\alpha} < 0$ otherwise. $ru = 1-\alpha$, which is decreasing in $\alpha$. This proves Proposition 7. □

**Proof of Lemmas 2 and 3.** Assume that there is no EPR legislation ($\alpha = 0$). The producer's problem is given by $\max_{q_n,q_u,q_r}(p_n(q_n,q_u,q_r)-c)q_n - p_u(q_n,q_u,q_r)q_u + (p_r(q_n,q_u,q_r)-c_r)q_r$, such that $q_r \leq q_u \leq q_n$ and $q_r, q_u, q_n \geq 0$. The Hessian of the per-period profit function is negative definite for $\delta < \delta_r$ and $\delta, \delta_r \in (0,1)$. Therefore, the profit function is jointly concave in $q_n, q_u$ and $q_r$. The Lagrangian of the problem is given by $L(q_n,q_u,q_r,\lambda,\mu,\beta_1,\beta_2,\beta_3) = \pi(q_n,q_u,q_r) - \lambda(q_r-q_u) - \mu(q_u-q_n) + \beta_1 q_n + \beta_2 q_u + \beta_3 q_r$. The first-order conditions are given by $\Psi_1(q_n,q_u,q_r,\mu,\beta_1) \doteq \frac{\partial L}{\partial q_n} = 0$,

$\Psi_2(q_n, q_u, q_r, \lambda, \mu, \beta_2) \doteq \frac{\partial L}{\partial q_u} = 0$, and $\Psi_3(q_n, q_u, q_r, \lambda, \beta_3) \doteq \frac{\partial L}{\partial q_r} = 0$. There are six candidate solutions:

**Case 1.** $q_r = q_u = q_n = 0$, which implies $\lambda, \mu, \beta_1, \beta_2, \beta_3 \geq 0$. Solving $\Psi_1(0,0,0,\mu,\beta_1) = 0$ gives $\mu + \beta_1 = c - 1 - \delta$. $\mu, \beta_1 \geq 0$ requires $c \geq 1 + \delta$. To restrict our analysis to parameters for the producer to have non-negative profit, we assume $c < 1 + \delta$, this case is ruled out.

**Case 2.** $0 < q_r = q_u = q_n$, which implies $\lambda, \mu \geq 0$ and $\beta_1, \beta_2, \beta_3 = 0$. Solving $\Psi_1(q_n, q_n, q_n, \mu, 0) = 0$, $\Psi_2(q_n, q_n, q_n, \lambda, \mu, 0) = 0$ and $\Psi_3(q_n, q_n, q_n, \lambda, 0) = 0$ gives $q_n = q_u = q_r = \frac{1-c-c_r+\delta_r}{2+6\delta_r}$, $\lambda = \frac{\delta_r(-1+2c+\delta_r)-c_r(1+\delta_r)}{1+3\delta_r}$, and $\mu = -c_r - \delta + \delta_r + \frac{2(-1+c+c_r-\delta_r)(\delta_r-\delta)}{1+3\delta_r}$. For $q_r > 0$, $\lambda \geq 0$ and $\mu \geq 0$, the required condition is $c_r \leq \frac{(\delta_r-\delta)(2c+\delta_r-1)}{1+2\delta+\delta_r} \doteq c_{r1}(c, \delta_r, \delta)$, where $c_{r1}(\cdot) \geq 0$ only if $2c + \delta_r \geq 1$.

**Case 3.** $0 < q_r = q_u < q_n$, which implies $\lambda \geq 0$ and $\mu, \beta_1, \beta_2, \beta_3 = 0$. Solving $\Psi_1(q_n, q_u, q_r, 0, 0) = 0$, $\Psi_2(q_n, q_u, q_r, \lambda, 0, 0) = 0$ and $\Psi_3(q_n, q_u, q_r, \lambda, 0) = 0$ gives $q_n = \frac{1-c+c_r+2\delta-\delta_r}{2+8\delta-2\delta_r}$, $q_r = q_u = \frac{1}{2}(\frac{c-c_r+2\delta}{1+4\delta-\delta_r} - \frac{c_r}{\delta_r-\delta})$, and $\lambda = \frac{\delta(-1+2c-2c_r+\delta_r)}{1+4\delta-\delta_r}$. For $\lambda \geq 0$, $0 < q_u$, and $q_u < q_n$, the required conditions are $c_r \leq \frac{-1+2c+\delta_r}{2} \doteq c_{r2}(c, \delta_r)$, $c_r < \frac{(c+2\delta)(\delta_r-\delta)}{1+3\delta} \doteq c_{r3}(c, \delta_r, \delta)$, and $c_r > c_{r1}(\cdot)$. As $c_{r2}(\cdot) < c_{r3}(\cdot)$ for $\delta + 2c < 1$, the conditions are simplified as $c_{r1}(\cdot) < c_r \leq c_{r2}(\cdot)$ for $\delta + 2c < 1$ and $c_{r1}(\cdot) < c_r < c_{r3}(\cdot)$ otherwise.

**Case 4.** $0 < q_r < q_u < q_n$, which implies $\lambda, \mu, \beta_1, \beta_2, \beta_3 = 0$. Solving $\Psi_1(q_n, q_u, q_r, 0, 0) = 0$, $\Psi_2(q_n, q_u, q_r, 0, 0, 0) = 0$ and $\Psi_3(q_n, q_u, q_r, 0, 0) = 0$ gives $q_n = \frac{1-c+c_r-\delta_r}{2(1-\delta_r)}$, $q_u = \frac{1}{2}(1 - \frac{c_r}{\delta_r-\delta} + \frac{c_r-c}{1-\delta_r})$ and $q_r = \frac{1}{2}(\frac{c-c_r}{1-\delta_r} - \frac{c_r}{\delta_r-\delta})$, where $q_u < q_n$. For $0 < q_r$ and $q_r < q_u$, the required conditions are $c_{r2}(\cdot) < c_r < \frac{c(\delta_r-\delta)}{1-\delta} \doteq c_{r4}(c, \delta_r, \delta)$, where $c_{r2}(\cdot) < c_{r4}(\cdot)$ holds only if $2c + \delta < 1$.

**Case 5.** $0 = q_r < q_u < q_n$, which implies $\beta_3 \geq 0$ and $\lambda, \mu, \beta_1, \beta_2 = 0$. Solving $\Psi_1(q_n, q_u, 0, 0, 0) = 0$, $\Psi_2(q_n, q_u, 0, 0, 0, 0) = 0$, and $\Psi_3(q_n, q_u, 0, 0, \beta_3) = 0$ gives $q_n = \frac{1-\delta-c}{2(1-\delta)}$ and $q_u = \frac{1-\delta-2c}{2(1-\delta)}$, where $q_n > q_u$ holds. For $q_u > 0$ and $\beta_3 \geq 0$, the required conditions are $c_r \geq c_{r4}(\delta, \delta_r, c)$ and $2c + \delta < 1$.

**Case 6.** $0 = q_r = q_u < q_n$, which implies $\mu, \beta_1 = 0$, and $\lambda, \beta_2, \beta_3 \geq 0$. For this case,

$q_n = \frac{1-c+\delta}{2+6\delta}$ and the required conditions for this case are $2c + \delta \geq 1$ and $c_r \geq c_{r3}(\cdot)$ (details available on request).

Summarizing the above: (i) if $\delta < 1 - 2c$: $0 < q_r = q_u = q_n$ if $c_r \leq c_{r1}(\cdot)$, $0 < q_r = q_u < q_n$ if $c_{r1}(\cdot) < c_r \leq c_{r2}(\cdot)$, $0 < q_r < q_u < q_n$ if $c_{r2}(\cdot) < c_r < c_{r4}(\cdot)$, and $0 = q_r < q_u < q_n$ otherwise. (ii) if $\delta \geq 1 - 2c$: $0 < q_r = q_u = q_n$ if $c_r \leq c_{r1}(\cdot)$, $0 < q_r = q_u < q_n$ if $c_{r1}(\cdot) < c_r < c_{r3}(\cdot)$, and $0 = q_r = q_u < q_n$ otherwise. Therefore, $q_r > 0$ if and only if $c_r < r_1(c, \delta_r, \delta)$, where $r_1(\cdot) = c_{r3}(\cdot)$ for $\delta \geq 1 - 2c$ and $r_1(\cdot) = c_{r4}(\cdot)$ otherwise. $q_u - q_r > 0$ only for $c_r > r_2(c, \delta_r, \delta) \doteq c_{r2}(\cdot)$ and $\delta < 1 - 2c$, where $c_{r2}(\cdot) < c_{r4}(\cdot), c_{r3}(\cdot)$ for $\delta + 2c < 1$, which implies $r_2(\cdot) < r_1(\cdot)$. Finally, it can be seen from above that when $c_r \geq r_1(\cdot)$, $q_u > 0$ only for $\delta < 1 - 2c$. $\square$

**Proof of Lemma 4 and Propositions 8-10.** The producer's problem is given by $\max_{q_n,q_u,q_r,q_{eol}} (p_n(q_n, q_u, q_r) - c)q_n - p_u(q_n, q_u, q_r)q_u + (p_r(q_n, q_u, q_r) - c_r)q_r - kq_{eol} - s\alpha q_n$, such that $q_r \leq q_u \leq q_n$, $\alpha q_n \leq q_u - q_r + q_{eol}$, $q_{eol} \leq q_n - q_u + q_r$, and $q_r, q_u, q_n, q_{eol} \geq 0$. The Hessian of the per-period profit function is negative definite for $\delta < \delta_r$ and $\delta, \delta_r \in (0, 1)$. Therefore, the profit function is jointly concave in $q_n, q_u, q_r$ and $q_{eol}$. The Lagrangian of the problem is given by $L(q_n, q_u, q_r, q_{eol}, \lambda, \mu, \eta, \omega, \beta_1, \beta_2, \beta_3, \beta_4) = \Pi(q_n, q_u, q_r, q_{eol}) - \lambda(q_r - q_u) - \mu(q_u - q_n) - \eta(\alpha q_n - q_u + q_r - q_{eol}) - \omega(q_{eol} - q_n + q_u - q_r) + \beta_1 q_n + \beta_2 q_u + \beta_3 q_r + \beta_4 q_{eol}$. The first-order conditions are given by $\Psi_1(q_n, q_u, q_r, \mu, \eta, \omega, \beta_1) \doteq \frac{\partial L}{\partial q_n} = 0$, $\Psi_2(q_n, q_u, q_r, \lambda, \mu, \eta, \omega, \beta_2) \doteq \frac{\partial L}{\partial q_u} = 0$, $\Psi_3(q_n, q_u, q_r, \lambda, \eta, \omega, \beta_3) \doteq \frac{\partial L}{\partial q_r} = 0$, and $\Psi_4(\eta, \omega, \beta_4) \doteq \frac{\partial L}{\partial q_{eol}} = 0$. There are fourteen candidate solutions as summarized below.

**Case 1.** $q_r = q_u = q_n = 0$, which implies $\lambda, \mu, \eta, \omega, \beta_1, \beta_2, \beta_3, \beta_4 \geq 0$. It is straightforward to show that the required condition for this case is $c \geq 1 - s\alpha - \alpha \min(k, \delta_r - c_r) + \delta_r - c_r$. To restrict our analysis to parameters for the producer to have non-negative profit, we assume $c < 1 - s\alpha - \alpha \min(k, \delta_r - c_r) + \delta_r - c_r$ holds, which rules out this case.

**Case 2.** $0 < q_r < q_u < q_n$, $q_{eol} = 0$, $q_u - q_r > \alpha q_n$, which implies

$\beta_4 \geq 0$ and $\lambda, \mu, \eta, \omega, \beta_1, \beta_2, \beta_3 = 0$. Solving $\Psi_1(q_n, q_u, q_r, 0, 0, 0, 0) = 0$, $\Psi_2(q_n, q_u, q_r, 0, 0, 0, 0, 0) = 0$, $\Psi_3(q_n, q_u, q_r, 0, 0, 0, 0) = 0$, and $\Psi_4(0, 0, \beta_4) = 0$ gives $q_n = \frac{1-c+c_r-s\alpha-\delta_r}{2(1-\delta_r)}$, $q_u = \frac{1}{2}(1 - \frac{c_r}{\delta_r-\delta} - \frac{c-c_r+s\alpha}{1-\delta_r})$, $q_r = \frac{1}{2}(\frac{c-c_r+s\alpha}{1-\delta_r} - \frac{c_r}{\delta_r-\delta})$, and $\beta_4 = k$, where $q_u < q_n$. The required conditions are $c_r < \frac{(c+\alpha s)(\delta_r-\delta)}{1-\delta} \doteq c_{r5}(c, s, \alpha, \delta, \delta_r)$ and $s < \frac{1-c(2-\alpha)+c_r(2-\alpha)-\alpha-\delta_r+\alpha\delta_r}{(2-\alpha)\alpha} \doteq s_4(\delta_r, \alpha, c, c_r)$. $q_n$ is decreasing in $s$ and $\alpha$. $ru = \frac{q_n-q_u+q_r}{q_n} = \frac{c-c_r+s\alpha}{1-c+c_r-s\alpha-\delta_r}$, which is increasing in $s$ and $\alpha$.

**Case 3.** $q_{eol} = 0$, $0 < q_r < q_u$, $q_u - q_r = \alpha q_n$, which implies $\eta, \beta_4 \geq 0$ and $\lambda, \mu, \omega, \beta_1, \beta_2, \beta_3 = 0$. Solving $\Psi_1(q_n, q_u, q_r, 0, \eta, 0, 0) = 0$, $\Psi_2(q_n, q_u, q_r, 0, 0, \eta, 0, 0) = 0$, $\Psi_3(q_n, q_u, q_r, 0, \eta, 0, 0) = 0$, and $\Psi_4(\eta, 0, \beta_4) = 0$ gives $q_n = \frac{1-c+c_r+2\delta-\alpha(s+\delta)-\delta_r}{2+2(2-\alpha)^2\delta-2\delta_r}$, $q_u = \frac{1}{2}(1 - \frac{c_r}{\delta_r-\delta} + \frac{(1-\alpha)(-1+c-c_r-2\delta+\alpha(s+\delta)+\delta_r)}{1+(2-\alpha)^2\delta-\delta_r})$, $q_r = \frac{c_r+c_r(3-\alpha)(1-\alpha)\delta+(c+s\alpha+(2-\alpha)(1-\alpha)\delta)(\delta-\delta_r)}{2(\delta-\delta_r)(1+(2-\alpha)^2\delta-\delta_r)}$, $\eta = \frac{\delta(-1+c(2-\alpha)+\alpha+(2-\alpha)(s\alpha-c_r)+\delta_r-\alpha\delta_r)}{1+(2-\alpha)^2\delta-\delta_r}$, and $\beta_4 = k - \delta - \frac{(2-\alpha)\delta(-1+c-c_r-2\delta+\alpha(s+\delta)+\delta_r)}{1+(2-\alpha)^2\delta-\delta_r}$. The required conditions are $c_r < \frac{(\delta_r-\delta)(c+s\alpha+\delta(2-\alpha)(1-\alpha))}{1+\delta(3-\alpha)(1-\alpha)} \doteq c_{r6}(c, s, \alpha, \delta, \delta_r)$, $s_4(\cdot) \leq s < \frac{(\delta_r-\delta)((1-\alpha)(1-\delta_r)-c(2-\alpha))+c_r(1+(2-\alpha)(1-\alpha)\delta+\delta_r-\alpha\delta_r)}{(2-\alpha)\alpha(\delta_r-\delta)} \doteq s_5(c, \alpha, c_r, \delta_r, \delta)$ and $s \leq \frac{k(1+(2-\alpha)^2\delta+\delta_r)+\delta((1-\alpha)(1-\delta_r)-(2-\alpha)(c-c_r))}{(2-\alpha)\alpha\delta} \doteq s_6(c, \alpha, c_r, \delta_r, \delta, k)$, where $s_4(\cdot) < s_5(\cdot), s_6(\cdot)$, and $s_5(\cdot) < s_6(\cdot)$ for $c_r < \frac{k(\delta_r-\delta)}{\delta}$. $q_n$ is decreasing in $s$ and increasing in $\alpha$ for $\alpha < \alpha_1^r(\cdot)$ (expression omitted for brevity). $ru = 1 - \alpha$, which is decreasing in $\alpha$.

**Case 4.** $0 < q_r < q_u = q_n$, $q_{eol} = 0$, $q_u - q_r = \alpha q_n$, which implies $\mu, \eta, \beta_4 \geq 0$ and $\lambda, \omega, \beta_1, \beta_2, \beta_3 = 0$. Solving $\Psi_1(q_n, q_n, q_r, \mu, \eta, 0, 0) = 0$, $\Psi_2(q_n, q_n, q_r, 0, \mu, \eta, 0, 0) = 0$, $\Psi_3(q_n, q_n, q_r, 0, \eta, 0, 0) = 0$, and $\Psi_4(\eta, 0, \beta_4) = 0$ gives $q_n = \frac{1-c+(\delta_r-c_r)(1-\alpha)-\alpha s}{2+2(3-\alpha)(1-\alpha)\delta_r}$, $q_r = \frac{(1-\alpha)(1-c-s\alpha+(1-\alpha)(\delta_r-c_r))}{2+2(3-\alpha)(1-\alpha)\delta_r}$, $\mu = -c_r - \delta + \delta_r + \frac{(2-\alpha)(\delta_r-\delta)(-1+c+s\alpha-(1-\alpha)(\delta_r-c_r))}{1+(3-\alpha)(1-\alpha)\delta_r}$, $\eta = -c_r + \delta_r + \frac{(2-\alpha)\delta_r(-1+c+s\alpha-(1-\alpha)(\delta_r-c_r))}{1+(3-\alpha)(1-\alpha)\delta_r}$, and $\beta_4 = c_r + k - \delta_r - \frac{(2-\alpha)\delta_r(-1+c+s\alpha-(1-\alpha)(\delta_r-c_r))}{1+(3-\alpha)(1-\alpha)\delta_r}$. The required conditions are $s_5(\cdot) \leq s \leq \frac{c_r(1+(1-\alpha)\delta_r)+k(1+(3-\alpha)(1-\alpha)\delta_r)+\delta_r((1-\alpha)(1-\delta_r)-c)}{(2-\alpha)\alpha\delta_r} \doteq s_7(c_r, \delta_r, k, \alpha, c)$ and $c_r < \delta_r + \frac{1-c-s\alpha}{1-\alpha} \doteq c_{r7}(c, s, \alpha, \delta_r)$, where $c_{r6}(\cdot) < c_{r7}(\cdot)$, and $s_5(\cdot) < s_7(\cdot)$ holds only for $c_r < \frac{k(\delta_r-\delta)}{\delta}$. $q_n$ is decreasing in $s$ and $\alpha$. $ru = 1 - \alpha$ is decreasing in $\alpha$.

**Case 5.** $0 < q_r < q_u = q_n$, $q_{eol} > 0$, $q_u - q_r + q_{eol} = \alpha q_n$, which implies $\mu, \eta \geq 0$ and $\lambda, \omega, \beta_1, \beta_2, \beta_3, \beta_4 = 0$. Solving $\Psi_1(q_n, q_n, q_r, \mu, \eta, 0, 0) = 0$, $\Psi_2(q_n, q_n, q_r, 0, \mu, \eta, 0, 0) =$

0, $\Psi_3(q_n, q_n, q_r, 0, \eta, 0, 0) = 0$, and $\Psi_4(\eta, 0, 0) = 0$ gives $q_n = \frac{1-c+c_r+2k-(k+s)\alpha-\delta_r}{2(1-\delta_r)}$, $q_r = \frac{(c-k+(k+s)\alpha)\delta_r-c_r-k}{2(1-\delta_r)\delta_r}$, $q_{eol} = \frac{1}{2}(\frac{\delta_r-c_r-k}{\delta_r} + \frac{(2-\alpha)(-1+c-c_r-2k+(k+s)\alpha+\delta_r)}{1-\delta_r})$, $\mu = k - \frac{\delta(c_r+k)}{\delta_r}$, and $\eta = k$. The required conditions are $s_7(\cdot) < s < \frac{c_r+k+\delta_r(1-2c+c_r+3k-2k\alpha)-\delta_r^2}{2\alpha\delta_r} \doteq s_8(c_r, k, c, \alpha, \delta, \delta_r)$, $c_r < \delta_r(c+s\alpha)-k(1-\delta_r(1-\alpha)) \doteq c_{r8}(c, s, \alpha, k, \delta_r)$ and $c_r < \frac{k(\delta_r-\delta)}{\delta}$, where $s_7(\cdot) < s_8(\cdot)$ holds only for $c_r < \delta_r - k$. $q_n$ is decreasing in $s$ and $\alpha$ but increasing in $k$. $ru = \frac{c_r+k-(c-k+(k+s)\alpha)\delta_r}{\delta_r(-1+c-c_r-2k+(k+s)\alpha+\delta_r)}$, which is increasing in $\alpha$ and $s$ but decreasing in $k$.

**Case 6.** $0 < q_r < q_u < q_n$, $q_{eol} > 0$, $q_u - q_r + q_{eol} = \alpha q_n$, which implies $\eta \geq 0$ and $\lambda, \mu, \omega, \beta_1, \beta_2, \beta_3, \beta_4 = 0$. Solving $\Psi_1(q_n, q_u, q_r, 0, \eta, 0, 0) = 0$, $\Psi_2(q_n, q_u, q_r, 0, 0, \eta, 0, 0) = 0$, $\Psi_3(q_n, q_u, q_r, 0, \eta, 0, 0) = 0$, and $\Psi_4(\eta, 0, 0) = 0$ gives $q_n = \frac{1-c+c_r+2k-(k+s)\alpha+\delta_r}{2(1-\delta_r)}$, $q_u = \frac{1}{2}(\frac{k+\delta}{\delta} - \frac{c_r}{\delta_r-\delta} - \frac{c-c_r-2k+(k+s)\alpha}{1-\delta_r})$, $q_r = \frac{(\delta_r-\delta)(c-2k+(k+s)\alpha)+c_r\delta-c_r}{2(\delta_r-\delta)(1-\delta_r)}$, $q_{eol} = \frac{1}{2}(1 - \frac{k}{\delta} + \frac{(2-\alpha)(-1+c-c_r-2k+(k+s)\alpha+\delta_r)}{1-\delta_r})$, and $\eta = k$. The required conditions are $s_6(\cdot) < s < \frac{\delta(1-2c+2c_r-\delta_r)-k(-1+2\delta(-2+\alpha)+\delta_r)}{2\alpha\delta} \doteq s_9(\delta, c, c_r, \delta_r, k, \alpha)$ and $\frac{k(\delta_r-\delta)}{\delta} < c_r < \frac{(\delta_r-\delta)(c+s\alpha-k(2-\alpha))}{1-\delta} \doteq c_{r9}(c, k, \alpha, s, \delta, \delta_r)$, where $s_6(\cdot) < s_9(\cdot)$ holds for $\delta > k$. $q_n$ is decreasing in $s$ and $\alpha$ but increasing in $k$. $ru = \frac{k(1+(2-\alpha)\delta-\delta_r)-(c-c_r+s\alpha)\delta}{\delta(-1+c-c_r-2k+(k+s)\alpha+\delta_r)}$ is increasing in $s$ and $\alpha$ but decreasing in $k$.

**Case 7.** $0 < q_r = q_u < q_n$, $q_{eol} = \alpha q_n$, which implies $\lambda, \eta \geq 0$ and $\mu, \omega, \beta_1, \beta_2, \beta_3, \beta_4 = 0$. Solving $\Psi_1(q_n, q_u, q_u, 0, \eta, 0, 0) = 0$, $\Psi_2(q_n, q_u, q_u, \lambda, 0, \eta, 0, 0) = 0$, $\Psi_3(q_n, q_u, q_u, \lambda, \eta, 0, 0) = 0$, and $\Psi_4(\eta, 0, 0) = 0$ gives $q_n = \frac{1-c+c_r-(k+s)\alpha+2\delta-\delta_r}{2+8\delta-2\delta_r}$, $q_u = \frac{c_r+3c_r\delta+(c+(k+s)\alpha+2\delta)(\delta-\delta_r)}{2(\delta-\delta_r)(1+4\delta-\delta_r)}$, $\lambda = \frac{\delta(-1+2c-2c_r+2s\alpha+\delta_r)+k(-1-2(2-\alpha)\delta+\delta_r)}{1+4\delta-\delta_r}$, and $\eta = k$. The required conditions are $s_9(\cdot) < s < \frac{(\delta_r-\delta)(-1+2c+2k\alpha+\delta_r)+c_r(1+2\delta+\delta_r)}{2\alpha(\delta_r-\delta)} \doteq s_{10}(\delta, \delta_r, c, k, \alpha)$ and $c_r < \frac{(\delta_r-\delta)(c+\alpha(k+s)+2\delta)}{1+3\delta} \doteq c_{r10}(\delta_r, \delta, c, \alpha, k, s)$, where $s_9(\cdot) < s_{10}(\cdot)$ holds only for $c_r > \frac{k(\delta_r-\delta)}{\delta}$. $q_n$ is decreasing in $s$, $\alpha$ and $k$, and $ru = 1$.

**Case 8.** $0 < q_r = q_u = q_n$, $q_{eol} = \alpha q_n$, which implies $\lambda, \mu, \eta \geq 0$ and $\omega, \beta_1, \beta_2, \beta_3, \beta_4 = 0$. Solving $\Psi_1(q_n, q_n, q_n, \mu, \eta, 0, 0) = 0$, $\Psi_2(q_n, q_n, q_n, \lambda, \mu, \eta, 0, 0) = 0$, $\Psi_3(q_n, q_n, q_n, \lambda, \eta, 0, 0) = 0$, and $\Psi_4(\eta, 0, 0) = 0$ gives $q_n = \frac{1-c-c_r-(k+s)\alpha-\delta_r}{2+6\delta_r}$, $\lambda = -c_r - k + \delta_r + \frac{2(-1+c+c_r+(k+s)\alpha-\delta_r)\delta_r}{1+3\delta_r}$, $\mu = -c_r - \delta + \delta_r + \frac{2(-1+c+c_r+(k+s)\alpha-\delta_r)(\delta_r-\delta)}{1+3\delta_r}$, and

$\eta = k$. The required conditions are $s_{10}(\cdot), s_8(\cdot) \le s$ and $c_r < 1 - c - k(\alpha + s) + \delta_r \doteq c_{r11}(c, k, \alpha, s, \delta_r)$, where $c_{r10}(\cdot) < c_{r11}(\cdot)$, and $s_8(\cdot) < s_{10}(\cdot)$ holds only if $c_r > \frac{k(\delta_r - \delta)}{\delta}$. $q_n$ is strictly decreasing in $s$, $\alpha$ and $k$, and $ru = 1$ for this case.

**Case 9.** $q_r = 0$, $q_{eol} = 0$, $q_u > 0$, $\alpha q_n = q_u$. This case is identical to Case 2 from the proof of Propositions 1 and 2, except with an additional condition $c_r \ge c_{r7}(\cdot)$.

**Case 10.** $q_r = 0$, $q_{eol} = 0$, $q_u > 0$, $\alpha q_n < q_u < q_n$. This case is identical to Case 3 from the proof of Propositions 1 and 2, except with an additional condition $c_r \ge c_{r5}(\cdot)$.

**Case 11.** $q_r = 0$, $q_u > 0$, $q_{eol} = 0$, $\alpha q_n < q_u = q_n$. This case is identical to Case 4 from the proof of Propositions 1 and 2 and is ruled out.

**Case 12.** $q_r = q_u = 0$, $0 < q_{eol} = \alpha q_n$. This case is identical to Case 5 from the proof of Propositions 1 and 2, except with an additional condition $c_r \ge c_{r11}(\cdot)$.

**Case 13.** $q_r = q_u = 0$, $0 < q_{eol}$ and $q_{eol} > \alpha q_n$. This case is identical to Case 6 from the proof of Propositions 1 and 2 and is ruled out.

**Case 14.** $q_r = 0$, $q_u > 0$, $q_{eol} > 0$, $\alpha q_n = q_u + q_{eol}$. This case is identical to Case 7 from the proof of Propositions 1 and 2, except with an additional condition $c_r \ge c_{r9}(\cdot)$.

Summarizing the above cases, $q_r > 0$ if and only if $c_r < r_3(c, \delta_r, \delta, k, s, \alpha)$, where: (i) if $c_r < \frac{k(\delta_r - \delta)}{\delta}$, we have $r_3(\cdot) = c_{r5}(\cdot)$ for $s < s_4(\cdot)$, $r_3(\cdot) = c_{r6}(\cdot)$ for $s_4(\cdot) \le s < s_5(\cdot)$, $r_3(\cdot) = c_{r7}(\cdot)$ for $s_5(\cdot) \le s \le s_7(\cdot)$, $r_3(\cdot) = c_{r8}(\cdot)$ for $s_7(\cdot) < s < s_8(\cdot)$ and $r_3(\cdot) = c_{r11}(\cdot)$ for $s_8(\cdot) \le s$, and (ii). if $c_r \ge \frac{k(\delta_r - \delta)}{\delta}$, we have $r_3(\cdot) = c_{r5}(\cdot)$ for $s < s_4(\cdot)$, $r_3(\cdot) = c_{r6}(\cdot)$ for $s_4(\cdot) \le s \le s_6(\cdot)$, $r_3(\cdot) = c_{r9}(\cdot)$ for $s_6(\cdot) < s < s_9(\cdot)$, $r_3(\cdot) = c_{r10}(\cdot)$ for $s_9(\cdot) \le s < s_{10}(\cdot)$ and $r_3(\cdot) = c_{r11}(\cdot)$ for $s_{10}(\cdot) \le s$. This proves Lemma 4.

To prove Propositions 8 and 9, assume $\delta \ge 1 - 2c$. Note that $q_u > 0$ for $s < \min\{s_6(\cdot), s_7(\cdot)\}$ (Cases 2, 3 and 4) and the condition for non-negative profit under $k \ge \delta_r - c_r$ can be written as $s < \frac{1-c+(1-\alpha)(\delta_r - c_r)}{\alpha}$, which is always lower than $\min\{s_6(\cdot), s_7(\cdot)\}$ for $k > \delta_r - c_r$. Therefore, for $k > \delta_r - c_r$, $q_u - q_r > 0$ and $q_{eol} = 0$, proving Proposition 8. The threshold for non-negative profit is higher than $\min\{s_6(\cdot), s_7(\cdot)\}$ for $k < \delta_r - c_r$. Therefore, under this condition, we have Used Product Recycling and $q_u - q_r > \alpha q_n$ (Case 2) for $s \leq s_0^r(\delta_r, \delta, \alpha, c, c_r) \doteq s_4(\cdot)$, Used Product Recycling and $q_u - q_r = \alpha q_n$ (Cases 2, 3 and 4) for $s \leq s_1^r(\delta_r, \delta, \alpha, c, k, c_r) \doteq \min\{s_6(\cdot), s_7(\cdot)\}$, Mixed Recycling for $s_1^r(\cdot) < s < s_2^r(\delta_r, \delta, \alpha, c, k, c_r) \doteq \min\{s_8(\cdot), s_9(\cdot)\}$ and End-of-Life Recycling otherwise. Note that if $\delta \geq 1 - 2c$, then $s_0^r(\cdot) < 0$. As $\frac{ds_6(\cdot)}{dc_r} = \frac{ds_9(\cdot)}{dc_r} = \frac{1}{\alpha} > 0$, $\frac{ds_8(\cdot)}{dc_r} = \frac{1+\delta_r}{2\alpha\delta_r} > 0$ and $\frac{ds_7(\cdot)}{dc_r} = \frac{1+\delta_r(1-\alpha)}{\alpha\delta_r(2-\alpha)} > 0$, the thresholds $s_1^r(\cdot)$ and $s_2^r(\cdot)$ are increasing in $c_r$, proving Proposition 9.

To prove Proposition 10, assume $\delta < 1 - 2c$ and $c_r < r_3(\cdot)$, which implies $q_r > 0$. The relevant cases from the analysis in the absence of EPR are Cases 2, 3 and 4. The relevant cases from the analysis in the presence of EPR are Cases 2-8. We begin by considering the setting with $c_r \leq c_{r2}(\cdot)$, which implies that $q_u - q_r = 0$ in the absence of EPR. In the presence of EPR, $q_u - q_r = 0$ for Cases 7 and 8 and $q_u - q_r > 0$ for Cases 2-6. Therefore, $q_u - q_r$ is weakly higher in the presence of EPR.

We next consider the setting with $c_{r2}(\cdot) < c_r$, which implies that $q_u - q_r = \frac{-1+2(c-c_r)+\delta_r}{2(1-\delta_r)}$ in the absence of EPR and under this case, $\frac{q_u - q_r}{q_n} = \frac{1-\delta_r}{1-c+c_r-\delta_r} \doteq \widehat{\alpha_4}^r(c, \delta_r, c_r)$. We compare this with Cases 2-8 in the presence of EPR. Comparing with Case 2, where $q_u - q_r = \frac{1}{2} - \frac{c-c_r+s\alpha}{1-\delta_r}$, we have $(\frac{-1+2(c-c_r)+\delta_r}{2(1-\delta_r)}) - (\frac{1}{2} - \frac{c-c_r+\alpha s}{1-\delta_r}) > 0$. Note that condition $s_4^r(\cdot) > 0$ is equivalent to $\alpha < \widehat{\alpha_4}^r(\cdot)$. Comparing with Case 3, where $q_u - q_r = \frac{\alpha(1-c+c_r+2\delta-\alpha(s+\delta)-\delta_r)}{2+2(2-\alpha)^2\delta-2\delta_r}$, we have $(\frac{-1+2(c-c_r)+\delta_r}{2(1-\delta_r)}) - (\frac{\alpha(1-c+c_r+2\delta-\alpha(s+\delta)-\delta_r)}{2+2(2-\alpha)^2\delta-2\delta_r}) < 0$ only if $s < \frac{(c(2-\alpha)-c_r(2-\alpha)-(1-\alpha)(1-\delta_r))(-1-2(2-\alpha)\delta-\delta_r)}{\alpha^2(1-\delta)} \doteq \widehat{s_1}^r(\delta, \delta_r, \alpha, c, c_r)$ and $\alpha > \widehat{\alpha_4}^r(\cdot)$. Comparing with Case 4, where $q_u - q_r = \frac{\alpha(1-c-c_r(1-\alpha)+\delta_r-\alpha(s+\delta_r))}{2+2(3-\alpha)(1-\alpha)\delta_r}$, we have $(\frac{-1+2(c-c_r)+\delta_r}{2(1-\delta_r)}) - (\frac{\alpha(1-c-c_r(1-\alpha)+\delta_r-\alpha(s+\delta_r))}{2+2(3-\alpha)(1-\alpha)\delta_r}) < 0$ only if $s < \frac{c(2-\alpha)(1+(3-2\alpha)\delta_r)-(1-\alpha)(1-\delta_r)(1+3\delta_r-2\alpha\delta_r)-c_r(2-\alpha)(1+\alpha+3(1-\alpha)\delta_r)}{\alpha^2(1-\delta_r)} \doteq \widehat{s_2}^r(\delta_r, \alpha, c, c_r)$ and $\alpha > \widehat{\alpha_4}^r(\cdot)$. Comparing with Case 5, where $q_u - q_r = \frac{1}{2} - \frac{c-c_r-2k_\alpha(k+s)}{1-\delta_r} + \frac{c_r+k}{2\delta_r}$, we have $(\frac{-1+2(c-c_r)+\delta_r}{2(1-\delta_r)}) - (\frac{1}{2} - \frac{c-c_r-2k_\alpha(k+s)}{1-\delta_r} + \frac{c_r+k}{2\delta_r}) < 0$ only if $s < \frac{c_r+k-(c_r-k(3-2\alpha))\delta_r}{2\alpha\delta_r} \doteq \widehat{s_3}^r(\delta_r, \alpha, c_r, k)$ and $\alpha > \widehat{\alpha_4}^r(\cdot)$. Comparing with Case 6, where $q_u - q_r =$

$\frac{k+\delta}{2\delta} - \frac{c-c_r-2k+\alpha(k+s)}{1-\delta_r}$, we have $(\frac{-1+2(c-c_r)+\delta_r}{2(1-\delta_r)}) - (\frac{k+\delta}{2\delta} - \frac{c-c_r-2k+\alpha(k+s)}{1-\delta_r}) < 0$ only if $s < \frac{k(1+2(2-\alpha)\delta-\delta_r)}{2\alpha\delta} \doteq \widehat{s_4}^r(\delta, \delta_r, k)$ and $\alpha > \widehat{\alpha_4}^r(\cdot)$. Finally, $q_u - q_r = 0$ under Cases 7 and 8, which implies $q_u - q_r$ is lower in the presence of EPR.

Summarizing the above, we have that $q_u - q_r$ is higher in the presence of EPR if $s < \widehat{s}^r(\delta, \alpha, c, k, c_r)$ and $\alpha \geq \widehat{\alpha}^r(c, \delta_r, c_r)$, where $\widehat{s}^r(\cdot) = \widehat{s_1}^r(\cdot)$ for $s \leq \min(s_5(\cdot), s_6(\cdot))$, $\widehat{s}^r(\cdot) = \widehat{s_2}^r(\cdot)$ for $s_5(\cdot) \leq s \leq s_7(\cdot)$ and $c_r < \frac{k(\delta_r-\delta)}{\delta}$, $\widehat{s}^r(\cdot) = \widehat{s_3}^r(\cdot)$ for $s_7(\cdot) < s < s_2^r(\cdot)$ and $c_r < \frac{k(\delta_r-\delta)}{\delta}$, and $\widehat{s}^r(\cdot) = \widehat{s_4}^r(\cdot)$ for $s_6(\cdot) < s < s_2^r(\cdot)$ and $c_r \geq \frac{k(\delta_r-\delta)}{\delta}$, proving Proposition 10.

Finally, we show that the Propositions 5-7 hold when $q_r > 0$. Proposition 5 holds because $q_n$ is decreasing and $ru$ is increasing in $s$ under all cases. As $\frac{dq_n}{dk} < 0$ under the End-of-Life strategy (Cases 7 and 8), $\frac{dq_n}{dk} > 0$ and $\frac{dru}{dk} < 0$ under the Mixed Recycling strategy (Cases 5 and 6), which shows that Proposition 6 holds. Under Used Product Recycling with $\alpha q_n = q_u - q_r$ and $q_u < q_n$ (Case 3) $\frac{dq_n}{d\alpha} > 0$ if and only if $\alpha < \alpha_1^r(\cdot)$ and $\frac{dru}{d\alpha} < 0$. Under all other strategies, $\frac{dq_n}{d\alpha} < 0$. □

**A3. Additional collection cost for used products.** Assume the producer also faces an additional collection cost for the used products (in addition to the price $p_u$). Let this cost be denoted by $x$ per unit. If the firm has no incentive to collect more than the target imposed by the regulation, we have $q_u = \alpha q_n - q_{eol}$. Substituting this into the firm's profit function $\Pi(q_n, q_u, q_{eol}) = (p_n(q_n, q_u) - c)q_n - (p_u(q_n, q_u) + x)q_u - kq_{eol} - s\alpha q_n$, we get $\Pi(q_n, q_u, q_{eol}) = (p_n(q_n, q_u) - \tilde{c})q_n - p_u(q_n, q_u)q_u - \tilde{k}q_{eol} - s\alpha q_n$, where $\tilde{c} = c + \alpha x$ and $\tilde{k} = k - x$. Therefore, an additional cost to collect used products can be easily captured in our model by internalizing this cost into the production cost and the cost to collect end-of-life products. Accordingly, our structural results remain unchanged.

**A4. Paying consumers for end-of-life products.** Assume that the municipal collection has to pay a fee $x'$ to recover an end-of-life product from the consumers, where $x' < k$, which captures that it recovers them at a lower cost than it charges to the producer. This additional payment to the consumers increases their valuation of the product. To differentiate the notation for this case, we use the superscript $'$. While the per-period utility from $N$ and $I$ remains the same, the per-period utility from $U$ is now given by $\delta\theta - p_u + \rho x'$. Following the derivation of the inverse demand functions in §A1, we find that $\theta_1' = \frac{p_n - p_u(1+\rho)+\rho x'}{1-\delta}$ and $\theta_2' = \frac{p_u - \rho x'}{\delta}$. Solving for the market-clearing price on the secondary market, we get the inverse demand functions as $p_n' = 1 + \rho\delta - q_n(1+\delta+2\rho\delta) + \delta q_u(1+\rho) + \rho(x')^2$ and $p_u' = \delta(1 - 2q_n + q_u) + \rho x'$, where $p_n' = p_n + \rho(x')^2$ and $p_u' = p_u + \rho x'$. The producer's problem is then given by $(p_n'(q_n, q_u) - c)q_n - (p_u'(q_n, q_u))q_u - kq_{eol} - s\alpha q_n$, which simplifies to $(p_n(q_n, q_u) - c + \rho(x')^2)q_n - (p_u'(q_n, q_u) + \rho x')q_u - kq_{eol} - s\alpha q_n$. Note that this can be rewritten as $(p_n(q_n, q_u) - c')q_n - (p_u'(q_n, q_u) + \rho x')q_u - kq_{eol} - s\alpha q_n$, where $c' = c - \rho(x')^2$. Note that this is similar to the producer's problem with an additional collection cost for used products as discussed in §A3. Substituting $q_u = \alpha q_n - q_{eol}$, we get that the producer's problem can be rewritten as $(p_n(q_n, q_u) - \tilde{c}')q_n - p_u(q_n, q_u)q_u - \tilde{k}'q_{eol} - s\alpha q_n$, where $\tilde{c}' = c - \rho(x')^2 + \alpha\rho x'$ and $\tilde{k} = k - \rho x'$. Therefore, an additional payment to consumers for end-of-life products can be easily captured in our model by internalizing this cost into the production cost and the cost to collect end-of-life products. Accordingly, our structural results remain unchanged.

**A5. Details of numerical study and estimation of parameter values.** We now provide a detailed description of how we estimate the parameters for our two examples in §2.4.3, viz., Apple iPods and iPhones.

In order to calibrate our model, we generalize it as follows: First, we assume that consumer willingness to pay is distributed between $[0, B]$, where $B > 1$ represents the maximum consumer willingness to pay for a new product. Second, we modify the consumers' utility by assuming that the per-period net utility is given by $\theta - b(p_n + \rho p_u)$ from $N$, $\delta\theta - bp_u$ from $U$, and 0 from $I$, where $b > 0$ captures the price sensitivity. Re-solving our model for no EPR, we get that $p_n^* = \frac{B(1+\delta)+bc}{2b}$ and $p_u^* = \frac{B\delta}{2b}$ for $q_u < q_n$.

We next describe how we estimate $B$, $b$ and $\delta$ for each of our two examples. We first begin by focusing on iPod Nanos. [2] find that the average maximum willingness-to-pay for new Apple iPod Nanos is approximately \$190. The price for a new iPod Nano is approximately \$150. Apple pays \$15 to recover any used iPod Nano. Substituting $p_n^* = 150$, $p_u^* = 15$, $c = 45$ and $B = 190$ into $p_n^* = \frac{B(1+\delta)+bc}{2b}$ and $p_u^* = \frac{B\delta}{2b}$ , we get $\delta = 0.13$ and $b = 0.84$. While we cannot find an estimate of $B$ for Apple iPhones, given the similarity between the product categories, we can assume that the ratio of the new-product price and $B$ for iPhones is similar to that for iPods, which is given by $190/150 = 1.267$. The average price for a new iPhone without a contract is approximately \$750, which also yields $B = 750(1.267) = 948.23$. We found that Apple pays \$85 for a used $5^{th}$ generation iPhone. Substituting $p_n^* = 600$, $p_u^* = 85$, $c = 200$ and $B = 759.6$ into $p_n^* = \frac{B(1+\delta)+bc}{2b}$ and $p_u^* = \frac{B\delta}{2b}$ , we get $\delta = 0.15$ and $b = 0.84$.

We can also conduct the above analysis by estimating the price of a used product using data from eBay auctions. We examined all ebay auctions for $5^{th}$ generation iPod Nano which had active bids on May $27^{th}$ 2015 that offered free shipping. There were 11 such auctions, with an average highest bid of \$37.5 (details available on request). Using this value of $p_u^*$ gives $\delta = 0.41$ and $b = 1.05$. We examined eBay auctions for $5^{th}$ generation iPhones which had active bids on May $27^{th}$ 2015 and were closing in less than 1 day. There were 11 such auctions, with an average highest bid of \$151 (details available on request). Using this value of $p_u^*$ gives $\delta = 0.3$ and $b = 0.95$. Therefore, using eBay data provides slightly higher estimates for $\delta$ and $b$. However, it can be shown that using these estimates further strengthens the insights and conclusions from our calibration study, i.e., increased interference occurs at even lower collection targets (details available on request).

**A6. Welfare Analysis.** We now provide a brief discussion of how the presence of EPR for durable products influences the total welfare. Consider a total welfare function ($W$) that consists of the following three terms: Producer's profit $\Pi$, consumer surplus (denoted by $CS$), and total environmental impact (denoted by $EI$), where $W = \Pi + CS - EI$. It is straightforward to show that the producer's profit and consumer surplus both decrease in the recycling cost $s$, collection cost for end-of-life products $k$, and collection target $\alpha$. This is intuitive because EPR imposes these additional recycling and collection costs, which decreases the producer's net margin. This has a detrimental effect on the producer's profit, requiring higher prices, which in turn, decreases the consumer surplus. The effect of EPR on total welfare then depends on how it influences the total environmental impact. $EI$ depends on the volume of products in each life-cycle phase arising from the producer's profit-maximizing decisions, and the per-unit impact of a product in each life-cycle phase. Let $i_p$, $i_{u1}$, $i_{u2}$, $i_r$, and $i_d$ denote the per-unit production impact, the per-unit use impact of a new product, the per-unit use impact of an used product, the per-unit impact due to recycling of a product, and the per-unit impact due to disposal of a product, respectively. As the product's use impact may degrade over time, we assume $i_{u2} \geq i_{u1}$. Moreover, as recycling is an environmentally superior alternative to disposal, we have $i_r < i_d$. The total environmental impact can then be written as $EI = (i_p + i_{u1})q_n + i_{u2}(q_n - q_u) + i_r(\alpha q_n) + i_d(1-\alpha)q_n = (i + i_{u2})q_n - i_{u2}q_u$, where $i = i_p + i_{u1} + i_r\alpha + i_d(1-\alpha)$. This effectively suggests that a total welfare analysis boils down to a comparison between how different EPR parameter choices affect $q_u$ and $q_n$, similarly to the analysis presented in the context of the Waste Management Hierarchy.

**A7. Derivation of inverse demand functions in presence of refurbishing.** We now explain how the inverse demand functions are modified to consider refurbished products. The action vector of consumer with type $\theta$ in period $t$ is now given by $C^t(\theta) = (N^t(\theta), R^t(\theta), U^t(\theta), I^t(\theta))$, where indicator variable $R^t$ corresponds to buying a refurbished product (R). Under stationarity, the per period net utility from $R$ is $\delta_r\theta - p_r$ where $0 < \delta < \delta_r < 1$. There are four additional strategies for the consumers, viz., $RN$, $RR$, $RU$ and $RI$. As discussed before, any strategy where a consumer chooses an action which is different than the action in the previous period ($RN$, $RU$ and $RI$) is dominated. The present value of $RR$ strategy can be calculated using the Bellman equation $V_\theta[R,p] = \delta_r\theta - p_r + \rho V_\theta[R,p]$ as $V_\theta[R,p] = \frac{\delta_r\theta - p_r}{1-\rho}$. It is straightforward to show that $\frac{d(V_\theta(N,p)-V_\theta(R,p))}{d\theta} > 0$, $\frac{d(V_\theta(R,p)-V_\theta(U,p))}{d\theta} > 0$ and $\frac{d(V_\theta(U,p)-V_\theta(I,p))}{d\theta} > 0$. This implies that the consumers who play $NN$ have higher valuation $\theta$ than the ones who play $RR$, who in turn have higher $\theta$ than the consumers who play $UU$. Let $\theta_1^r$, $\theta_2^r$, and $\theta_3^r$ represent the indifferent consumer types between $NN$ and $RR$, $RR$ and $UU$, and between $UU$ and $II$ strategies, respectively. The consumers with valuations $\theta \in (0, \theta_3^r]$ play the $II$ strategy, the consumers with valuations $\theta \in (\theta_3^r, \theta_2^r]$ play the $UU$ strategy, the consumers with valuations $\theta \in (\theta_2^r, \theta_1^r]$ play the $RR$ strategy, and the consumers with valuations $\theta \in (\theta_1^r, 1]$ play the $NN$ strategy, where we obtain $\theta_3^r \doteq \frac{p_u}{\delta}$ by solving $V_\theta[U,p] = V_\theta[I,p]$, $\theta_2^r \doteq \frac{p_r - p_u}{\delta_r - \delta}$ by solving $V_\theta[R,p] = V_\theta[U,p]$ and $\theta_1^r \doteq \frac{p_n - p_r - \rho p_u}{1-\delta_r}$ by solving $V_\theta[N,p] = V_\theta[R,p]$. Note that we retain the assumption $\rho = 1$ for the rest of the analysis.

As before, in the secondary market, the supply of used products is given by $1-\theta_1^r$. Demand for the used products is given by $\theta_2^r - \theta_3^r + q_u$. The market-clearing price for the used products on the secondary market is obtained by solving $1-\theta_1^r = \theta_2^r - \theta_3^r + q_u$, and the demand for new and refurbished products is given by $q_n = 1-\theta_1^r$ and $q_r = \theta_1^r - \theta_2^r$. Solving these simultaneously, the inverse demand functions are given by $p_n(q_n, q_r, q_u) = 1 + \delta + 2q_u\delta - q_n(1+3\delta) - q_r(\delta+\delta_r)$, $p_r(q_n, q_r, q_u) = q_u\delta + \delta_r(1 - q_r) - q_n(\delta + \delta_r)$, and $p_u(q_n, q_r, q_u) = \delta(1 - 2q_n - q_r + q_u)$.

**A8. Limited access to used and end-of-life products.** We now consider the case where some consumers hold onto their used or end-of-life products even though they have purchased a new or used product. We use superscript $l$ to denote this case. Let $\gamma \in (0,1)$ denote the fraction of consumers that do *not* hold onto their product. As this influences the secondary market price, we begin by discussing the change in the inverse demand functions. The per-period net utility from $U$ and $I$ remains the same. However, as a fraction $\gamma$ of the consumers playing $N$ hold onto their used products, the per-period net utility from $N$ is now given by $\theta - p_n + \gamma\rho p_u$. Following the derivation of the inverse demand functions from §A1, we find that $\theta_1 = \frac{p_n-(1+\gamma\rho)p_u}{1-\delta}$ and $\theta_2 = \frac{p_u}{\delta}$. In order to solve for the market clearing price, the supply of used products is now given by $\gamma(1-\theta_1)$. Therefore, solving $\gamma(1-\theta_1) = \theta_1 - \theta_2 + q_u$ and $1-\theta_1 = q_n$ for $p_u$ and $p_n$, we get $p_n = 1+\delta(\gamma+q_u+\gamma q_u) - q_n(1+\gamma(2+\gamma)\delta)$ and $p_u = \delta(1-q_n(1+\gamma)+q_u)$. For the rest of the analysis, we assume $\rho = 1$ as in our basic model.

We begin by considering the no EPR case, i.e., $\alpha = 0$. The producer's problem is given by $\max_{q_n,q_u}(p_n(q_n,q_u)-c)q_n - p_u(q_n,q_u)q_u$, such that $q_u \le \gamma q_n$ and $q_u, q_n \ge 0$. The profit function is jointly concave in $q_n$ and $q_u$. The Lagrangian of the problem is given by $L(q_n,q_u,\lambda,\mu_1,\mu_2) = (p_n(q_n,q_u)-c)q_n - p_u(q_n,q_u)q_u - \lambda(q_u - \gamma q_n) + \mu_1 q_n + \mu_2 q_u$. The first-order conditions are given by $\Psi_1(q_n,q_u,\lambda,\mu_1) \doteq \frac{\partial L}{\partial q_n} = 0$ and $\Psi_2(q_n,q_u,\lambda,\mu_2) \doteq \frac{\partial L}{\partial q_u} = 0$. There are four candidate solutions:

**Case 1.** $q_u = q_n = 0$, which implies $\lambda, \mu_1, \mu_2 \ge 0$. Solving $\Psi_1(0,0,\lambda,\mu_1) = 0$ gives $\lambda + \mu_1 = c - 1 - \gamma\delta$. $\lambda, \mu_1 \ge 0$ requires $c \ge 1+\gamma\delta$. To restrict our analysis to parameters for the producer to have non-negative profit, we assume $c < 1+\gamma\delta$, and this case is ruled out.

**Case 2.** $0 = q_u < q_n$, which implies $\lambda, \mu_1 = 0$, and $\mu_2 \ge 0$. Solving $\Psi_1(q_n,0,0,0) = 0$ and $\Psi_2(q_n,0,0,\mu_2) = 0$ gives $q_n = \frac{1-c+\gamma\delta}{2+2\gamma\delta(2+\gamma)}$ and $\mu_2 = \frac{\delta(-\gamma(1-\delta)+c(1+\gamma))}{1+3\delta}$. $q_n > 0$ due to the assumption $c < 1+\gamma\delta$. $\mu_2 \ge 0$ if and only if $\delta \ge \frac{\gamma - c(1+\gamma)}{\gamma}$.

**Case 3.** $0 < q_u = q_n$, which implies $\lambda \ge 0$, and $\mu_1 = \mu_2 = 0$. Solving $\Psi_1(q_n,q_n,\lambda,0) = 0$ and $\Psi_2(q_n,q_n,\lambda,0) = 0$ gives $\lambda = \frac{-\delta(1-\delta-\gamma(1-c-\delta))}{1-\delta(1-\gamma)} < 0$, hence this case is ruled out.

**Case 4.** $0 < q_u < q_n$, which implies $\lambda = \mu_1 = \mu_2 = 0$. Solving $\Psi_1(q_n,q_u,0,0) = 0$ and $\Psi_2(q_n,q_u,0,0) = 0$ gives $q_n = \frac{1-\delta-c}{2(1-\delta)}$ and $q_u = \frac{\gamma(1-\delta)-(1+\gamma)c}{2(1-\delta)}$, where $q_n > q_u$ holds. $q_u > 0$ if and only if $\delta < \frac{\gamma - c(1+\gamma)}{\gamma}$.

Summarizing the above: if $\delta < \frac{\gamma - c(1+\gamma)}{\gamma}$, then $0 < q_u < q_n$, otherwise, $q_u = 0$.

We next consider the EPR case and assume $\alpha < \gamma$. Otherwise, the producer will not be able to meet the target. The producer's problem is given by $\max_{q_n,q_u,q_{eol}} \Pi(q_n, q_u, q_{eol}) = (p_n(q_n, q_u) - c)q_n - p_u(q_n, q_u)q_u - s\alpha q_n - kq_{eol}$, such that $q_{eol} \leq \gamma(\gamma q_n - q_u)$, $\alpha q_n \leq q_u + q_{eol}$, and $q_n, q_u, q_{eol} \geq 0$. The profit function is jointly concave in $q_n$, $q_u$, and $q_{eol}$. The Lagrangian of the problem is given by $L(q_n, q_u, q_{eol}, \lambda, \mu, \beta_1, \beta_2, \beta_3) = \pi(q_n, q_u, q_{eol}, 0) - \lambda(q_{eol} + \gamma q_u - \gamma^2 q_n) - \mu(\alpha q_n - q_u - q_{eol}) + \beta_1 q_n + \beta_2 q_u + \beta_3 q_{eol}$. The first-order conditions are $\Psi_1(q_n, q_u, \lambda, \mu, \beta_1) \doteq \frac{\partial L}{\partial q_n} = 0$, $\Psi_2(q_n, q_u, \lambda, \mu, \beta_2) \doteq \frac{\partial L}{\partial q_u} = 0$, and $\Psi_3(\lambda, \mu, \beta_3) \doteq \frac{\partial L}{\partial q_{eol}} = 0$. There are seven candidate solutions (summarized below).

**Case 1.** $q_u = q_{eol} = 0$, which implies $q_n = 0$ and $\lambda, \mu, \beta_1, \beta_2, \beta_3 \geq 0$. It is straightforward to show that the required condition for this case is $s \geq \max\{\frac{1-c-\alpha k+\gamma\delta}{\alpha} \doteq s_*^{1l}\delta, \alpha, c, k, \gamma), \frac{1-c-\alpha\delta+\gamma\delta}{\alpha} \doteq s_*^{2l}(\delta, \alpha, c, \gamma), \frac{(1-\gamma)(1-c)+(\alpha-\gamma)(k\gamma-\delta)}{\alpha(1-\gamma)}\}$, which can be simplified as $c \geq 1 - \alpha s + \max\{\gamma\delta - \alpha k, \frac{(\gamma-\alpha)(\delta-\gamma k)}{1-\gamma}\}$. To ensure non-negativity of the producer's profit, we hereafter assume $c < 1 - \alpha s + \max\{\gamma\delta - \alpha k, \frac{(\gamma-\alpha)(\delta-\gamma k)}{1-\gamma}\}$ holds, which rules out this case.

**Case 2.** $q_u > 0$, $q_{eol} = 0$, $\alpha q_n = q_u < \gamma q_n$, which implies $\lambda = \beta_1 = \beta_2 = 0$ and $\mu, \beta_3 \geq 0$. Solving $\Psi_1(q_n, \alpha q_n, 0, \mu, 0) = 0$, $\Psi_2(q_n, \alpha q_n, 0, \mu, 0) = 0$ and $\Psi_3(0, \mu, \beta_3) = 0$ gives $q_n = \frac{1-c+(\gamma-\alpha)\delta-\alpha s}{2+2(2+\gamma-\alpha)(\gamma-\alpha)\delta}$, $\mu = \frac{\delta(\alpha-(c+s\alpha)(-1+\alpha-\gamma)-\gamma+\delta(\gamma-\alpha))}{1+\delta(\gamma-\alpha)(2+\gamma-\alpha)}$, and $\beta_3 = k - \delta + \frac{(-1+\alpha-\gamma)\delta(-1+c+s\alpha+\delta(\alpha-\gamma))}{1+\delta(\gamma-\alpha)(2+\gamma-\alpha)}$. For $q_u > 0$, $\mu \geq 0$ and $\beta_3 \geq 0$, the required conditions are $s < s_*^{2l}(\cdot)$, $s \leq s_1^l(\delta, \alpha, c, k, \gamma)$ (expression not provided for brevity) and $s \geq \frac{-c(1+\gamma-\alpha)+(\gamma-\alpha)(1-\delta)}{\alpha(1+\gamma-\alpha)} \doteq s_0^l(\delta, \alpha, c)$. As $s_0^l(\cdot) < s_1^l(\cdot)$, $s_0^l(\cdot) < s_2^{*l}(\cdot)$, and $s_1^l(\cdot) \leq s_2^{*l}(\cdot)$ only for $\delta > k$, the required conditions are $s_0^l(\cdot) \leq s < s_2^{*l}(\cdot)$ for $\delta \leq k$, and $s_0^l(\cdot) \leq s \leq s_1^l(\cdot)$ for $k < \delta$. $q_n$ is decreasing in $s$ and increasing in $\alpha$ for $\alpha < \alpha_1^l(\cdot)$. $r_u = 1 - \alpha$ is decreasing in $\alpha$.

**Case 3.** $q_u > 0$, $q_{eol} = 0$ and $\alpha q_n < q_u < \gamma q_n$, which implies $\lambda = \mu = \beta_1 = \beta_2 = 0$ and $\beta_3 \geq 0$. Solving $\Psi_1(q_n, q_u, 0, 0, 0) = 0$, $\Psi_2(q_n, q_u, 0, 0, 0) = 0$ and $\Psi_3(0, 0, \beta_3) = 0$

gives $q_n = \frac{1-\delta-c-\alpha s}{2(1-\delta)}$, $q_u = \frac{(1-\delta)\gamma+(c+s\alpha)(1+\gamma)}{2(1-\delta)}$, and $\beta_3 = k$. For $\alpha q_n < q_u$ and $q_u > 0$, the required condition is $s < s_0^l(\cdot)$, where $s_0^l(\cdot) \geq 0$ only if $\delta \leq \frac{\gamma-c(1+\gamma)}{\gamma}$. $q_n$ is decreasing and $ru = \frac{1-\delta-\gamma(1-c-s\alpha-\delta)}{1-c-s\alpha-\delta}$ is increasing in $\alpha$ and $s$.

**Case 4.** $q_u > 0$, $q_{eol} = 0$ and $\alpha q_n < q_u = \gamma q_n$, which implies $\beta_1 = \beta_2 = \mu = 0$ and $\lambda, \beta_3 \geq 0$. Solving $\Psi_1(q_n, q_n, \lambda, 0, 0) = 0$ and $\Psi_2(q_n, q_n, \lambda, 0, 0) = 0$ gives $\lambda = -\frac{\delta(c+\alpha s)}{\gamma} < 0$, and this case is ruled out.

**Case 5.** $q_u = 0$, $q_{eol} > 0$ and $\alpha q_n = q_{eol} < \gamma^2 q_n$, which implies $\lambda = \beta_1 = \beta_3 = 0$ and $\mu, \beta_2 \geq 0$. Solving $\Psi_1(q_n, 0, 0, \mu, 0) = 0$ and $\Psi_2(q_n, 0, 0, \mu, \beta_2) = 0$, and $\Psi_3(0, \mu, 0) = 0$ gives $q_n = \frac{1+\gamma\delta-c-\alpha(s+k)}{2(1+\gamma(2+\gamma)\delta)}$, $\mu = k$, and $\beta_2 = \frac{c\delta+k(-1+\alpha\delta(1+\gamma)-\gamma(2+\gamma)\delta)+\delta(s\alpha(1+\gamma)-\gamma(1-c-\delta))}{1+\gamma\delta(2+\gamma)}$. For $q_{eol} > 0$ and $\beta_2 \geq 0$, the required conditions are $\frac{k-c\delta+k(-\alpha(1+\gamma)+\gamma(2+\gamma))\delta+\gamma\delta(1-c-\delta)}{(1+\gamma)\alpha\delta} \doteq s_2^l(\delta, \alpha, c, k) \leq s < s_*^1(\cdot)$, where $s_2^l(\cdot) < s_*^{1l}(\cdot)$ holds only for $k < \delta$. Note that this case can only hold when $\alpha q_n < \gamma^2 q_n$ or $\alpha < \gamma^2$. $q_n$ is decreasing in $\alpha$, $s$ and $k$.

**Case 6.** $q_u \geq 0$, $q_{eol} > 0$ and $\alpha q_n < q_{eol} \leq \gamma^2 q_n$, which gives $\mu = \beta_1 = \beta_3 = 0$ and $\lambda \geq 0$. In this case, $\Psi_3(0, 0, 0) = -\lambda - k < 0$, hence this case is ruled out.

**Case 7.** $q_u > 0$, $q_{eol} > 0$ and $\alpha q_n - q_u = q_{eol} < \gamma^2 q_n - \gamma q_u$, which gives $\lambda = \beta_1 = \beta_2 = \beta_3 = 0$ and $\mu \geq 0$. Solving $\Psi_1(q_n, q_u, 0, \mu, 0) = 0$, $\Psi_2(q_n, q_u, 0, \mu, 0) = 0$ and $\Psi_3(0, \mu, 0) = 0$ gives $q_n = \frac{1-c-s\alpha-\delta+k(1+\gamma-\alpha)}{2(1-\delta)}$, $q_u = \frac{c\delta+k(-1+\alpha\delta(1+\gamma)-\gamma\delta(2+\gamma))+\delta(s\alpha(1+\gamma)-\gamma(1-c-\delta))}{2(1-\delta)\delta}$, $q_{eol} = \frac{k-\delta(\alpha-\gamma)(2-\alpha+\gamma)+\delta(-\alpha+(c+s\alpha)(-1+\alpha-\gamma)+\gamma+\delta(\alpha-\gamma))}{2\delta(1-\delta)}$, and $\mu = k$. For $q_u > 0$ and $q_{eol} > 0$, the required conditions are $s_1^l(\cdot) < s < s_2^l(\cdot)$, where $s_1^l(\cdot) < s_2^l(\cdot)$ holds only for $k < \delta$. $q_n$ is decreasing in $s$ and $\alpha$ but increasing in $k$. $ru = \frac{k+k(-1+\gamma-\alpha\gamma+\gamma^2)\delta+\delta(-1+\delta-\gamma(-1+c+\alpha s+\delta))}{\delta(-1+c+\alpha s+k(-1+\alpha-\gamma)+\delta)}$, which is increasing in $s$ and $\alpha$ but decreasing in $k$.

When $\alpha \leq \gamma^2$, the above cases can be summarized as follows: (i) $\delta \leq k$: if $s < s_0^l(\cdot)$, $\alpha q_n < q_u < \gamma q_n$, $q_{eol} = 0$; if $s \geq s_0^l(\cdot)$, $q_u = \alpha q_n$, $q_{eol} = 0$. (ii) $k < \delta$: if $s < s_0^l(\cdot)$, $\alpha q_n < q_u < \gamma q_n$, $q_{eol} = 0$; if $s_0^l(\cdot) \leq s \leq s_1^l(\cdot)$, $q_u = \alpha q_n$, $q_{eol} = 0$; if $s_1^l(\cdot) < s < s_2^l(\cdot)$, $q_u, q_{eol} > 0$, $q_u + q_{eol} = \alpha q_n$, and if $s \geq s_2^l(\cdot)$, $q_u = 0$, $q_{eol} = \alpha q_n$. However, when $\alpha > \gamma^2$, then the result for $\delta \leq k$ is similar as above, but for $k < \delta$,

$q_u > 0$ always holds. This shows that for the case with limited access, Propositions 1 and 2 structurally hold for $\alpha \le \gamma^2$. The only difference for $\alpha > \gamma^2$ is that $q_u$ is always positive.

To show that Proposition 3 holds, assume $\delta < \frac{\gamma - c(1+\gamma)}{\gamma}$. We need to compare the $q_u = \frac{\gamma(1-\delta)-(1+\gamma)c}{2(1-\delta)} (> 0)$ in the absence of EPR with the cases above that hold for $\delta < \frac{\gamma - c(1+\gamma)}{\gamma}$, viz., Cases 2, 3, 5, and 7. If $s < s_0^l(\cdot)$, then comparing with Case 3, $\frac{\gamma(1-\delta)-(1+\gamma)c}{2(1-\delta)} - \frac{(1-\delta)\gamma+(c+s\alpha)(1+\gamma)}{2(1-\delta)} = \frac{\alpha s(1+\gamma)}{2(1-\delta)} > 0$. Note that the condition $s_0^l(\cdot) > 0$ can be written as $\alpha < \widehat{\alpha}^l(\delta, c, \gamma) \doteq \frac{\gamma - c(1+\gamma)-\gamma\delta}{1-c-\delta}$. If $s_0^l(\cdot) \le s \le s_1^l(\cdot)$, then comparing with Case 2 gives $\frac{\gamma(1-\delta)-(1+\gamma)c}{2(1-\delta)} - \alpha\big(\frac{1-c+(\gamma-\alpha)\delta-\alpha s}{2+2(2+\gamma-\alpha)(\gamma-\alpha)\delta}\big) < 0$ for $s < \frac{(c(1+\gamma-\alpha)-(\gamma-\alpha)(1-\delta))(1+((2+\gamma)\gamma-2(1+\gamma)\alpha)\delta)}{\alpha^2(1-\delta)} \doteq \widehat{s_1}^l(\delta, \alpha, c)$ and $\alpha \ge \widehat{\alpha}^l(\cdot)$. Comparison with Case 7 (where $s_1^l(\cdot) < s < s_2^l(\cdot)$) gives $\frac{\gamma(1-\delta)-(1+\gamma)c}{2(1-\delta)} - \frac{1-c-s\alpha-\delta+k(1+\gamma-\alpha)}{2(1-\delta)} < 0$ for $s < \frac{k(1+(\gamma(2+\gamma)-(1+\gamma)\alpha)\delta)}{(1+\gamma)\alpha\delta} \doteq \widehat{s_2}^l(\delta, \alpha, k)$ and $\alpha \ge \widehat{\alpha}^l(\cdot)$, where $\widehat{s_2}^l(\cdot) < s_2^l(\cdot)$. Finally, comparing with Case 5 (where $s \ge s_2^l(\cdot)$), $\frac{\gamma(1-\delta)-(1+\gamma)c}{2(1-\delta)} - 0 > 0$. Therefore, this analysis shows that EPR increases interference if $\alpha \ge \widehat{\alpha}^l(\cdot)$ and $s < \widehat{s}^l(\cdot)$, which implies that Proposition 3 holds for this case.

We next show that Propositions 4-7 hold for this case. We have that $\frac{ds_0^l(\delta,\alpha,c)}{d\delta} = -(\frac{\gamma-\alpha}{\alpha(1+\gamma-\alpha)}) < 0$, $\frac{ds_1^l(\delta,\alpha,c,k)}{d\delta} = -(\frac{(\gamma-\alpha)\delta^2+k}{(1+\gamma-\alpha)\alpha\delta^2}) < 0$ and $\frac{ds_2^l(\delta,\alpha,c,k)}{d\delta} = -(\frac{\gamma\delta^2+k}{(1+\gamma)\alpha\delta^2}) < 0$, which shows that Proposition 4 also holds for this case. $q_n$ is decreasing and $ru$ is increasing in $s$ under all cases, which implies that Proposition 5 holds. $\frac{dq_n}{dk} < 0$ under the End-of-Life strategy (Case 5), $\frac{dq_n}{dk} > 0$ and $\frac{dru}{dk} < 0$ under the Mixed Recycling strategy (Case 7), which shows that Proposition 6 holds. Under Used Product Recycling strategy with $s \ge s_0^l(\cdot)$ (Case 2), $\frac{dq_n}{d\alpha} > 0$ if and only if $\alpha < \alpha_1^l(\cdot)$ and $\frac{dru}{d\alpha}$ is decreasing in $\alpha$. Under all other strategies (Cases 3, 5 and 7), $\frac{dq_n}{d\alpha} < 0$.

**A9. EPR implementations with Recycling Fees.** Recall that the producer's problem under EPR where they are operationally responsible is given by $\max_{q_n,q_u,q_{eol}} \Pi(q_n, q_u, q_{eol}) = (p_n(q_n, q_u) - c)q_n - p_u(q_n, q_u)q_u - s\alpha q_n - kq_{eol}$, such that $q_{eol} \le q_n - q_u$, $\alpha q_n \le q_u + q_{eol}$, and $q_n, q_u, q_{eol} \ge 0$. Assume that the producer collects only the volume required to meet the EPR target, i.e., $q_{eol} + q_u = \alpha q_n$. Substituting the value of $q_{eol}$ from this into the producer's profit yields, $\max_{0 \le q_u \le q_n}(p_n(q_n, q_u) - c)q_n - (p_u(q_n, q_u) - k)q_u - \alpha(s + k)q_n$. We now consider an implementation where a state authority manages the recycling system and charges a unit recycling fee, and the producer can bring in used products as a collector. The producer's problem under such a setting is given by $\max_{0 \le q_u \le q_n}(p_n(q_n, q_u) - c)q_n - (p_u(q_n, q_u) - \kappa)q_u - \sigma q_n$. Comparing these two, it can be seen that they are equivalent in structure with $\kappa \equiv k$ and $\sigma \equiv \alpha(s + k)$.

We next solve the producer's problem under such an implementation. The profit function is jointly concave in $q_n$ and $q_u$. The Lagrangian of the problem is given by $L(q_n, q_u, \lambda, \mu_1, \mu_2) = (p_n(q_n, q_u) - c)q_n - (p_u(q_n, q_u) - \kappa)q_u - \sigma q_n - \lambda(q_u - q_n) + \mu_1 q_n + \mu_2 q_u$. The first-order conditions are given by $\Psi_1(q_n, q_u, \lambda, \mu_1) \doteq \frac{\partial L}{\partial q_n} = 1 - c + \delta + \lambda + \mu_1 - 2(1 + 3\delta)q_n + 4\delta q_u - \sigma = 0$ and $\Psi_2(q_n, q_u, \lambda, \mu_2) \doteq \frac{\partial L}{\partial q_u} = -\lambda + \mu_2 - \delta(1 - 4q_n + 2q_u) + \kappa = 0$. There are four candidate solutions summarized below.

**Case 1.** $q_u = q_n = 0$, which implies $\lambda, \mu_1, \mu_2 \ge 0$. Solving $\Psi_1(0, 0, \lambda, \mu_1) = 0$ gives $\lambda + \mu_1 = c - 1 - \delta + \sigma$. $\lambda, \mu_1 \ge 0$ requires $c + \sigma \ge 1 + \delta$. To restrict our analysis to parameters for the producer to have non-negative profit, we assume $c + \sigma < 1 + \delta$, and this case is ruled out.

**Case 2.** $0 = q_u < q_n$, which implies $\lambda = \mu_1 = 0$, and $\mu_2 \ge 0$. Solving $\Psi_1(q_n, 0, 0, 0) = 0$ and $\Psi_2(q_n, 0, 0, \mu_2) = 0$ gives $q_n = \frac{1+\delta-c-\sigma}{2(1+3\delta)}$ and $\mu_2 = \frac{\delta(\delta+2c-1-3\kappa+2\sigma)-\kappa}{1+3\delta}$. $q_n > 0$ due to the assumption $c + \sigma < 1 + \delta$. $ru = 1$ and $q_n$ is decreasing in $\sigma$.

**Case 3.** $0 < q_u = q_n$, which implies $\lambda \ge 0$ and $\mu_1 = \mu_2 = 0$. Solving $\Psi_1(q_n, q_n, \lambda, 0) = 0$ and $\Psi_2(q_n, q_n, \lambda, 0) = 0$ gives $q_n = \frac{1-c+\kappa-\sigma}{2}$, which is decreasing in $\sigma$ and increasing in $\kappa$. $q_u (= q_n)$ is higher than that under no EPR if $\sigma < S_1$ (expression not provided for brevity).

**Case 4.** $0 < q_u < q_n$, which implies $\lambda = \mu_1 = \mu_2 = 0$. Solving $\Psi_1(q_n, q_u, 0, 0) = 0$ and $\Psi_2(q_n, q_u, 0, 0) = 0$ gives $q_n = \frac{1-\delta-c-\sigma+2\kappa}{2(1-\delta)}$ and $q_u = \frac{\kappa-\delta(-1+2c+\delta-3\kappa+2\sigma)}{2\delta(1-\delta)}$, where $q_n$

is decreasing in $\sigma$ and increasing in $\kappa$. $ru = \frac{\kappa-\delta(c-\kappa+\sigma)}{\delta(-1+c+\delta-2\kappa+\sigma)}$, which is decreasing in $\kappa$ and is increasing in $\sigma$ when $\delta > \kappa$. $q_u$ is higher than that under no EPR if $\sigma < S_2$ (expression not provided for brevity).

As can be seen from above, a higher $\sigma$ may lead to greater reuse and lower production, a higher $\kappa$ may lead to higher production and lower reuse, and EPR may lead to greater interference.

**A10. Charging unit recycling fee to consumers.** We now show that the model where the recycling fee is directly charged to the consumers, is equivalent to the model where it is directly charged to the producer. We first analyze how the demand functions change if the consumers are charged a unit recycling fee denoted by $\sigma$. To differentiate the notation for this case, we use the superscript $''$. The per-period net utility from $N$ is now given by $\theta - p_n + \rho p_u - \sigma$, while from $U$ and $I$ remain the same. Following the derivation of inverse demand functions in §A1, we find that $\theta_1'' = \frac{p_n'' - (1+\rho)p_u'' + \sigma}{1-\delta}$ and $\theta_2'' = \frac{p_u}{\delta}$. Solving for the market-clearing price on the secondary market, we get $p_u'' = \delta(1-2q_n+q_u)$ and $p_n'' = 1-q_n+\delta(-q_n+q_u+\rho(1-2q_n+q_u))-\sigma$. Note that the price of used products $p_u''$ in this case is identical to our base case (i.e., $p_u'' = p_u$) and the price of new products is lower by $\sigma$, i.e., $p_n'' = p_n - \sigma$. The producer's problem is given by $(p_n''(q_n, q_u) - c)q_n - (p_u''(q_n, q_u) - \kappa)q_u = (p_n(q_n, q_u) - c - \sigma)q_n - (p_u(q_n, q_u) - \kappa)q_u$, which is identical to the case where the recycling fee is directly charged to the producer (as discussed in §A9).

# APPENDIX B

# EXTENDED PRODUCER RESPONSIBILITY FOR PHARMACEUTICALS

## A1. Proofs.

**Proof of Lemma 5:** The utility maximization problem of the doctor is given by $q_p^*(p, \eta_d, \eta_p) = argmax\ _{q_p} U_d(q_p) = u_p\ \theta_n - p\ q_p + \eta_d\ q_p - o_d\ (1-\eta_p)\ (q_p - \theta_n)^+$, such that $\theta_n \leq q_p \leq 1$. Due to the constraint $q_p \geq \theta_n$, the utility reduces to $(\eta_d - o_d\ (1-\eta_p) - p)\ q_p + (o_d\ (1-\eta_p) + u_p)\ \theta_n$. Since $\frac{\partial U_d(q_p)}{\partial q_p} = \eta_d - o_d\ (1-\eta_p) - p$ and $\theta_n \leq q_p \leq 1$, the doctor provides $q_p^*(p, \eta_d, \eta_p) = 1 > \theta_n$, i.e., over-prescription, if $\eta_d - o_d\ (1-\eta_p) - p \geq 0$; and $q_p^*(p, \eta_d, \eta_p) = \theta_n$ if $\eta_d - o_d\ (1-\eta_p) - p < 0$. Note that when the doctor provides over-prescription doctor utility is always non-negative, otherwise $\eta_d - p + u_p \geq 0$ is the required condition. This proves Lemma 5. $\square$

**Proof of Proposition 11-12:** Assume that the policy is $EC$ ($SR$). The producer knows how $p$, $\eta_d$ and $\eta_p$ affect the doctor prescription behavior as given by Lemma 5. Accordingly, the producer calculates his expected profits from the following two problems based on $\theta_n, \theta_u \backsim U[0,1]$ ($\theta_n \backsim U[0,1]$).

**Problem (i):** Set $p, \eta_d, \eta_p$ such that $p - u_p \leq \eta_d < o_d\ (1-\eta_p) + p$ to have $q_p^*(p, \eta_d, \eta_p) = \theta_n$. Note that $q_u^*(p, \eta_d, \eta_p) = \min\{\theta_n, \theta_u\}$. The producer's problem is $\max_{p,\eta_d,\eta_p} \Pi_m^{EC(i)}(p, \eta_d, \eta_p) = E_{\theta_n,\theta_u}[p\ \theta_n - k\ r_{EC}\ (\theta_n - \min\{\theta_n, \theta_u\}) - \alpha\ \eta_d^2 - \beta\ \eta_p^2] = p\ \frac{1}{2} - k\ r_{EC}\ \frac{1}{6} - \alpha\ \eta_d^2 - \beta\ \eta_p^2$ ($\max_{\eta_d,\eta_p,p} \Pi_m^{SR(i)}(p, \eta_d, \eta_p) = E_{\theta_n}[(p-t)\ \theta_n - \alpha\ \eta_d^2 - \beta\ \eta_p^2] = (p-t)\ \frac{1}{2} - \alpha\ \eta_d^2 - \beta\ \eta_p^2$), such that $-u_p \leq \eta_d - p < o_d\ (1-\eta_p)$, $0 \leq \eta_d \leq 1$, and $0 \leq \eta_p \leq 1$. The Hessian of the expected profit function is $\begin{pmatrix} -2 & 0 & 0 \\ 0 & -2 & 0 \\ 0 & 0 & 0 \end{pmatrix}$, which is negative definite. Hence, the expected profit function is jointly concave in $p$, $\eta_d$ and $\eta_p$. Lagrangian of the problem is $L(p, \eta_d, \eta_p, \lambda, \mu, \omega_1, \omega_2, \omega_3, \omega_4) = p\ \frac{1}{2} - k\ r_{EC}\ \frac{1}{6} - \alpha\ \eta_d^2 - \beta\ \eta_p^2 -$

$\lambda\ (-u_p-\eta_d+p)-\mu\ (\eta_d-p-o_d\ (1-\eta_p))+\omega_1\ \eta_d+\omega_2\ (1-\eta_d)+\omega_3\ \eta_p+\omega_4\ (1-\eta_p)$ $(L(p,\eta_d,\eta_p,\lambda,\mu,\omega_1,\omega_2,\omega_3,\omega_4)=(p-t)\ \frac{1}{2}-\alpha\ \eta_d^2-\beta\ \eta_p^2-\lambda\ (-u_p-\eta_d+p)-\mu\ (\eta_d-p-o_d\ (1-\eta_p))+\omega_1\ \eta_d+\omega_2\ (1-\eta_d)+\omega_3\ \eta_p+\omega_4\ (1-\eta_p))$. The first-order conditions are given by $\Psi_1(\lambda,\mu)\doteq\frac{\partial L}{\partial p}=\frac{1}{2}-\lambda+\mu=0$, $\Psi_2(\omega_1,\omega_2,\lambda,\mu)\doteq\frac{\partial L}{\partial\eta_d}=\omega_1-\omega_2+\lambda-\mu-2\alpha\ \eta_d=0$, and $\Psi_3(\omega_3,\omega_4,\mu)\doteq\frac{\partial L}{\partial\eta_p}=\omega_3-\omega_4-\mu\ o_d-2\beta\ \eta_p=0$. $\Psi_3(\omega_3,\omega_4,\mu)\doteq0$ gives $\omega_3=\omega_4+\mu\ o_d+2\beta\ \eta_p$. This implies when $\eta_p>0$, $\omega_3>0$ should hold, which contradicts with $\omega_3\ \eta_p=0$. Hence, $\eta_p=0$ and $\omega_4=0$. $\Psi_1(\lambda,\mu)\doteq0$ gives $\lambda=\frac{1}{2}+\mu$. This implies $\lambda>0$ and $-u_p=\eta_d-p$, leading to $\mu=0$ and $\lambda=\frac{1}{2}$. Using $\Psi_3(\omega_3,\omega_4,\mu)\doteq0$, $\omega_3=\omega_4=0$. Since $\omega_1$ and $\omega_2$ can not be both positive, there are three candidate solutions, which are summarized below.

**Case 1.** $\omega_1,\omega_2=0$, which implies $0\le\eta_d\le1$. Solving $\Psi_3(\omega_3,\omega_4,\mu)\doteq0$ gives $\eta_d=\frac{1}{4\alpha}$. $-u_p=\eta_d-p$ leads to $p=\frac{1}{4\alpha}+u_p$. $\eta_d\le1$ requires $4\alpha\ge1$. Given $r_{EC}(t)$, the producer's expected profit is $\Pi_m^{EC(i)}[r_{EC}]=\frac{3-6\alpha-k\ r_{EC}+3u_p}{2}$ $(\Pi_m^{SR(i)}[t]=\frac{1-2\alpha-t+u_p}{2})$.

**Case 2.** $\omega_1=0$, $\omega_2>0$, which implies $\eta_d=1$. $-u_p=\eta_d-p$ leads to $p=1+u_p$. Solving $\Psi_3(\omega_3,\omega_4,\mu)\doteq0$ gives $\omega_2=\frac{1}{2}-2\ \alpha\ \eta_d=\frac{1}{2}-2\alpha$. $\omega_2>0$ requires $4\alpha<1$. Given $r_{EC}(t)$, the producer's expected profit is $\Pi_m^{EC(i)}[r_{EC}]=\frac{3-8\alpha\ (k\ r_{EC}-3u_p)}{48\alpha}$ $(\Pi_m^{SR(i)}[t]=\frac{1-8\alpha\ (t-u_p)}{16\alpha})$.

**Case 3.** $\omega_1>0$, $\omega_2=0$, which implies $\eta_d=0$. Solving $\Psi_3(\omega_3,\omega_4,\mu)\doteq0$ gives $\omega_2=\frac{1}{2}$, which contradicts with $\omega_2=0$. Hence, this case is ruled out.

Summarizing the above cases; if $4\alpha<1$, $p=1+u_p$, $\eta_d=1$, $\eta_p=0$, and $\Pi_m^{EC(i)}[r_{EC}]=\frac{3-6\alpha-k\ r_{EC}+3u_p}{6}$ $(\Pi_m^{SR(i)}[t]=\frac{1-2\alpha-t+u_p}{2})$; otherwise, $p=\frac{1}{4\alpha}+u_p$, $\eta_d=\frac{1}{4\alpha}$, $\eta_p=0$, and $\Pi_m^{EC(i)}[r_{EC}]=\frac{3-8\alpha\ (k\ r_{EC}-3u_p)}{48\alpha}$ $(\Pi_m^{SR(i)}[t]=\frac{1-8\alpha\ (t-u_p)}{16\alpha})$.

**Problem (ii):** Set $p,\eta_d,\eta_p$ such that $o_d(1-\eta_p)+p\le\eta_d$ to have $q_p^*(p,\eta_d,\eta_p)=1$. Note that $q_u^*(p,\eta_d,\eta_p)=\min\{1,\theta_u\}=\theta_u$. The producer's problem is $\max_{p,\eta_d,\eta_p}\Pi_m^{EC(ii)}(p,\eta_d,\eta_p)=E_{\theta_n,\theta_u}[p\ 1-k\ r_{EC}(1-\theta_u)^+-\alpha\ \eta_d^2-\beta\ \eta_p^2]=p-k\ r_{EC}\ \frac{1}{2}-\alpha\ \eta_d^2-\beta\ \eta_p^2$ $(\max_{\eta_d,\eta_p,p}\Pi_m^{SR(ii)}(p,\eta_d,\eta_p)=E_{\theta_n}[(p-t)\ 1-\alpha\ \eta_d^2-\beta\ \eta_p^2]=(p-t)-\alpha\ \eta_d^2-\beta\ \eta_p^2)$, such that $o_d\ (1-\eta_p)+p\le\eta_d$, $0\le\eta_d\le1$, and $0\le\eta_p\le1$.

The Hessian of the profit function is $\begin{pmatrix} -2 & 0 & 0 \\ 0 & -2 & 0 \\ 0 & 0 & 0 \end{pmatrix}$, which is negative definite. Hence, the profit function is jointly concave in $p$, $\eta_d$ and $\eta_p$. Lagrangian of the problem is $L(p, \eta_d, \eta_p, \lambda, \omega_1, \omega_2, \omega_3, \omega_4) = p - k\ r_{EC}\ \frac{1}{2} - \alpha\ \eta_d^2 - \beta\ \eta_p^2 - \lambda\ (o_d\ (1-\eta_p) + p - \eta_d) + \omega_1\ \eta_d + \omega_2\ (1-\eta_d) + \omega_3\ \eta_p + \omega_4\ (1-\eta_p)$ ($L(p, \eta_d, \eta_p, \lambda, \omega_1, \omega_2, \omega_3, \omega_4) = (p-t) - \alpha\ \eta_d^2 - \beta\ \eta_p^2 - \lambda\ (o_d\ (1-\eta_p) + p - \eta_d) + \omega_1\ \eta_d + \omega_2\ (1-\eta_d) + \omega_3\ \eta_p + \omega_4\ (1-\eta_p)$). The first-order conditions are given by $\Psi_1(\lambda) \doteq \frac{\partial L}{\partial p} = 1 - \lambda = 0$, $\Psi_2(\omega_1, \omega_2, \lambda) \doteq \frac{\partial L}{\partial \eta_d} = \omega_1 - \omega_2 + \lambda - 2\alpha\ \eta_d = 0$, and $\Psi_3(\omega_3, \omega_4) \doteq \frac{\partial L}{\partial \eta_p} = \omega_3 - \omega_4 + \lambda\ o_d - 2\beta\ \eta_p = 0$. Solving $\Psi_1(\lambda, \mu) \doteq 0$ gives $\lambda = 1$, which implies $\eta_d = p + o_d(1-\eta_p)$. $\omega_1$ and $\omega_2$ can not be both positive. Similarly, $\omega_3$ and $\omega_4$ can not be both positive. Hence, there are six candidate solutions, which are summarized below.

**Case 1.** $\omega_1 > 0$, $\omega_2 = 0$, which implies $\eta_d = 0$. Solving $\Psi_2(\omega_1, \omega_2, \lambda) \doteq 0$ gives $\omega_1 = -1 < 0$, hence this case is ruled out.

**Case 2.** $\omega_3 > 0$, $\omega_4 = 0$, which implies $\eta_p = 0$. Solving $\Psi_3(\omega_3, \omega_4) \doteq 0$ gives $\omega_3 = -o_d < 0$, hence this case is ruled out.

**Case 3.** $\omega_1, \omega_3, \omega_4 = 0$ and $\omega_2 > 0$, which implies $\eta_d = 1$ and $0 \le \eta_p \le 1$. Solving $\Psi_2(\omega_1, \omega_2, \lambda) \doteq 0$ and $\Psi_3(\omega_3, \omega_4) \doteq 0$ give $\omega_1 = 2\alpha - 1$ and $\eta_p = \frac{o_d}{2\beta}$. $\eta_d = p + o_d(1-\eta_p)$ leads to $p = 1 - o_d + \frac{o_d^2}{2\beta}$. $\omega_1 > 0$ and $\eta_p \le 1$ require $2\alpha < 1$ and $o_d \le 2\beta$. Given $r_{EC}(t)$, the producer's expected profit is $\Pi_m^{EC(ii)}[r_{EC}] = \frac{o_d^2 - 2\beta\ (2\alpha + k\ r_{EC} + 2(-1+o_d))}{4\beta}$ ($\Pi_m^{SR(ii)}[t] = \frac{o_d^2 + 4\beta\ (1-\alpha-o_d-t)}{4\beta}$).

**Case 4.** $\omega_1, \omega_3 = 0$ and $\omega_2, \omega_4 > 0$, which implies $\eta_d = 1$ and $\eta_p = 1$. Solving $\Psi_2(\omega_1, \omega_2, \lambda) \doteq 0$ and $\Psi_3(\omega_3, \omega_4) \doteq 0$ give $\omega_2 = 1 - 2\alpha$ and $\omega_4 = o_d - 2\beta$. $\eta_d = p + o_d(1-\eta_p)$ leads to $p = 1$. $\omega_2 > 0$ and $\omega_4 > 0$ require $2\alpha < 1$ and $o_d > 2\beta$. Given $r_{EC}(t)$, the producer's expected profit is $\Pi_m^{EC(ii)}[r_{EC}] = 1 - \alpha - \beta - \frac{k\ r_{EC}}{2}$ ($\Pi_m^{SR(ii)}[t] = 1 - \alpha - \beta - t$).

**Case 5.** $\omega_1, \omega_2, \omega_3, \omega_4 = 0$, which implies $0 \le \eta_d \le 1$ and $0 \le \eta_p \le 1$. Solving $\Psi_2(\omega_1, \omega_2, \lambda) \doteq 0$ and $\Psi_3(\omega_3, \omega_4) \doteq 0$ give $\eta_d = \frac{1}{2\alpha}$ and $\eta_p = \frac{o_d}{2\beta}$. $\eta_d = p + o_d(1-\eta_p)$ leads to $p = \frac{1}{2}(\frac{1}{\alpha} + \frac{o_d(o_d - 2\beta))}{\beta})$. $\eta_d \le 1$ and $\eta_p \le 1$ require $2\alpha \ge 1$ and $2\beta \ge o_d$. Given

$r_{EC}(t)$, the producer's expected profit is $\Pi_m^{EC(ii)}[r_{EC}] = \frac{\frac{1}{\alpha}-2k\ r_{EC}-4o_d+\frac{o_d^2}{\beta}}{4}$ $(\Pi_m^{SR(ii)}[t] = \frac{1}{4}(\frac{1}{\alpha} + \frac{o-d^2-4\beta\ (o_d+t)}{\beta}))$.

**Case 6.** $\omega_1, \omega_2, \omega_3 = 0$, $\omega_4 > 0$, which implies $0 \leq \eta_d \leq 1$ and $\eta_p = 1$. Solving $\Psi_2(\omega_1, \omega_2, \lambda) \doteq 0$ and $\Psi_3(\omega_3, \omega_4) \doteq 0$ give $\eta_d = \frac{1}{2\alpha}$ and $\omega_4 = o_d - 2\beta$. $\eta_d = p + o_d(1-\eta_p)$ leads to $p = \frac{1}{2\alpha}$. $\eta_d \leq 1$ and $\omega_4 > 0$ require $2\alpha \geq 1$ and $o_d > 2\beta$. Given $r_{EC}(t)$, the producer's expected profit is $\Pi_m^{EC(ii)}[r_{EC}] = \frac{\frac{1}{\alpha}-2(2\beta+k\ r_{EC})}{4}$ $(\Pi_m^{SR(ii)}[t] = \frac{1-4\alpha\ (\beta+t)}{4\alpha})$.

Summarizing the above cases; if $2\alpha < 1$ and $2\beta < o_d$, $p = \eta_d = \eta_p = 1$, and $\Pi_m^{EC(ii)}[r_{EC}] = 1 - \alpha - \beta - \frac{k\ r_{EC}}{2}$ $(\Pi_m^{SR(ii)}[t] = 1 - \alpha - \beta - t)$; if $2\alpha < 1$ and $2\beta \geq o_d$, $p = 1 - o_d + \frac{o_d^2}{2\beta}$, $\eta_d = 1$, $\eta_p = \frac{o_d}{2\beta}$, and $\Pi_m^{EC(ii)}[r_{EC}] = \frac{o_d^2-2\beta\ (2\alpha+k\ r_{EC}+2(-1+o_d))}{4\beta}$ $(\Pi_m^{SR(ii)}[t] = \frac{o_d^2+4\beta\ (1-\alpha-o_d-t)}{4\beta})$; if $2\alpha \geq 1$ and $2\beta < o_d$, $p = \frac{1}{2\alpha}$, $\eta_d = \frac{1}{2\alpha}$, $\eta_p = 1$, and $\Pi_m^{EC(ii)}[r_{EC}] = \frac{\frac{1}{\alpha}-2(2\beta+k\ r_{EC})}{4}$ $(\Pi_m^{SR(ii)}[t] = \frac{1-4\alpha\ (\beta+t)}{4\alpha})$; and if $2\alpha \geq 1$ and $2\beta \geq o_d$, $p = \frac{1}{2}(\frac{1}{\alpha} + \frac{o_d(o_d-2\beta)}{\beta})$, $\eta_d = \frac{1}{2\alpha}$, $\eta_p = \frac{o_d}{2\beta}$, and $\Pi_m^{EC(ii)}[r_{EC}] = \frac{\frac{1}{\alpha}-2k\ r_{EC}-4o_d+\frac{o_d^2}{\beta}}{4}$ $(\Pi_m^{SR(ii)}[t] = \frac{1}{4}(\frac{1}{\alpha} + \frac{o_d^2-4\beta\ (o_d+t)}{\beta}))$.

We now need to compare expected profit of the producer in problems (i) and (ii) under six cases: (I) $\alpha < \frac{1}{4}$ and $2\beta < o_d$; (II) $\alpha < \frac{1}{4}$ and $2\beta \geq o_d$; (III) $\frac{1}{2} \leq \alpha < \frac{1}{2}$ and $2\beta < o_d$; (IV) $\frac{1}{2} \leq \alpha < \frac{1}{2}$ and $2\beta \geq o_d$; (V) $\alpha \geq \frac{1}{2}$ and $2\beta < o_d$; and (VI) $\alpha \geq \frac{1}{2}$ and $2\beta \geq o_d$. To simplify the analysis, we make the following definitions:

· $\Pi_m^{EC/SR(i)}$: producer's expected profit under problem (i) given $EC/SR$ policy

· $\Pi_m^{EC/SR(ii)}$: producer's expected profit under problem (ii) given $EC/SR$ policy

· $r^i/t^i$: critical collection rate below which the producer obtains non-negative expected profit under problem (i) given $EC/SR$ policy

· $r^{ii}/t^{ii}$: critical collection rate below which the producer obtains non-negative expected profit under problem (ii) given $EC/SR$ policy

For brevity, we only provide the proof for (I) $\alpha < \frac{1}{4}$ and $2\beta < o_d$ and (II) $\alpha < \frac{1}{4}$ and $2\beta \geq o_d$. The result can be similarly proved for other cases (details are available on request). We restrict our analysis to parameters for the producer have non-negative profit, i.e., $r^i/t^i \geq 0$ and $r^{ii}/t^{ii} \geq 0$.

**Case I.** $\alpha < \frac{1}{4}$ and $2\beta < o_d$, which implies $r^i = \frac{3-6\alpha+3u_p}{k}$ and $r^{ii} = \frac{2(1-\alpha-\beta)}{k}$ ($t^i = 1-2\alpha+u_p$ and $t^{ii} = 1-\alpha-\beta$). $\Pi_m^{EC(ii)}[r_{EC}] > \Pi_m^{EC(i)}[r_{EC}]$ ($\Pi_m^{SR(ii)}[r_{SR},t] > \Pi_m^{SR(i)}[r_{SR},t]$) when $r_{EC} < \frac{3(1-2\beta-u_p)}{2k} = \bar{r}_{EC}(u_p,\beta,k) \doteq \bar{r}_{EC}$ ($t < 1-2\beta-u_p = \bar{t}(u_p,\beta) \doteq \bar{t}$) and $\Pi_m^{EC(ii)}[r_{EC}] \leq \Pi_m^{EC(i)}[r_{EC}]$ ($\Pi_m^{SR(ii)}[r_{SR},t] \leq \Pi_m^{SR(i)}[r_{SR},t]$ otherwise. It is straightforward to show that $\bar{r}_{EC} > r^{ii} > r^i$ ($\bar{t} > t^{ii} > t^i$) for $u_p < \frac{4\alpha-2\beta-1}{3} = \bar{u}_p^{EC}(\alpha,\beta) \doteq \bar{u}_p^{EC}$ ($u_p < \alpha-\beta = \bar{u}_p^{SR}(\alpha,\beta) \doteq \bar{u}_p^{SR}$) and $\bar{r}_{EC} \leq r^{ii} \leq r^i$ ($\bar{t} \leq t^{ii} \leq t^i$) for $u_p \geq \bar{u}_p^{EC}$ ($u_p \geq \bar{u}_p^{SR}$). When $u_p < \bar{u}_p^{EC}$, there does not exist any $r_{EC}$ ($t$) that satisfies $\bar{r}_{EC} < r_{EC} < r^i$ ($\bar{t} < t < t^i$). This implies $\Pi_m^{EC(ii)}[r_{EC}] > \Pi_m^{EC(i)}[r_{EC}]$ ($\Pi_m^{SR(ii)}[r_{SR},t] > \Pi_m^{SR(i)}[r_{SR},t]$) for any $r_{EC} \in [0,1]$ ($t \geq 0$). $\bar{u}_p^{EC} < \bar{u}_p^{SR}$ as $r_{EC}^{ii}(t^{ii}) \geq 0$. Furthermore, if $k < 2(1-\alpha-\beta) = \hat{k}(o_d,\alpha,\beta) \doteq \hat{k}$, then $r^{ii} > 1$, meaning that $\Pi_m^{EC(ii)}[r_{EC}] > \Pi_m^{EC(i)}[r_{EC}]$ for any $r_{EC} \in [0,1]$. When $u_p \geq \bar{u}_p^{EC}$, if $k < \frac{3(1-2\beta-u_p)}{2} = \tilde{k}(u_p,\beta) \doteq \tilde{k}$, $\bar{r}_{EC} > 1$, meaning that $\Pi_m^{EC(ii)}[r_{EC}] > \Pi_m^{EC(i)}[r_{EC}]$ for any $r_{EC} \in [0,1]$.

**Case II.** $\alpha < \frac{1}{4}$ and $2\beta \geq o_d$, which implies $r^i = \frac{3-6\alpha+3u_p}{k}$ and $r^{ii} = \frac{o_d^2-4\beta(-1+\alpha+o_d)}{2\beta k}$ ($t^i = 1-2\alpha+u_p$ and $t^{ii} = \frac{o_d^2-4\beta(-1+\alpha+o_d)}{4\beta}$). $\Pi_m^{EC(ii)}[r_{EC}] > \Pi_m^{EC(i)}[r_{EC}]$ ($\Pi_m^{SR(ii)}[r_{SR},t] > \Pi_m^{SR(i)}[r_{SR},t]$) when $r_{EC} < \frac{3(o_d^2+2\beta(1-2o_d-u_p))}{4\beta k} = \bar{r}_{EC}(u_p,o_d,\beta,k) \doteq \bar{r}_{EC}$ and $\Pi_m^{EC(ii)}[r_{EC}] \leq \Pi_m^{EC(i)}[r_{EC}]$ ($\Pi_m^{SR(ii)}[r_{SR},t] \leq \Pi_m^{SR(i)}[r_{SR},t]$) otherwise. It is straightforward to show that $\bar{r}_{EC} > r^{ii} > r^i$ ($\bar{t} > t^{ii} > t^i$) for $u_p < \frac{1+2o_d-\frac{o_d^2}{2\beta}-4\alpha}{3} = \bar{u}_p^{EC}(o_d,\alpha,\beta) \doteq \bar{u}_p^{EC}$ ($u_p < \alpha + \frac{o_d^2}{4\beta} - o_d = \bar{u}_p^{SR}(o_d,\alpha,\beta) \doteq \bar{u}_p^{SR}$), and $\bar{r}_{EC} \leq r^{ii} \leq r^i$ ($\bar{t}(\cdot) \leq t^{ii} \leq t^i$) for $u_p \geq \bar{u}_p^{EC}$ ($u_p \geq \bar{u}_p^{SR}$), where $\frac{\partial \bar{u}_p^{EC}}{\partial o_d} = -\frac{o_d^2}{3\beta} < 0$ ($\frac{\partial \bar{u}_p^{EC}}{\partial o_d} = -\frac{2\beta-o_d}{2\beta} < 0$). When $u_p < \bar{u}_p^{EC}$ ($u_p < \bar{u}_p^{SR}$), there does not exist any $r_{EC}$ ($t$) that satisfies $\bar{r}_{EC} < r_{EC} < r_{EC}^i$ ($\bar{t} < t < t^i$). This implies $\Pi_m^{EC(ii)}[r_{EC}] > \Pi_m^{EC(i)}[r_{EC}]$ ($\Pi_m^{SR(ii)}[r_{SR},t] > \Pi_m^{SR(i)}[r_{SR},t]$) for any $r_{EC} \in [0,1]$ ($t \geq 0$). $\bar{u}_p^{EC} < \bar{u}_p^{SR}$ as $r_{EC}^{ii}(t^i) \geq 0$. Furthermore, if $k < \frac{o_d^2-4\beta(-1+\alpha+o_d)}{2\beta} = \hat{k}(o_d,\alpha,\beta) \doteq \hat{k}$, then $r^{ii} > 1$, meaning that $\Pi_m^{EC(ii)}[r_{EC}] > \Pi_m^{EC(i)}[r_{EC}]$ for any $r_{EC} \in [0,1]$. When $u_p \geq \bar{u}_p^{EC}$, if $k < \frac{3(o_d^2+2\beta\ (1-2o_d-u_p))}{4\beta} = \tilde{k}(u_p,\beta) \doteq \tilde{k}$, $\bar{r}_{EC} > 1$, meaning that $\Pi_m^{EC(ii)}[r_{EC}] > \Pi_m^{EC(i)}[r_{EC}]$ for any $r_{EC} \in [0,1]$.

Summarizing the above cases, there exists a health unit benefit threshold $\bar{u}_p^{EC}$

($\bar{u}_p^{SR}$) under the $EC$ ($SR$) policy such that if $u_p < \bar{u}_p^{EC}$ ($u_p < \bar{u}_p^{SR}$), $\Pi_m^{EC(ii)}[r_{EC}] > \Pi_m^{EC(i)}[r_{EC}]$ ($\Pi_m^{SR(ii)}[r_{SR}, t] > \Pi_m^{SR(i)}[r_{SR}, t]$), i.e., the producer's profit is higher when it induces the over-prescription outcome, where $\frac{\partial \bar{u}_p^{EC(SR)}}{\partial o_d} \leq 0$ and $\bar{u}_p^{EC} < \bar{u}_p^{SR}$.This proves Proposition 11. Furthermore, there also exists a collection cost threshold $\bar{k} = \min\{\hat{k}, \tilde{k}\}$ under the $EC$ policy such that if $k < \bar{k}$, $\Pi_m^{EC(ii)}[r_{EC}] > \Pi_m^{EC(i)}[r_{EC}]$, i.e., the producer's profit is higher when it induces the over-prescription outcome. This proves Proposition 12. $\square$

**Proof of Proposition 13:** Assume that the chosen policy is $EC$ ($SR$). The social planner calculates the expected welfare at the equilibrium and sets the welfare-maximizing collection rate $r_{EC}^*$ (collection rate $r_{SR}^*$ and fee $t^*$). Total welfare depends on the problems (i) and (ii) that the producer solves based on $\theta_n, \theta_u \backsim U[0,1]$ ($\theta_n \backsim U[0,1]$), as summarized below.

**Problem (i):** The producer sets $p = \eta_d + u_p$ to have $q_p^*(p, \eta_d, \eta_p) = \theta_n$, which gives $E_{\theta_n}[U_d^{(i)}(q_p^*(p, \eta_d, \eta_p))] = E_{\theta_n}[\eta_d\theta_n - o_d(1-\eta_p)(\theta_n - \theta_n) + u_p\theta_n - p\theta_n] = E_{\theta_n}[\theta_n(\eta_d + u_p - p)] = 0$, $DU_e^{EC(i)}[r_{EC}] = E_{\theta_n,\theta_u}[\epsilon_e(q_u^*(p, \eta_d, \eta_p) + (1 - r_{EC})(\theta_n - q_u^*(p, \eta_d, \eta_p))^+)] = \epsilon_e[\frac{1}{3} + \frac{(1-r_{EC})}{6}]$ and $DU_s^{EC(i)}[r_{EC}] = E_{\theta_n,\theta_u}[\epsilon_s(1 - r_{EC})(\theta_n - q_u^*(p, \eta_d, \eta_p))^+] = \epsilon_s\frac{(1-r_{EC})}{6}$ as $E_{\theta_n,\theta_u}[q_u^*(p, \eta_d, \eta_p)] = E_{\theta_n,\theta_u}[\min\{\theta_n, \theta_u\}] = \frac{1}{3}$ and $E_{\theta_n,\theta_u}[(\theta_n - q_u^*(p, \eta_d, \eta_p))^+] = \frac{1}{6}$; and $\Pi_{sp}^{EC(i)}[r_{EC}] = 0$ ($E_{\theta_n}[U_d^{(i)}(q_p^*(p, \eta_d, \eta_p))] = 0$, $DU_e^{SR(i)}[r_{SR}] = E_{\theta_n,\theta_u}[\epsilon_e(q_u^*(p, \eta_d, \eta_p) + (1 - r_{SR})(\theta_n - q_u^*(p, \eta_d, \eta_p))^+)] = \epsilon_e[\frac{1}{3} + \frac{(1-r_{SR})}{6}]$, $DU_s^{SR(i)}[r_{SR}] = E_{\theta_n,\theta_u}[\epsilon_s(1 - r_{SR})(\theta_n - q_u^*(p, \eta_d, \eta_p))^+] = \epsilon_s\frac{(1-r_{SR})}{6}$ and $\Pi_{sp}^{SR(i)}[r_{SR}, t] = E_{\theta_n,\theta_u}[t\ \theta_n - k\ r_{SR}\ (\theta_n - q_u^*(p, \eta_d, \eta_p))^+] = t\ \frac{1}{2} - k\ r_{SR}\ \frac{1}{6}$ as $E_{\theta_n,\theta_u}[q_u^*(p, \eta_d, \eta_p)] = E_{\theta_n,\theta_u}[\min\{\theta_n, \theta_u\}] = \frac{1}{3}$ and $E_{\theta_n,\theta_u}[(\theta_n - q_u^*(p, \eta_d, \eta_p))^+] = \frac{1}{6}$). Given the assumptions $u_p \geq \bar{u}_p^{EC}$ and $k \geq \tilde{k} = \min\{\tilde{k}, \hat{k}\} = \bar{k}$ ($u_p \geq \bar{u}_p^{SR}$), there may exist $r_{EC}$ ($t$) that can satisfy $\bar{r}_{EC} < r < \min(r^i, 1)$ ($\bar{t} < t < t^i$). The social planner's problem is $\max_{r_{EC}} W^{EC(i)}(r_{EC}) = E_{\theta_n,\theta_u}[U_d^{(i)}(q_p^*(p, \eta_d, \eta_p)) + \Pi_m^{EC(i)}[r_{EC}] + \Pi_{sp}^{EC(i)}[r_{EC}] - DU_e^{EC(i)}[r_{EC}] - DU_s^{EC(i)}[r_{EC}]$ ($\max_{r_{SR},t} W^{SR(i)}(r_{SR}, t) = E_{\theta_n,\theta_u}[U_d^{(i)}(q_p^*(p, \eta_d, \eta_p)) + \Pi_m^{SR(i)}[t] + \Pi_{sp}^{SR(i)}[r_{SR}, t] - DU_e^{SR(i)}[r_{SR}] - DU_s^{SR(i)}[r_{SR}]$), such that $\bar{r}_{EC} < r < \min(r^i, 1)$ ($\bar{t} < t < t^i$). Constraint $\bar{r}_{EC} < r < \min(r^i, 1)$ ensures that the producer's profit is higher when it sets $p = \eta_d + u_p$ than the case it sets $\eta_d = p + o_d(1-\eta_p)$, to avoid over-prescription. Consequently, the producer's decisions under Problem (ii) determine the total expected welfare at the equilibrium.

**Problem (ii):** The producer sets $\eta_d = p + o_d(1-\eta_p)$ to have $q_p^*(p, \eta_d, \eta_p) = 1 > \theta_n$, which gives $E_{\theta_n}[U_d^{(ii)}(q_p^*(p, \eta_d, \eta_p))] = E_{\theta_n}[\eta_d - o_d(1-\eta_p)(1-\theta_n) + u_p\theta_n - p] = \eta_d - p + \frac{u_p - o_d(1-\eta_p)}{2}$; $DU_e^{EC(ii)}(r_{EC}) = E_{\theta_n,\theta_u}[\epsilon_e\ [\min(1, \theta_n) + (1 - r_{EC})\ (1 - q_u^*(p, \eta_d, \eta_p))^+] = \epsilon_e\ [\frac{1}{2} + (1 - r_{EC})\ \frac{1}{2}$ and $DU_s^{EC(ii)}(r_{EC}) = E_{\theta_n,\theta_u}[\epsilon_s\ (1 - r_{EC})(1 - q_u^*(p, \eta_d, \eta_p))] = \epsilon_s\ (1 - r_{EC})\ \frac{1}{2}$ as $E_{\theta_n,\theta_u}[\min\{\theta_n, \theta_u\}] = E_{\theta_n,\theta_u}[q_u^*(p, \eta_d, \eta_p)] = \frac{1}{2}$ and $E_{\theta_n,\theta_u}[(\theta_n - q_u^*(p, \eta_d, \eta_p))^+] = \frac{1}{2}$; and $E_{\theta_n,\theta_u}[\Pi_{sp}^{EC(ii)}(r_{EC})] = 0$ ($E_{\theta_n}[U_d^{(ii)}(q_p^*(p, \eta_d, \eta_p))] = \eta_d - p + \frac{u_p - o_d(1-\eta_p)}{2}$; $DU_e^{SR(ii)}(r_{SR}) = E_{\theta_n,\theta_u}[\epsilon_e\ [\min(1, \theta_n) + (1 - r_{SR})\ (1 - q_u^*(p, \eta_d, \eta_p))^+] = \epsilon_e\ [\frac{1}{2} + (1 - r_{SR})\ \frac{1}{2}$ and $DU_s^{SR(ii)}(r_{SR}) = E_{\theta_n,\theta_u}[\epsilon_s\ (1 - r_{SR})(1 - q_u^*(p, \eta_d, \eta_p))] = \epsilon_s\ (1 - r_{SR})\ \frac{1}{2}$ and $\Pi_{sp}^{SR(ii)}(r_{SR}) = E_{\theta_n,\theta_u}[t - k\ r_{SR}\ (1 - \theta_n)] = t - k\ r_{SR}\ \frac{1}{2}$ as $E_{\theta_n,\theta_u}[\min\{\theta_n, \theta_u\}] = E_{\theta_n,\theta_u}[q_u^*(p, \eta_d, \eta_p)] = \frac{1}{2}$ and $E_{\theta_n,\theta_u}[(\theta_n - q_u^*(p, \eta_d, \eta_p))^+] = \frac{1}{2}$). There exists $r_{EC}$ ($t$) that can satisfy $r < \bar{r}_{EC}$ ($t < \bar{t}$). The social planner's problem is $\max_{r_{EC}} W^{EC(ii)}(r_{EC}) = E_{\theta_n,\theta_u}[U_d^{(ii)}(q_p^*(p, \eta_d, \eta_p)) + \Pi_m^{EC(ii)}[r_{EC}] + \Pi_{sp}^{EC(ii)}[r_{EC}] - DU_e^{EC(ii)}[r_{EC}] - DU_s^{EC(ii)}[r_{EC}]$ ($\max_{r_{SR},t} W^{SR(ii)}(r_{SR}, t) = E_{\theta_n,\theta_u}[U_d^{(ii)}(q_p^*(p, \eta_d, \eta_p)) + \Pi_m^{SR(ii)}[t] + \Pi_{sp}^{SR(ii)}[r_{SR}, t] - DU_e^{SR(ii)}[r_{SR}] - DU_s^{SR(ii)}[r_{SR}]$), such that $r_{EC} < \bar{r}_{EC}$ ($t < \bar{t}$). Constraint $r_{EC} < \bar{r}$ ($t < \bar{t}$) ensures that the producer's profit is higher when it sets $\eta_d = p + o_d(1 - \eta_p)$ than the case it sets $p = \eta_d + u_p$, to induce over-prescription. Consequently, the producer's decisions under Problem (i) determine the total expected welfare at the equilibrium.

We now need to compare $W^{EC(i)}(r_{EC}^*)$ and $W^{EC(ii)}(r_{EC}^*)$ ($W^{SR(i)}(r_{SR}^*, t^*)$ and $W^{SR(ii)}(r_{SR}^*, t^*)$) to obtain the welfare-maximizing preferred prescription outcome under six cases: (I) $\alpha < \frac{1}{4}$ and $2\beta < o_d$; (II) $\alpha < \frac{1}{4}$ and $2\beta \geq o_d$; (III) $\frac{1}{2} \leq \alpha < \frac{1}{2}$ and $2\beta < o_d$; (IV) $\frac{1}{2} \leq \alpha < \frac{1}{2}$ and $2\beta \geq o_d$; (V) $\alpha \geq \frac{1}{2}$ and $2\beta < o_d$; and (VI) $\alpha \geq \frac{1}{2}$ and $2\beta \geq o_d$. For brevity, we only provide the proof for case (I)

$\alpha < \frac{1}{4}$ and $2\beta < o_d$. The result can be similarly proved for other cases (details are available on request). First consider the $EC$ policy. $\Pi_m^{EC(i)}[r_{EC}] = \frac{3-6\alpha-k\ r_{EC}+3u_p}{6}$ and $W^{EC(i)}(r_{EC}) = \frac{3-6\alpha-(3-r_{EC})\epsilon_e-(1-r_{EC})\epsilon_s-k\ r_{EC}+3u_p}{6}$, where $\frac{\partial W^{EC(i)}(r_{EC})}{\partial r_{EC}} = \frac{\epsilon_e+\epsilon_s-k}{6}$. If $k \geq \epsilon_e+\epsilon_s$, $r_{EC}^* = \bar{r}_{EC} = \frac{3(1-2\beta-u_p)}{2k}$, leading to $W^{EC(i)}(r_{EC}^*) = \frac{1}{6}(3-6\alpha-3\epsilon_e-\epsilon_s+3u_p-\frac{3(\epsilon_e+\epsilon_s-k)(-1+2\beta+u_p)}{2k})$; and if $k < \epsilon_e+\epsilon_s$, $r_{EC}^* = \min(r_{EC}^i, 1)$, leading to $W^{EC(i)}(r_{EC}^*) = \frac{3-6\alpha-2\epsilon_e-k+3u_p}{6}$ when $r_{EC}^* = 1$ (or equivalently $k < 3-6\alpha+3u_p$) and $W^{EC(i)}(r_{EC}^*) = \frac{\epsilon_s(3-6\alpha-k+3u_p)+3\epsilon_e(1-2\alpha-k+u_p)}{6}$ when $r_{EC}^* = r_{EC}^i$ (or equivalently $k \geq 3-6\alpha+3u_p$). $\Pi_m^{EC(ii)}[r_{EC}] = 1-\alpha-\beta-\frac{k\ r_{EC}}{2}$ and $W^{EC(ii)}(r_{EC}) = \frac{2(1-\alpha-\beta)-(2-r_{EC})\epsilon_e-(1-r_{EC})\epsilon_s-k\ r_{EC}+u_p}{2}$, where $\frac{\partial W^{EC(ii)}(r_{EC})}{\partial r_{EC}} = \frac{\epsilon_e+\epsilon_s-k}{2}$. If $k \geq \epsilon_e+\epsilon_s$, $r_{EC}^* = 0$, leading to $W^{EC(ii)}(r_{EC}^*) = \frac{2(1-\alpha-\beta-\epsilon_e)-\epsilon_s+u_p}{2}$; and if $k < \epsilon_e+\epsilon_s$, $r_{EC}^* = \bar{r}_{EC}$, leading to $W^{EC(ii)}(r_{EC}(r_{EC}^*) = \frac{1}{2}(2(1-\alpha-\beta-\epsilon_e)-\epsilon_s+u_p-\frac{3(\epsilon_e+\epsilon_s-k)(-1+2\beta+u_p)}{2k})$. Comparing the total welfare under problems (i) and (ii): if $k \geq \epsilon_e+\epsilon_s$, $W^{EC(ii)}(r_{EC}^*) > W^{EC(i)}(r_{EC}^*)$ only when $\epsilon_e < -\epsilon_s+k+\frac{2k(-3+6\beta-\epsilon_s+3k)}{3(-1+2\beta-2k+u_p)} = \bar{\epsilon}_e^{EC}(\epsilon_s, u_p, \beta, k) \doteq \bar{\epsilon}_e^{EC}$, where $\frac{\partial \bar{\epsilon}_e^{EC}}{\partial \epsilon_s} < 0$; if $k < \epsilon_e+\epsilon_s$ and $k < 3-6\alpha+3u_p$, $W^{EC(ii)}(r_{EC}^*) > W^{EC(i)}(r_{EC}^*)$ only when $\epsilon_e < -\epsilon_s+k+\frac{2(3-6\beta+\epsilon_s-3k)k}{-9+18\beta+8k+9u_p} = \bar{\epsilon}_e^{EC}(\epsilon_s, \beta, k) \doteq \bar{\epsilon}_e^{EC}$, where $\frac{\partial \bar{\epsilon}_e^{EC}}{\partial \epsilon_s} = \frac{3}{4} < 0$; and if $k < \epsilon_e+\epsilon_s$ and $k \geq 3-6\alpha+3u_p$, $W^{EC(ii)}(r_{EC}^*) > W^{EC(i)}(r_{EC}^*)$ only when $\epsilon_e < -\epsilon_s+k-\frac{2k(-3+6\beta-\epsilon_s+3k)}{3(-1-4\alpha+6\beta+2k+5u-p)} = \bar{\epsilon}_e^{EC}(\epsilon_s, u_p, \beta, k) \doteq \bar{\epsilon}_e^{EC}$, where $\frac{\partial \bar{\epsilon}_e^{EC}}{\partial \epsilon_s} < 0$.

Second consider the policy $SR$. $\Pi_m^{SR(i)}[t] = \frac{1-2\alpha-t+u_p}{2}$ and $W^{EC(i)}(r_{SR}, t) = \frac{3-6\alpha-(3-r_{SR})\epsilon_e-(1-r_{SR})\epsilon_s-k\ r_{SR}+3u_p}{6}$, where $\frac{\partial W^{SR(i)}(r_{SR},t)}{\partial r_{SR}} = \frac{\epsilon_e+\epsilon_s-k}{6}$. If $k \geq \epsilon_e+\epsilon_s$, $t^* \in [\bar{t}, t^i]$ and $r_{SR}^* = 0$, leading to $W^{EC}(r_{SR}^*, t^*) = \frac{3-6\alpha-2\epsilon_e-k+3u_p}{6}$; and if $k < \epsilon_e+\epsilon_s$, $t^* \in [\bar{t}, t^i]$ and $r_{SR}^* = 1$, leading to $W^{SR(i)}(r_{SR}^*, t^*) = \frac{3-6\alpha-2\epsilon_e-k+3u_p}{6}$. $\Pi_m^{SR(ii)}[t] = 1-\alpha-\beta-t$ and $W^{SR(ii)}(r_{SR}, t) = \frac{2(1-\alpha-\beta)-(2-r_{SR})\epsilon_e-(1-r_{SR})\epsilon_s-k\ r_{SR}+u_p}{2}$, where $\frac{\partial W^{SR(ii)}(r_{SR},t)}{\partial r_{SR}} = \frac{\epsilon_e+\epsilon_s-k}{2}$. If $k \geq \epsilon_e+\epsilon_s$, $t^* \in [0, \bar{t})$ and $r_{SR}^* = 0$, leading to $W^{EC(i)}(r_{SR}^*, t^*) = \frac{2(1-\alpha-\beta-\epsilon_e)-\epsilon_s+u_p}{2}$; and if $k < \epsilon_e+\epsilon_s$, $t^* \in [0, \bar{t})$ and $r_{SR}^* = 1$, leading to $W^{SR(i)}(r_{SR}^*, t^*) = \frac{2(1-\alpha-\beta)-\epsilon_e-k+u_p}{2}$. Comparing the total welfare under problems (i) and (ii): If $k \geq \epsilon_e+\epsilon_s$, $W^{SR(ii)}(r_{SR}^*, t^*) > W^{SR(i)}(r_{SR}^*, t^*)$ only when $\epsilon_e < 1-2\beta-\frac{2\epsilon_s}{3} = \bar{\epsilon}_e^{SR}(\epsilon_s, \beta) \doteq \bar{\epsilon}_e^{EC}$, where $\frac{\partial \bar{\epsilon}_e^{SR}}{\partial \epsilon_s} = -\frac{2}{3} < 0$; and if $k < \epsilon_e+\epsilon_s$,

$W^{EC(ii)}(r^*_{EC}) > W^{EC(i)}(r^*_{EC})$ only when $\epsilon_e < 3 - \beta - 2k = \bar{\epsilon}^{EC}_e(\beta, k) \doteq \bar{\epsilon}^{EC}_e$, where $\frac{\partial \bar{\epsilon}^{SR}_e}{\partial \epsilon_s} = 0$.

Summarizing the above; there exists a environmental externality threshold $\bar{\epsilon}^{EC}_e$ ($\bar{\epsilon}^{SR}_e$) such that if $\epsilon_e < \bar{\epsilon}^{EC}_e$ ($\epsilon_e < \bar{\epsilon}^{SR}_e$), $W^{EC(ii)}(r^*_{EC}) > W^{EC(i)}(r^*_{EC})$ ($W^{SR(ii)}(r^*_{SR}, t^*) > W^{SR(i)}(r^*_{SR}, t^*)$), i.e., the total expected welfare is higher when the outcome is over-prescription. Moreover, $\frac{\partial \bar{\epsilon}^{EC}_e}{\partial \epsilon_s} \leq 0$.This proves Proposition 13. □

**Proof of Proposition 14:** We now calculate the total welfare under each policy at the equilibrium and compare them to obtain the welfare-maximizing policy. We need to make the comparison for six cases: (I) $\alpha < \frac{1}{4}$ and $2\beta < o_d$; (II) $\alpha < \frac{1}{4}$ and $2\beta \geq o_d$; (III) $\frac{1}{2} \leq \alpha < \frac{1}{2}$ and $2\beta < o_d$; (IV) $\frac{1}{2} \leq \alpha < \frac{1}{2}$ and $2\beta \geq o_d$; (V) $\alpha \geq \frac{1}{2}$ and $2\beta < o_d$; and (VI) $\alpha \geq \frac{1}{2}$ and $2\beta \geq o_d$. For brevity, we only provide the proof for case (I) $\alpha < \frac{1}{4}$ and $2\beta < o_d$. The result can be similarly proved for other cases (details are available on request). Based on Proposition 11, the producer's profit depends on $u_p$ vs. $\bar{u}_p$. Hence, first assume that $u_p < \bar{u}_p$. The producer always obtains higher profit with inducing over-prescription of the doctor, hence both policies result in over-prescription. Following the proof of Proposition 13, under the $SR$ policy, the planner solves the problem given by $\max_{r_{SR},t} W^{SR(ii)}(r_{SR}, t) = \frac{2(1-\alpha-\beta)-(2-r_{SR})\epsilon_e-(1-r_{SR})\epsilon_s-k\ r_{SR}+u_p}{2}$, such that $0 \leq r_{SR} \leq 1$ and $0 < t < t^{ii}$. Note that any $t$ satisfying $0 < t < t^{ii}$ can be considered as the equilibrium fee. On the other hand, under the $EC$ policy, the planner solves the problem given by $\max_{r_{EC}} W^{EC(ii)}(r_{EC}) = \frac{2(1-\alpha-\beta)-(2-r_{EC})\epsilon_e-(1-r_{EC})\epsilon_s-k\ r_{EC}+u_p}{2}$, such that $0 \leq r_{EC} \leq \min\{r^{ii}, 1\}$. When $k < \min\{\hat{k}, \tilde{k}\} = \hat{k} = 2(1 - \alpha - \beta)$, $r^{ii} > 1$ and both problems become equivalent. Therefore, when $u_p < \bar{u}_p$ and $k < \bar{k}$, both policies leads to same level of total welfare at the equilibrium. When $k \geq \min\{\hat{k}, \tilde{k}\} = \hat{k}$, $r^{ii} \leq 1$, implying that $r^*_{SR} \geq r^*_{EC}$. Therefore, when $u_p < \bar{u}_p$ and $k \geq \bar{k}$, $SR$ leads to same or higher level of total welfare at the equilibrium. Second assume that $u_p \geq \bar{u}_p$. The $SR$ policy still results in over-prescription and the planner solves the same problem: $\max_{r_{SR,t}} W^{SR(ii)}(r_{SR}, t) = \frac{2(1-\alpha-\beta)-(2-r_{SR})\epsilon_e-(1-r_{SR})\epsilon_s-k\ r_{SR}+u_p}{2}$, such that $0 \leq r_{SR} \leq 1$ and $0 < t < t^{ii}$. However, in this case, the $EC$ policy may or may not avoid over-prescription based on the unit collection cost $k$, as Proposition 12 states. When $k < \tilde{k} = \min\{\hat{k}, \tilde{k}\} = \bar{k}$, $\bar{r}_{EC} > 1$ and the producer always obtains higher profit with inducing over-prescription of the doctor, hence both policies result in over-prescription. In this case, the planner solves the problem given by $\max_{r_{EC}} W^{EC(ii)}(r_{EC}) = \frac{2(1-\alpha-\beta)-(2-r_{EC})\epsilon_e-(1-r_{EC})\epsilon_s-k\ r_{EC}+u_p}{2}$, such that $0 \leq r_{EC} \leq 1$, which is equivalent to the problem under $SR$. Therefore, when $u_p \geq \bar{u}_p$ and $k < \bar{k}$, both policies leads to same level of total welfare at the equilibrium. When $k \geq \tilde{k} = \min\{\hat{k}, \tilde{k}\} = \bar{k}$, $\bar{r}_{EC} \leq 1$ and the producer can avoid over-prescription. In this case, the planner solves the problem given by $\max_{r_{EC}} W^{EC(i)}(r_{EC}) = \frac{3-6\alpha-(3-r_{EC})\epsilon_e-(1-r_{EC})\epsilon_s-k\ r_{EC}+3u_p}{6}$, such that $\bar{r} < r_{EC} < \min\{r^i, 1\}$ to avoid over-prescription; and $\max_{r_{EC}} W^{EC(ii)}(r_{EC}) = \frac{2(1-\alpha-\beta)-(2-r_{EC})\epsilon_e-(1-r_{EC})\epsilon_s-k\ r_{EC}+u_p}{2}$, such that $0 < r_{EC} < \bar{r}$ to induce over-prescription. Based on Proposition 13, when $\epsilon_e < \bar{\epsilon}_e^{EC}$, the total welfare is higher with the over-prescription outcome, i.e., $W^{EC(ii)}(r^*_{EC}) > W^{EC(i)}(r^*_{EC})$. As the $SR$ policy induces over-prescription and $r^*_{SR} \geq r^*_{EC}$, $W^{SR(ii)}(r^*_{SR}, t^*) > W^{EC(ii)}(r^*_{EC})$, i.e., the total welfare at the equilibrium is equal or higher under $SR$. When $\epsilon_e \geq \bar{\epsilon}_e^{EC}$, solution under the $EC$ policy gives $W^{EC(ii)}(r^*_{EC}) \leq W^{EC(i)}(r^*_{EC})$, where $W^{EC(i)}(r^*_{EC}) = \frac{1}{6}(3 - 6\alpha - 3\epsilon_e - \epsilon_s + 3u_p - \frac{3(\epsilon_e+\epsilon_s-k)(-1+2\beta+u_p)}{2k})$ if $k \geq \epsilon_e + \epsilon_s$; $W^{EC(i)}(r^*_{EC}) = \frac{3-6\alpha-2\epsilon_e-k+3u_p}{6}$ if $\epsilon_e + \epsilon_s \geq k$ and $k < 3 - 6\alpha + 3u_p$ (or equivalently $r^*_{EC} = 1$); and $W^{EC(i)}(r^*_{EC}) = \frac{\epsilon_s(3-6\alpha-k+3u_p)+3\epsilon_e(1-2\alpha-k+u_p)}{6}$ if $\epsilon_e + \epsilon_s \geq k$ and $k \geq 3 - 6\alpha + 3u_p$ (or equivalently $r^*_{EC} = r^i_{EC}$). Solution under the $SR$ policy gives $W^{SR(ii)}(r^*_{SR}, t^*) = \frac{2(1-\alpha-\beta-\epsilon_e)-\epsilon_s+u_p}{2}$ if $k \geq \epsilon_e + \epsilon_s$ and $W^{SR(ii)}(r^*_{SR}, t^*) = \frac{2(1-\alpha-\beta)-\epsilon_e-k+u_p}{2}$ if $k < \epsilon_e + \epsilon_s$. Comparing the welfare under each policy: if $k \geq \epsilon_e + \epsilon_s$, $W^{EC(i)}(r^*_{EC}) > W^{SR(ii)}(r^*_{SR}, t^*)$ only when $\epsilon_e > -\epsilon_s + k + \frac{2k(3-6\beta-\epsilon_s+3k)}{3(1-2\beta+2k-u_p)} = \tilde{\epsilon}_e(\epsilon_s, u_p, \beta, k) \doteq \tilde{\epsilon}_e$, where $\tilde{\epsilon}_e = \bar{\epsilon}_e$; if $k < \epsilon_e + \epsilon_s$ and $k < 3-6\alpha+3u_p$, $W^{EC(i)}(r^*_{EC}) > W^{SR(ii)}(r^*_{SR}, t^*)$ only when $\epsilon_e > 3-6\beta-2k = \tilde{\epsilon}_e(\beta, k) \doteq \tilde{\epsilon}_e$, where $\tilde{\epsilon}_e > \bar{\epsilon}_e$; and if $k < \epsilon_e+\epsilon_s$ and $k \geq 3-6\alpha+3u_p$, $W^{EC(i)}(r^*_{EC}) > W^{SR(ii)}(r^*_{SR}, t^*)$ only when $\epsilon_e > -\epsilon_s+k+\frac{k(3-6\beta+\epsilon_s-3k)}{3(1-2\alpha+u_p)} = \tilde{\epsilon}_e(\epsilon_s, u_p, \beta, k) \doteq \tilde{\epsilon}_e$, where $\tilde{\epsilon}_e > \bar{\epsilon}_e$. Therefore, when $u_p \geq \bar{u}_p$ and $k \geq \bar{k}$, the $EC$ policy leads to higher total welfare at equilibrium only when $\epsilon_e > \tilde{\epsilon}_e$, otherwise the $SR$ policy leads to higher total welfare. This proves Proposition 14. □

**Proof of Proposition 15:** We restrict our analysis to the cases where $\epsilon_e > \bar{\epsilon}_e$, i.e., the social planner avoids over-prescription if possible. For brevity, we only provide the proof for $\alpha < \frac{1}{4}$ and $2\beta < o_d$. The result can be similarly proved for other cases (details are available on request). To obtain the preferred policy from the producer's perspective, we compare his profit at the equilibrium $\Pi^P_m[x^*_P]$ under each policy, where $P = EC/SR$ and $x_P = r_{EC}/r_{SR}, t$. Given the assumption $u_p < \bar{u}^{SR}_p$, the producer's profit is always higher with over-prescription under $SR$, hence $\Pi^{SR(ii)}_m[t^*] = 1-\alpha-\beta-t^*$, where $0 \leq t \leq t^{ii} = 1-\alpha-\beta$. On the other hand, the producer's profit depends on $u_p$ w.r.t. $\bar{u}_p$ and $k$ w.r.t. $\bar{k}$, following Propositions 11-12. First consider $u_p < \bar{u}_p = \frac{4\alpha-2\beta-1}{3}$ and $k < \bar{k} = \min\{\hat{k}, \tilde{k}\} = \hat{k} = 2(1-\alpha-\beta)$. In this case, the producer's profit is higher with over-prescription, hence $\Pi^{EC(ii)}_m[r_{EC}] = 1-\alpha-\beta-\frac{kr_{EC}}{2}$, where $r_{EC} \in [0,1]$. If $k < \epsilon_e+\epsilon_s$, then $r^*_{EC} = 1$ and $\Pi^{EC(ii)}_m[r^*_{EC}] > \Pi^{SR(ii)}_m[t^*]$ only when $t > \frac{k}{2} = \bar{t}(k) \doteq \bar{t}$. If $k \geq \epsilon_e+\epsilon_s$, then $r^*_{EC} = 0$ and $\Pi^{EC(ii)}_m[r^*_{EC}] > \Pi^{SR(ii)}_m[t^*]$. Second consider $u_p \geq \bar{u}_p$ and $k < \bar{k} = \min\{\bar{k}, \tilde{k}\} = \tilde{k} = \frac{3(1-2\beta-u_p)}{2}$. In this case, the producer's profit is higher with over-prescription, hence $\Pi^{EC(ii)}_m[r_{EC}] = 1-\alpha-\beta-\frac{kr_{EC}}{2}$, where $r_{EC} \in [0,1]$. If $k < \epsilon_e+\epsilon_s$, then $r^*_{EC} = 1$ and $\Pi^{EC(ii)}_m[r^*_{EC}] > \Pi^{SR(ii)}_m[t^*]$ only when $t > \frac{k}{2} = \bar{t}(k) \doteq \bar{t}$. If $k \geq \epsilon_e+\epsilon_s$, then $r^*_{EC} = 0$ and $\Pi^{EC(ii)}_m[r^*_{EC}] > \Pi^{SR(ii)}_m[t^*]$. Third consider $u_p < \bar{u}_p$ and $k \geq \bar{k} = \min\{\hat{k}, \tilde{k}\} = \hat{k}$. In this case, the producer's profit is higher with over-prescription, hence $\Pi^{EC(ii)}_m[r_{EC}] = 1-\alpha-\beta-\frac{kr_{EC}}{2}$, where $r_{EC} \in [0, r^{ii} = \frac{2(1-\alpha-\beta)}{k}]$. If $k < \epsilon_e+\epsilon_s$, then $r^*_{EC} = r^{ii}$ and $\Pi^{EC(ii)}_m[r^*_{EC}] > \Pi^{SR(ii)}_m[t^*]$ only when $t > 1-\alpha-\beta$, which contradicts with $t < t^{ii}$. Therefore, $\Pi^{EC(ii)}_m[r^*_{EC}] < \Pi^{SR(ii)}_m[t^*]$. If $k \geq \epsilon_e+\epsilon_s$ where $r^*_{EC} = 0$ and $\Pi^{EC(ii)}_m[r^*_{EC}] > \Pi^{SR(ii)}_m[t^*]$. Finally consider $u_p \geq \bar{u}_p$ and $k \geq \bar{k} = \min\{\hat{k}, \tilde{k}\} = \tilde{k}$. In this case, the social planner can avoid over-prescription, hence producer's profit is $\Pi_m^{EC(i)}[r_{EC}] = \frac{3-6\alpha-kr_{EC}+3u_p}{6}$, where $r_{EC} \in [\bar{r} = \frac{3(1-2\beta-u_p)}{2k}, \min\{r^i = \frac{3-6\alpha+3u_p}{k}, 1\}]$. If $k \geq \epsilon_e + \epsilon_s$, then $r^*_{EC} = \bar{r}$ and $\Pi_m^{EC(i)}[r^*_{EC}] > \Pi_m^{SR(ii)}[t^*]$ only when $t > \frac{3(1-2\beta-u_p)}{4} = \bar{t}(u_p, \beta) \doteq \bar{t}$. If $k < \epsilon_e + \epsilon_s$, $r^*_{EC} = \min\{r^i, 1\}$. When $k < 3-6\alpha+3u_p = \bar{\bar{k}}(u_p, \alpha) \doteq \bar{\bar{k}}$, $r^*_{EC} = 1$ and $\Pi_m^{EC(i)}[r^*_{EC}] > \Pi_m^{SR(ii)}[t^*]$ only when $t > \frac{3-6\beta-+k-3u_p}{6} = \bar{t}(u_p, \beta, k) \doteq \bar{t}$. When $k \geq \bar{\bar{k}}$, $r^*_{EC} = r^i$ and $\Pi_m^{EC(i)}[r^*_{EC}] = 0$, hence $\Pi_m^{EC(ii)}[r^*_{EC}] < \Pi_m^{SR(ii)}[t^*]$. This proves Proposition 15. $\square$

**Proof of Proposition 16-17:** As before, we restrict our analysis to the cases where $\epsilon_e > \bar{\epsilon}_e$, i.e., the social planner avoids over-prescription if possible. For brevity, we only provide the proof for $\alpha < \frac{1}{4}$ and $2\beta < o_d$. The result can be similarly proved for other cases (details are available on request). To obtain the preferred policy from the environmental and public health perspectives, we compare the total environmental and social disutility at equilibrium $DU^P[x^*_P]$ under each policy, where $DU^P[x_P] = DU^P_e[x_P] + DU^P_s[x_P] = \epsilon_e(q_u + (1-r_P)(q_p - q_u)^+) + \epsilon_s(1-r_P)(q_p - q_u)^+$ where $P = EC/SR$ and $x_P = r_{EC}/r_{SR}, t$. Note that $DU^P[x_P]$ depends on the collection rate choice of the planner $r_P$ and the prescription outcome $q_p$, which in turn affects the used quantity $q_u$, where $q_u = \min\{q_p, \theta_n\}$. With the $SR$ policy, the planner can set any collection rate, $r_{SR} \in [0, 1]$. On the other hand, with $EC$ policy, the range for collection rate $r_{EC}$ depends on $u_p$ w.r.t. $\bar{u}_p$ and $k$ w.r.t. $\bar{k}$, following Propositions 11-12. First consider $u_p < \bar{u}_p = \frac{4\alpha-2\beta-1}{3}$ and $k < \bar{k} = \min\{\hat{k}, \tilde{k}\} = \hat{k} = 2(1-\alpha-\beta)$. In this case, both policies result in over-prescription; $DU^P[x_P] = \epsilon_e(\frac{1}{2} + \frac{1-r_P}{2})$ for any $x_P$, where $r_{EC} \in [0, 1]$ under $EC$ and $r_{SR} \in [0, 1]$ under $SR$. Therefore, both policies lead to same level of total disutility at the equilibrium. Second consider $u_p \geq \bar{u}_p$ and $k < \bar{k} = \min\{\hat{k}, \tilde{k}\} = \tilde{k} = \frac{3(1-2\beta-u_p)}{2}$. In this case, both policies result in over-prescription, where $r_{EC} \in [0, 1]$ under $EC$ and $r_{SR} \in [0, 1]$ under $SR$. Therefore, both policies lead to same level of total disutility. Third consider $u_p < \bar{u}_p = \frac{4\alpha-2\beta-1}{3}$ and $k \geq \bar{k} = \min\{\hat{k}, \tilde{k}\} = \hat{k}$. In this case, both policies result in over-prescription, where $r_{EC} \in [0, r^{ii} = \frac{2(1-\alpha-\beta)}{k}]$ under $EC$ and $r_{SR} \in [0,1]$ under $SR$. If $k \geq \epsilon_e + \epsilon_s$, $r^*_{EC} = r^*_{SR} = 0$, hence $DU^{EC}(r^*_{EC}) = DU^{SR}(r^*_{SR}, t^*)$. If $k < \epsilon_e + \epsilon_s$, $r^*_{EC} = r^{ii} < 1 = r^*_{SR}$, hence $DU^{EC}[r^*_{EC}] > DU^{SR}[r^*_{SR}, t^*]$. Finally consider $u_p \geq \bar{u}_p$ and $k \geq \bar{k} = \min\{\hat{k}, \tilde{k}\} = \tilde{k}$. In this case, the $SR$ policy results in over-prescription whereas the $EC$ policy avoids over-prescription; $DU^{EC}[r_{EC}] = \epsilon_e(\frac{1}{3} + \frac{1-r_{EC}}{6})$ and $DU^{SR}[r_{SR}, t] = \epsilon_e(\frac{1}{2} + \frac{1-r_{SR}}{2})$, where $r_{EC} \in [\bar{r} = \frac{3(1-2\beta-u_p)}{2k}, \min\{r^i = \frac{3-6\alpha+3u_p}{k}, 1\}]$ under $EC$ and $r_{SR} \in [0,1]$ under $SR$. If $k \geq \epsilon_e + \epsilon_s$, $r^*_{EC} = \bar{r} > r^*_{SR} = 0$, hence $DU^{EC}[r^*_{EC}] < DU^{SR}[r^*_{SR}, t^*]$. If $k < \epsilon_e + \epsilon_s$, $r^*_{EC} = \min\{r^i, 1\}$ and $r^*_{SR} = 1$. When $k < 3 - 6\alpha + 3u_p = \bar{\bar{k}}(u_p, \alpha) \doteq \bar{\bar{k}}$, $r^*_{EC} = 1 = r^*_{SR}$, hence $DU^{EC}[r^*_{EC}] < DU^{SR}[r^*_{SR}, t^*]$. When $k \geq \bar{\bar{k}}$, $r^*_{EC} = r^i < 1 = r^*_{SR}$, hence $DU^{EC}[r^*_{EC}] < DU^{SR}[r^*_{SR}, t^*]$ only when $\epsilon_s < \epsilon_e(-1 + \frac{k}{-3+6\alpha+k-3u_p}) = \bar{\epsilon}_s(\epsilon_e, u_p, \alpha, k) \doteq \bar{\epsilon}_s$. This proves Proposition 16. Combining the conditions in Table 2-4 gives the conditions in Table 5, proving Proposition 17.

**A2. Policy Choice when $\boldsymbol{u_p \geq \bar{u}_p^{SR}}$.** Recall that we restrict the policy analysis to the cases where $u_p < \bar{u}_p^{SR}$. In this section, we extend our analysis by investigating the policy choice when $u_p \geq \bar{u}_p^{SR}$. This condition implies that $\bar{t} < t^{ii} < t^i$. Accordingly, under the $SR$ policy, the planner solves the problem given by $\max_{r_{SR},t} W^{SR(i)}(r_{SR}, t) = \frac{3-6\alpha-(3-r_{SR})\epsilon_e-(1-r_{SR})\epsilon_s-k\ r_{SR}+3u_p}{6}$, such that $0 < r_{SR} < 1$ and $\bar{t} < t < t^i$ to avoid over-prescription; and $\max_{r_{SR},t} W^{SR(ii)}(r_{SR}, t) = \frac{2(1-\alpha-\beta)-(2-r_{SR})\epsilon_e-(1-r_{SR})\epsilon_s-k\ r_{SR}+u_p}{2}$, such that $0 < r_{SR} < 1$ and $0 < t < \bar{t}$ to induce over-prescription. Following Proposition 11, $u_p \geq \bar{u}_p^{SR}$ gives $u_p \geq \bar{u}_p^{EC}$, implying $\bar{r} < r^{ii} < r^i$. Under the $EC$ policy, the planner's problem depends on value of $k$ w.r.t. $\bar{k}$ (See Proposition 12). If $k < \bar{k}$, then $\bar{r} > 1$ and the planner solves the problem given by $\max_{r_{EC}} W^{EC(ii)}(r_{EC}) = \frac{2(1-\alpha-\beta)-(2-r_{EC})\epsilon_e-(1-r_{EC})\epsilon_s-k\ r_{EC}+u_p}{2}$, such that $0 \leq r_{EC} \leq 1$. If $k \geq \bar{k}$, then $\bar{r} \leq 1$ and the planner solves the problem given by $\max_{r_{EC}} W^{EC(i)}(r_{EC}) = \frac{3-6\alpha-(3-r_{EC})\epsilon_e-(1-r_{EC})\epsilon_s-k\ r_{EC}+3u_p}{6}$, such that $\bar{r} < r_{EC} < \min\{r^i, 1\}$ to avoid over-prescription; and $\max_{r_{EC}} W^{EC(ii)}(r_{EC}) = \frac{2(1-\alpha-\beta)-(2-r_{EC})\epsilon_e-(1-r_{EC})\epsilon_s-k\ r_{EC}+u_p}{2}$, such that $0 < r_{EC} < \bar{r}$ to induce over-prescription. As the planner can set equal of wider range of collection rate under the $SR$ policy to maximize the same total welfare function, the planner can obtain the same or higher level of welfare under $SR$. This suggests that the state-operated programs appear to be appropriate for the collection and disposal of medicine with very high health impact such as controlled substances.

**A3. Extensions.**

**A3.1. Insurance Coverage.** In the base model, we focus on a patient base with no insurance paying the whole price $p$ charged by the producer. In order to capture the insurance effects, we consider a normalized population with both insured and uninsured patients. We assume that $n$ portion of the population is insured, and the insured patients pay $i_p$ portion of the medicine cost, i.e., insurance coverage is equal to $(1-i_p)$. We explain the change in doctor prescribing behavior and producer decisions below. We use subscripts $I$ and $UI$ for insured and uninsured patients, respectively.

**Doctor Prescribing Behavior:** The doctor gains separate and independent utilities from each patient, she determines the prescription amount for each patient by only considering the utility she gets from providing prescription to that patient. For uninsured patients, the doctor's prescribing behavior remains same: Given the type of the patient is $\theta_n^{UI}$, $q_p^{*UI}[p, \eta_d, \eta_p] = \theta_n$ for $\eta_d < o_d(1-\eta_p) + p$ and $q_p^{*UI}[p, \eta_d, \eta_p] = 1$ for $\eta_d \geq o_d(1-\eta_p)+p$. For insured patients, he solves the problem given by $q_p^{*I}[p, \eta_d, \eta_p] = argmax_{q_p} U_d(q_p) = u_p\ \theta_n - i_p\ p\ q_p + \eta_d\ q_p - o_d\ (1-\eta_p)(q_p - \theta_n)^+$. In this case, given the type of the patient is $\theta_n^I$, $q_p^{*I}[p, \eta_d, \eta_p] = \theta_n$ for $\eta_d < o_d(1-\eta_p)+i_p p$ and $q_p^{*I}[p, \eta_d, \eta_p] = 1$ for $\eta_d \geq o_d(1-\eta_p) + i_p p$. Therefore, depending on the relation between pricing and promotional efforts of the producer, three different doctor prescription behaviors can arise: (i) $q_p^{*UI}[p, \eta_d, \eta_p] = \theta_n^{UI}$, $q_p^{*I}[p, \eta_d, \eta_p] = \theta_n^I$ for $o_d(1-\eta_p) + i_p\ p \leq \eta_d < o_d(1-\eta_p) + p$, leading to total prescription quantity $q_p[p, \eta_d, \eta_p] = n\theta_n^I + (1-n)\theta_n^{UI}$; (ii) $q_p^{*UI}[p, \eta_d, \eta_p] = \theta_n^{UI}$, $q_p^{*I}[p, \eta_d, \eta_p] = 1$ for $\eta_d < o_d(1-\eta_p) + i_p\ p$, leading to total prescription quantity $q_p[p, \eta_d, \eta_p] = n\ 1 + (1-n)\theta_n^{UI}$; and (iii) $q_p^{*UI}[p, \eta_d, \eta_p] =$

1, $q_p^{*I}[p,\eta_d,\eta_p] = 1$ for $\eta_d \geq o_d(1-\eta_p)+p$, leading to total prescription quantity $q_p[p,\eta_d,\eta_p] = n\theta_n^I + (1-n)\ 1 = 1$.

**Producer Decisions:** In the presence of insured and uninsured patients, the producer calculates his profit in three problems under the $EC(SR)$ policy as below.

**Problem (i):** Set $p,\eta_d,\eta_p$ such that $p-u_p \leq \eta_d < o_d\ (1-\eta_p) + i_p\ p$ to have $E_{\theta_n}[q_p^*(p,\eta_d,\eta_p)] = E_{\theta_n}[n\theta_n^I + (1-n)\theta_n^{UI}] = \frac{1}{2}$. Note that $E_{\theta_n,\theta_u}[q_u^*(p,\eta_d,\eta_p)] = E_{\theta_n,\theta_u}[n(\min\{\theta_n^I,\theta_u^I\}) + (1-n)(\min\{\theta_n^{UI},\theta_u^{UI}\})] = \frac{1}{6}$. The producer's problem is $\max_{p,\eta_d,\eta_p} \Pi_m^{EC(i)}(p,\eta_d,\eta_p) = (p-c)\ \frac{1}{2} - k\ r_{EC}\ \frac{1}{6} - \alpha\ \eta_d^2 - \beta\ \eta_p^2$, ($\max_{\eta_d,\eta_p,p} \Pi_m^{SR(i)}(p,\eta_d,\eta_p) = (p-c-t)\ \frac{1}{2} - \alpha\ \eta_d^2 - \beta\ \eta_p^2$), such that $p-u_p \leq \eta_d < o_d\ (1-\eta_p) + i_p\ p$, $0 \leq \eta_d \leq 1$, and $0 \leq \eta_p \leq 1$. Given $r_{EC}$, if $1 > o_d + i_p(u_p+1)$, $\alpha \geq \frac{1-i_p}{4(o_d+i_pu_p)}$; or $1 \leq o_d + i_p(u_p+1)$, $\alpha \geq \frac{1}{4}$, $p = \frac{1}{4\alpha} + u_p$, $\eta_d = \frac{1}{4\alpha}$, $\eta_p = 0$ and $\Pi_m^{EC(i)}[r_{EC}] = \frac{1}{48}(\frac{3}{\alpha} - 8kr_{EC} + 24u_p)$ ($\Pi_m^{SR(i)}[r_{SR},t] = \frac{1-8\alpha t+\alpha u_p}{16\alpha}$); if $1 > o_d + i_p(u_p+1)$, $\alpha < \frac{1-i_p}{4(o_d+i_pu_p)}$, $p = \frac{o_d+u_p}{1-i_p}$, $\eta_d = \frac{o_d+i_pu_p}{1-i_p}$, $\eta_p = 0$, and $\Pi_m^{EC(i)}[r_{EC}] = \frac{3-6\alpha-kr_{EC}+3u_p)}{6}$ ($\Pi_m^{SR(i)}[r_{SR},t] = \frac{1-2\alpha-t+u_p}{2}$); and if $1 \leq o_d + i_p(u_p+1)$, $\alpha \geq \frac{1-i_p}{4(o_d+i_pu_p)}$ and $\alpha \geq \frac{1}{4}$, $p = \frac{1}{4\alpha} + u_p$, $\eta_d = \frac{1}{4\alpha}$, $\eta_p = 0$, and $\Pi_m^{EC(i)}[r_{EC}] = \frac{o_d+u_p}{2-2i_p} - \frac{kr_{EC}}{6} - \frac{\alpha(o_d+i_pu_p)^2}{(1-i_p)^2}$ ($\Pi_m^{SR(i)}[r_{SR},t] = \frac{1}{2}(\frac{o_d+u_p}{1-i_p} - t - \frac{2\alpha(o_d+i_pu_p)^2}{(1-i_p)^2})$).

**Problem (ii):** Set $p,\eta_d,\eta_p$ such that $o_d\ (1-\eta_p) + i_p\ p \leq \eta_d < o_d\ (1-\eta_p) + p$ to have $E_{\theta_n}[q_p^*(p,\eta_d,\eta_p)] = E_{\theta_n}[n\ 1 + (1-n)\theta_n^{UI}] = \frac{n+1}{2}$. Note that $E_{\theta_n,\theta_u}[q_u^*(p,\eta_d,\eta_p)] = E_{\theta_n,\theta_u}[n(\min\{1,\theta_u^I\}) + (1-n)(\min\{\theta_n^{UI},\theta_u^{UI}\})] = \frac{2n+1}{6}$. The producer's problem is $\max_{p,\eta_d,\eta_p} \Pi_m^{EC(i)}(p,\eta_d,\eta_p) = (p-c)\ \frac{n+1}{2} - k\ r_{EC}\ \frac{2n+1}{6} - \alpha\ \eta_d^2 - \beta\ \eta_p^2$, ($\max_{\eta_d,\eta_p,p} \Pi_m^{SR(i)}(p,\eta_d,\eta_p) = (p-c-t)\ \frac{n+1}{2} - \alpha\ \eta_d^2 - \beta\ \eta_p^2$), such that $o_d\ (1-\eta_p) + i_p\ p \leq \eta_d < o_d\ (1-\eta_p) + p$, $0 \leq \eta_d \leq 1$, and $0 \leq \eta_p \leq 1$. Given $r_{EC}$, if $\alpha < \frac{1+n}{4i_p}$ and $\beta < \frac{(1+n)o_d}{4i_p}$, $p = \frac{1}{i_p}$, $\eta_d = 1$, $\eta_p = 1$ and $\Pi_m^{EC(i)}[r_{EC}] = \frac{3(1+n)(\alpha(1+n)o_d^2 + \beta(1+n-8\alpha i_p o_d)) - 8\alpha\beta i_p^2 k(1+2n)r_{EC}}{48\alpha\beta i_p^2}$ ($\Pi_m^{SR(i)}[r_{SR},t] = \frac{(1+n)(\alpha(1+n)o_d^2 + \beta(1+n-8\alpha i_p(o_d+i_pt)))}{16\alpha\beta i_p^2}$); if $\alpha < \frac{1+n}{4i_p}$ and $\beta \geq \frac{(1+n)o_d}{4i_p}$, $p = \frac{4\beta i_p(o_d-1) + (1+n)o_d^2}{4\beta i_p^2}$, $\eta_d = 1$, $\eta_p = \frac{(1+n)o_d}{4\beta i_p}$ and $\Pi_m^{EC(i)}[r_{EC}] = \frac{(1+n)^2}{16\alpha i_p^2 - \beta - \frac{k(1+2n)r_{EC}}{6}}$ ($\Pi_m^{SR(i)}[r_{SR},t] = \frac{(1+n)^2 - 8\alpha i_p^2(2\beta+t+nt)}{16\alpha i_p^2}$); if $\alpha \geq \frac{1+n}{4i_p}$ and $\beta < \frac{(1+n)o_d}{4i_p}$, $p = \frac{1+n}{4\alpha i_p^2}$, $\eta_d = \frac{1+n}{4\alpha i_p}$, $\eta_p = \frac{(1+n)o_d}{4\beta i_p}$ and $\Pi_m^{EC(i)}[r_{EC}] = \frac{1+n}{2i_p} - \alpha - \beta - \frac{k(1+2n)r_{EC}}{6}$

$(\Pi_m^{SR(i)}[r_{SR},t] = \frac{(1+n)^2 o_d^2 - 8\beta i_p(2\alpha i_p + (1+n)(-1+o_d+i_p t))}{16\beta i_p^2})$; and if $\alpha \geq \frac{1+n}{4i_p}$ and $\beta \geq \frac{(1+n)o_d}{4i_p}$, $p = \frac{\alpha(1+n)o_d^2 + \beta(1+n-4\alpha i_p o_d)}{4\alpha\beta i_p^2}$, $\eta_d = 1$, $\eta_p = \frac{(1+n)o_d}{4\beta i_p}$ and $\Pi_m^{EC(i)}[r_{EC}] = \frac{1+n}{2i_p} - \alpha - \beta - \frac{k(1+2n)r_{EC}}{6}$ $(\Pi_m^{SR(i)}[r_{SR},t] = \frac{1}{2}(1+n)(\frac{1}{i_p} - t) - \alpha - \beta)$.

**Problem (iii):** Set $p, \eta_d, \eta_p$ such that $\eta_d \geq o_d\ (1-\eta_p) + p$ to have $E_{\theta_n}[q_p^*(p,\eta_d,\eta_p)] = E_{\theta_n}[n\ \ 1 + (1-n)1] = 1$. Note that $E_{\theta_u}[q_u^*(p,\eta_d,\eta_p)] = E_{\theta_u}[n(\min\{1,\theta_u^I\}) + (1-n)(\min\{1,\theta_u^{UI}\})] = \frac{1}{2}$. The producer's problem is $\max_{p,\eta_d,\eta_p} \Pi_m^{EC(i)}(p,\eta_d,\eta_p) = (p-c) - k\ \ r_{EC}\ \ \frac{1}{2} - \alpha\ \ \eta_d^2 - \beta\ \ \eta_p^2$, $(\max_{\eta_d,\eta_p,p} \Pi_m^{SR(i)}(p,\eta_d,\eta_p) = (p-c-t) - \alpha\ \eta_d^2 - \beta\ \eta_p^2)$, such that $\eta_d \geq o_d\ (1-\eta_p) + p$, $0 \leq \eta_d \leq 1$, and $0 \leq \eta_p \leq 1$. The solution of this problem is identical to problem (ii) in Propositions 11-12.

Although it is possible to characterize the optimal pricing and promotional efforts of the producer, it is algebraically intractable to compare the resulting profit values and obtain the conditions that yield different prescription outcomes. Consequently, we conduct a numerical analysis and we focus on the regions where the policy choice shifts from $SR$ to $EC$ and show the validity of our base model results. Further details are available on request.

**A3.2. DTC Advertising.** In our base model, we assume that an increase in the promotional effort level of the producer targeting the patient, i.e., the level of DTC advertising, decreases the bad-reputation associated with a doctor's over-prescription. In this section, we model the effect of DTC advertising in a different way: We assume that the patient obtains a unit promotional benefit $\eta_p$ from each prescription medicine, giving the total promotional benefit of $\eta_p q_p$ to the patient. This can be interpreted as the patient gets utility as he has the advertised medicine and its benefits. In this case, $\eta_p q_p$ becomes the part of patient-relevant doctor utility and over-prescription bad-reputation to the doctor becomes $o_d(q_p - \theta_n)^+$. Accordingly, the doctor solves the problem given by $q_p^*[p,\eta_d,\eta_p] = argmax_{q_p} U_d(q_p) = u_p\theta_n - p\ q_p + \eta_d\ q_p + \eta_p\ q_p - o_d(q_p - \theta_n)^+$. She provides $q_p^*[p,\eta_d,\eta_p] = 1$ for $\eta_d + \eta_p \geq o_d + p$

and $q_p^*[p,\eta_d,\eta_p] = \theta_n$ for $\eta_d + \eta_p < o_d + p$, where $\eta_d + \eta_p + u_p \geq p$ is the required condition for non-negative doctor utility. Problem (i) for the producer becomes $\max_{p,\eta_d,\eta_p} \Pi_m(p,\eta_d,\eta_p) = E_{\theta_n,\theta_u}[p\ \theta_n - k\ r_{EC}\ (\theta_n - \min\{\theta_n,\theta_u\}) - \alpha\ \eta_d^2 - \beta\ \eta_p^2] = \frac{p}{2} - k\ r_{EC}\frac{1}{6} - \alpha\ \eta_d^2 - \beta\ \eta_p^2$ ($\max_{p,\eta_d,\eta_p} \Pi_m(p,\eta_d,\eta_p) = E_{\theta_n}[(p-t)\ \theta_n - \alpha\eta_d^2 - \beta\eta_p^2] = (p-t)\frac{1}{2} - \alpha\ \eta_d^2 - \beta\ \eta_p^2$), such that $p - u_p \leq \eta_d + \eta_p < o_d + p$ under the $EC(SR)$ policy. The solution gives $p = \frac{1}{4}(\frac{1}{\alpha} + \frac{1}{\beta} + 4u_p)$, $\eta_d = \frac{1}{4\alpha}$, $\eta_p = \frac{1}{4\beta}$, and $\pi_m^{EC(i)} = \frac{1}{48}(\frac{3}{\alpha} + \frac{3}{\beta} - 8kr_{EC} + 24u_p)$ ($\pi_m^{SR(i)} = \frac{\alpha+\beta-8\alpha\beta t+8\alpha\beta u_p}{16\alpha\beta}$) under $EC(SR)$, where $r^i = \frac{3(\alpha+\beta+8\alpha\beta u_p)}{8\alpha\beta k}$ ($t^i = \frac{1}{8}(\frac{1}{\alpha} + \frac{1}{\beta} + 8u_p)$). Problem (ii) for the producer becomes $\max_{p,\eta_d,\eta_p} \Pi_m(p,\eta_d,\eta_p) = E_{\theta_n,\theta_u}[p\ 1 - k\ r_{EC}\ (\theta_n - \theta_u) - \alpha\ \eta_d^2 - \beta\ \eta_p^2] = p - k\ r_{EC}\frac{1}{2} - \alpha\ \eta_d^2 - \beta\ \eta_p^2$ ($\max_{p,\eta_d,\eta_p} \Pi_m(p,\eta_d,\eta_p) = E_{\theta_n}[(p-t)\ 1 - \alpha\eta_d^2 - \beta\eta_p^2] = (p-t) - \alpha\ \eta_d^2 - \beta\ \eta_p^2$), such that $\eta_d + \eta_p \geq o_d + p$ under the $EC(SR)$ policy. The solution gives $p = \frac{1}{2}(\frac{1}{\alpha} + \frac{1}{\beta} - 2o_d)$, $\eta_d = \frac{1}{2\alpha}$, $\eta_p = \frac{1}{2\beta}$, and $\pi_m^{EC(ii)} = \frac{1}{4}(\frac{1}{\alpha} + \frac{1}{\beta} - 4o_d - 2kr_{EC})$ ($\pi_m^{SR(ii)} = \frac{1}{4}(\frac{1}{\alpha} + \frac{1}{\beta} - 4(o_d - t))$) under $EC(SR)$, where $r^{ii} = \frac{\alpha+\beta-4\alpha\beta o_d}{2\alpha\beta k}$ ($t^{ii} = \frac{1}{4}(\frac{1}{\alpha} + \frac{1}{\beta} - 4o_d)$). Comparison of the producer profits under problems (i) and (ii) leads to $\bar{r} = \frac{9\beta - 3\alpha(-3+8\beta(2o_d+u_p))}{16\alpha\beta k}$ ($\bar{t} = \frac{3}{8\alpha} + \frac{3}{8\beta} - 2o_d - u_p$). It is straightforward to show that $\bar{r} < r^{ii} < r^i$ ($\bar{t} < t^{ii} < t^i$) for $u_p < \frac{\alpha+\beta-16\alpha\beta o_d}{24\alpha\beta} = \bar{u}_p^{EC}(o_d,\alpha,\beta) \doteq \bar{u}_p^{EC}$ ($u_p < \frac{1}{8}(\frac{1}{\alpha} + \frac{1}{\beta} - 8o_d) = \bar{u}_p^{SR}(o_d,\alpha,\beta) \doteq \bar{u}_p^{SR}$) and $\bar{r} \geq r^{ii} \geq r^i$ ($\bar{t} \geq t^{ii} \geq t^i$) for $u_p \geq \bar{u}_p^{EC}$ ($u_p \geq \bar{u}_p^{SR}$), where $\bar{u_p}^{SR} > \bar{u_p}^{EC}$. This means that the producer always induces over-prescription when $u_p < \bar{u}_p^{EC}$ ($u_p < \bar{u}_p^{SR}$). This proves Proposition 11. Under the $EC$ policy, when $u_p < \bar{u}_p^{EC}$, if $k < \frac{\alpha+\beta-4\alpha\beta o_d}{2\alpha\beta} = \hat{k}(o_d,\alpha,\beta) \doteq \hat{k}$, then $r^{ii} > 1$ and the producer always induces over-prescription. When $u_p \geq \bar{u}_p^{EC}$, if $k < \frac{9\beta-3\alpha(-3+8\beta(2o_d+u_p))}{16\alpha\beta} = \tilde{k}(u_p,o_d,\alpha,\beta) \doteq \tilde{k}$, then $r^{ii} > 1$ and the producer always induces over-prescription. This implies that the produce always induces over-prescription when $k < \min\{\hat{k},\tilde{k}\} = \bar{k}$ under the $EC$ policy. This proves Proposition 12. In order to prove Proposition 13, first assume that the chosen policy is $EC$ ($SR$). The social planner calculates the expected welfare at the equilibrium and sets the welfare-maximizing collection rate $r_{EC}^*$ (collection rate $r_{SR}^*$ and fee $t^*$). Total welfare depends on the problems (i) and (ii) that the producer solves based on $\theta_n, \theta_u \backsim U[0,1]$ ($\theta_n \backsim U[0,1]$), as summarized below.

**Problem (i):** The producer sets $\eta_d + \eta_p = p - u_p$ to have $q_p^*(p, \eta_d, \eta_p) = \theta_n$, which gives $E_{\theta_n}[U_d^{(i)}(q_p^*(p, \eta_d, \eta_p))] = E_{\theta_n}[(\eta_d + \eta_p)\theta_n - o_d(\theta_n - \theta_n) + u_p\theta_n - p\theta_n] = E_{\theta_n}[\theta_n(\eta_d + \eta_p + u_p - p)] = 0$, $DU_e^{EC(i)}[r_{EC}] = E_{\theta_n,\theta_u}[\epsilon_e(q_u^*(p, \eta_d, \eta_p) + (1 - r_{EC})(\theta_n - q_u^*(p, \eta_d, \eta_p))^+)] = \epsilon_e[\frac{1}{3} + \frac{(1-r_{EC})}{6}]$ and $DU_s^{EC(i)}[r_{EC}] = E_{\theta_n,\theta_u}[\epsilon_s(1 - r_{EC})(\theta_n - q_u^*(p, \eta_d, \eta_p))^+] = \epsilon_s\frac{(1-r_{EC})}{6}$ as $E_{\theta_n,\theta_u}[q_u^*(p, \eta_d, \eta_p)] = E_{\theta_n,\theta_u}[\min\{\theta_n, \theta_u\}] = \frac{1}{3}$ and $E_{\theta_n,\theta_u}[(\theta_n - q_u^*(p, \eta_d, \eta_p))^+] = \frac{1}{6}$; and $\Pi_{sp}^{EC(i)}[r_{EC}] = 0$ ($E_{\theta_n}[U_d^{(i)}(q_p^*(p, \eta_d, \eta_p))] = 0$, $DU_e^{SR(i)}[r_{SR}] = E_{\theta_n,\theta_u}[\epsilon_e(q_u^*(p, \eta_d, \eta_p) + (1 - r_{SR})(\theta_n - q_u^*(p, \eta_d, \eta_p))^+)] = \epsilon_e[\frac{1}{3} + \frac{(1-r_{SR})}{6}]$, $DU_s^{SR(i)}[r_{SR}] = E_{\theta_n,\theta_u}[\epsilon_s(1 - r_{SR})(\theta_n - q_u^*(p, \eta_d, \eta_p))^+] = \epsilon_s\frac{(1-r_{SR})}{6}$ and $\Pi_{sp}^{SR(i)}[r_{SR}, t] = E_{\theta_n,\theta_u}[t\ \theta_n - k\ r_{SR}\ (\theta_n - q_u^*(p, \eta_d, \eta_p))^+] = t\ \frac{1}{2} - k\ r_{SR}\ \frac{1}{6}$ as $E_{\theta_n,\theta_u}[q_u^*(p, \eta_d, \eta_p)] = E_{\theta_n,\theta_u}[\min\{\theta_n, \theta_u\}] = \frac{1}{3}$ and$E_{\theta_n,\theta_u}[(\theta_n - q_u^*(p, \eta_d, \eta_p))^+] = \frac{1}{6}$). Given the assumptions $u_p \geq \bar{u}_p^{EC}$ and $k \geq \tilde{k} = \min\{\tilde{k}, \hat{k}\} = \bar{k}$ ($u_p \geq \bar{u}_p^{SR}$), there may exist $r_{EC}$ ($t$) that can satisfy $\bar{r}_{EC} < r < \min(r^i, 1)$ ($\bar{t} < t < t^i$). The social planner's problem is $\max_{r_{EC}} W^{EC(i)}(r_{EC}) = E_{\theta_n,\theta_u}[U_d^{(i)}(q_p^*(p, \eta_d, \eta_p)) + \Pi_m^{EC(i)}[r_{EC}] + \Pi_{sp}^{EC(i)}[r_{EC}] - DU_e^{EC(i)}[r_{EC}] - DU_s^{EC(i)}[r_{EC}]$ ($\max_{r_{SR},t} W^{SR(i)}(r_{SR}, t) = E_{\theta_n,\theta_u}[U_d^{(i)}(q_p^*(p, \eta_d, \eta_p)) + \Pi_m^{SR(i)}[t] + \Pi_{sp}^{SR(i)}[r_{SR}, t] - DU_e^{SR(i)}[r_{SR}] - DU_s^{SR(i)}[r_{SR}]$), such that $\bar{r}_{EC} < r < \min(r^i, 1)$ ($\bar{t} < t < t^i$). Constraint $\bar{r}_{EC} < r < \min(r^i, 1)$ ensures that the producer's profit is higher when it sets $\eta_d + \eta_p = p - u_p$ than the case it sets $\eta_d + \eta_p = p + o_d$, to avoid over-prescription. Consequently, the producer's decisions under Problem (ii) determine the total expected welfare at the equilibrium.

**Problem (ii):** The producer sets $\eta_d + \eta_p = p + o_d$ to have $q_p^*(p, \eta_d, \eta_p) = 1 > \theta_n$, which gives $E_{\theta_n}[U_d^{(ii)}(q_p^*(p, \eta_d, \eta_p))] = E_{\theta_n}[(\eta_d + \eta_p) - o_d(1 - \theta_n) + u_p\theta_n - p] = (\eta_d + \eta_p) - p + \frac{u_p - o_d}{2} = \frac{o_d + u_p}{2}$; $DU_e^{EC(ii)}(r_{EC}) = E_{\theta_n,\theta_u}[\epsilon_e\ [\min(1, \theta_n) + (1 - r_{EC})\ (1 - q_u^*(p, \eta_d, \eta_p))^+] = \epsilon_e\ [\frac{1}{2} + (1 - r_{EC})\ \frac{1}{2}$ and $DU_s^{EC(ii)}(r_{EC}) = E_{\theta_n,\theta_u}[\epsilon_s\ (1 - r_{EC})(1 - q_u^*(p, \eta_d, \eta_p))] = \epsilon_s\ (1 - r_{EC})\ \frac{1}{2}$ as $E_{\theta_n,\theta_u}[\min\{\theta_n, \theta_u\}] = E_{\theta_n,\theta_u}[q_u^*(p, \eta_d, \eta_p)] = \frac{1}{2}$ and $E_{\theta_n,\theta_u}[(\theta_n - q_u^*(p, \eta_d, \eta_p))^+] = \frac{1}{2}$; and $E_{\theta_n,\theta_u}[\Pi_{sp}^{EC(ii)}(r_{EC})] = 0$ ($E_{\theta_n}[U_d^{(ii)}(q_p^*(p, \eta_d, \eta_p))] = \frac{o_d + u_p}{2}$; $DU_e^{SR(ii)}(r_{SR}) = E_{\theta_n,\theta_u}[\epsilon_e\ [\min(1, \theta_n) + (1 -$

$r_{SR})\,(1-q_u^*(p,\eta_d,\eta_p))^+] = \epsilon_e\,[\frac{1}{2}+(1-r_{SR})\,\frac{1}{2}$ and $DU_s^{SR(ii)}(r_{SR}) = E_{\theta_n,\theta_u}[\epsilon_s\,(1-r_{SR})(1-q_u^*(p,\eta_d,\eta_p))] = \epsilon_s\,(1-r_{SR})\,\frac{1}{2}$ and $\Pi_{sp}^{SR(ii)}(r_{SR}) = E_{\theta_n,\theta_u}[t-k\,r_{SR}\,(1-\theta_n)] = t-k\,r_{SR}\,\frac{1}{2}$ as $E_{\theta_n,\theta_u}[\min\{\theta_n,\theta_u\}] = E_{\theta_n,\theta_u}[q_u^*(p,\eta_d,\eta_p)] = \frac{1}{2}$ and $E_{\theta_n,\theta_u}[(\theta_n - q_u^*(p,\eta_d,\eta_p))^+] = \frac{1}{2}$). There exists $r_{EC}$ $(t)$ that can satisfy $r_{EC} < \bar{r}$ $(t < \bar{t})$. The social planner's problem is $\max_{r_{EC}} W^{EC(ii)}(r_{EC}) = E_{\theta_n,\theta_u}[U_d^{(ii)}(q_p^*(p,\eta_d,\eta_p)) + \Pi_m^{EC(ii)}[r_{EC}] + \Pi_{sp}^{EC(ii)}[r_{EC}] - DU_e^{EC(ii)}[r_{EC}] - DU_s^{EC(ii)}[r_{EC}]$ $(\max_{r_{SR},t} W^{SR(ii)}(r_{SR},t) = E_{\theta_n,\theta_u}[U_d^{(ii)}(q_p^*(p,\eta_d,\eta_p)) + \Pi_m^{SR(ii)}[t] + \Pi_{sp}^{SR(ii)}[r_{SR},t] - DU_e^{SR(ii)}[r_{SR}] - DU_s^{SR(ii)}[r_{SR}])$, such that $r < \bar{r}$ $(t < \bar{t})$. Constraint $r < \bar{r}$ $(t < \bar{t})$ ensures that the producer's profit is higher when it sets $\eta_d = p + o_d(1-\eta_p)$ than the case it sets $p = \eta_d + u_p$, to induce over-prescription. Consequently, the producer's decisions under Problem (i) determine the total expected welfare at the equilibrium. We now need to compare $W^{EC(i)}(r_{EC}^*)$ and $W^{EC(ii)}(r_{EC}^*)$ $(W^{SR(i)}(r_{SR}^*,t^*)$ and $W^{SR(ii)}(r_{SR}^*,t^*))$ to obtain the welfare-maximizing preferred prescription outcome. First consider the $EC$ policy. $\Pi_m^{EC(i)}[r_{EC}] = \frac{1}{4}(\frac{1}{\alpha}+\frac{1}{\beta}-4o_d-2kr_{EC})$ and $W^{EC(i)}(r_{EC}) = \frac{1}{48}(\frac{3}{\alpha}+\frac{3+8\beta(-3\epsilon_e-\epsilon_s+(\epsilon_e+\epsilon_s-k)r_{EC}+3u_p)}{\beta})$, where $\frac{\partial W^{EC(i)}(r_{EC})}{\partial r_{EC}} = \frac{\epsilon_e+\epsilon_s-k}{6}$. If $k \geq \epsilon_e+\epsilon_s$, $r_{EC}^* = \bar{r}_{EC} = \frac{9\beta-3\alpha(-3+8\beta(2o_d+u_p))}{16\alpha\beta k}$, leading to $W^{EC(i)}(r_{EC}^*) = \frac{1}{48}(\frac{3}{\alpha}+\frac{3+8\beta(-3\epsilon_e-\epsilon_s+3u_p+\frac{(\epsilon_e+\epsilon_s-k)(9\beta-3\alpha(-3+8\beta(2o_d+u_p)))}{16\alpha\beta k})}{\beta})$; and if $k < \epsilon_e+\epsilon_s$, $r_{EC}^* = \min(r^i,1)$, leading to $W^{EC(i)}(r_{EC}^*) = \frac{1}{48}(\frac{3}{\alpha}+\frac{3}{\beta}-8(2\epsilon_e+k-3u_p))$ when $r_{EC}^* = 1$ (or equivalently $k < \frac{3(\alpha+\beta+8\alpha\beta u_p)}{8\alpha\beta}$) and $W^{EC(i)}(r_{EC}^*) = \frac{3\beta(\epsilon_e+\epsilon_s)+\alpha(3\epsilon_e+3\epsilon_s-24\beta\epsilon_e k-8\beta\epsilon_s k+24\beta(\epsilon_e+\epsilon_s)u_p)}{48\alpha\beta k}$ when $r_{EC}^* = r_{EC}^i$ (or equivalently $k \geq \frac{3(\alpha+\beta+8\alpha\beta u_p)}{8\alpha\beta}$). $\Pi_m^{EC(ii)}[r_{EC}] = \frac{1}{4}(\frac{1}{\alpha}+\frac{1}{\beta}-4o_d-2kr_{EC})$ and $W^{EC(ii)}(r_{EC}) = \frac{1}{4}(\frac{1}{\alpha}+\frac{1}{\beta}-2(2\epsilon_e+\epsilon_s+2o_d)+2(\epsilon_e+\epsilon_s-k)r_{EC})$, where $\frac{\partial W^{EC(ii)}(r_{EC})}{\partial r_{EC}} = \frac{\epsilon_e+\epsilon_s-k}{2}$. If $k \geq \epsilon_e+\epsilon_s$, $r_{EC}^* = 0$, leading to $W^{EC(ii)}(r_{EC}^*) = \frac{1}{4}(\frac{1}{\alpha}+\frac{1}{\beta}-2(2\epsilon_e+\epsilon_s+2o_d))$; and if $k < \epsilon_e+\epsilon_s$, $r_{EC}^* = \bar{r}_{EC}$, leading to $W^{EC}(r_{EC(ii)}(r_{EC}^*) = \frac{1}{48}(\frac{3}{\alpha}+\frac{3+8\beta(-3\epsilon_e-\epsilon_s+3u_p+\frac{(\epsilon_e+\epsilon_s-k)(9\beta-3\alpha(-3+8\beta(2o_d+u_p)))}{16\alpha\beta k})}{\beta})$. Comparing the total welfare under problems (i) and (ii): if $k \geq \epsilon_e+\epsilon_s$, $W^{EC(ii)}(r_{EC}^*) > W^{EC(i)}(r_{EC}^*)$ only when $\epsilon_e < -\epsilon_s+3k+\frac{16\alpha\beta(\epsilon_s-9k)k}{9\beta+3\alpha(3+8\beta(2k-2o_d-u_p))} = \bar{\epsilon}_e^{EC}(\epsilon_s,u_p,o_d,\alpha,\beta,k) \doteq \bar{\epsilon}_e^{EC}$, where $\frac{\partial\bar{\epsilon}_e^{EC}}{\partial\epsilon_s} < 0$; if $k < \epsilon_e+\epsilon_s$ and $k < \frac{3(\alpha+\beta+8\alpha\beta u_p)}{8\alpha\beta}$, $W^{EC(ii)}(r_{EC}^*) > W^{EC(i)}(r_{EC}^*)$ only when $\epsilon_e < -\epsilon_s+k = \bar{\epsilon}_e^{EC}(\epsilon_s,k) \doteq \bar{\epsilon}_e^{EC}$, where

$\frac{\partial \bar{\epsilon}_e^{EC}}{\partial \epsilon_s} = -1 < 0$; and if $k < \epsilon_e + \epsilon_s$ and $k \geq \frac{3(\alpha+\beta+8\alpha\beta u_p)}{8\alpha\beta}$, $W^{EC(ii)}(r_{EC}^*) > W^{EC(i)}(r_{EC}^*)$ only when $\epsilon_e < -\epsilon_s + k = \bar{\epsilon}_e^{EC}(\epsilon_s, k) \doteq \bar{\epsilon}_e^{EC}$, where $\frac{\partial \bar{\epsilon}_e^{EC}}{\partial \epsilon_s} < 0$.

Second consider the policy $SR$. $\Pi_m^{SR(i)}[t] = \frac{\alpha+\beta-8\alpha\beta t+8\alpha\beta u_p}{16\alpha\beta}$ and $W^{EC(i)}(r_{SR}, t) = \frac{1}{48}(\frac{3}{\alpha} + \frac{3+8\beta(-3\epsilon_e-\epsilon_s+(\epsilon_e+\epsilon_s-k)r_{SR}+3u_p)}{\beta})$, where $\frac{\partial W^{SR(i)}(r_{SR},t)}{\partial r_{SR}} = \frac{\epsilon_e+\epsilon_s-k}{6}$. If $k \geq \epsilon_e + \epsilon_s$, $t^* \in [\bar{t}, t^i]$ and $r_{SR}^* = 0$, leading to $W^{EC}(r_{SR}^*, t^*) = \frac{1}{48}(\frac{3}{\alpha} + \frac{3}{\beta} - 8(3\epsilon_e + \epsilon_s - 3u_p))$; and if $k < \epsilon_e + \epsilon_s$, $t^* \in [\bar{t}, t^i]$ and $r_{SR}^* = 1$, leading to $W^{SR(i)}(r_{SR}^*, t^*) = \frac{1}{48}(\frac{3}{\alpha} + \frac{3}{\beta} - 8(3\epsilon_e + k - 3u_p))$. $\Pi_m^{SR(ii)}[t] = \frac{1}{4}(\frac{1}{\alpha} + \frac{1}{\beta} - 4(o_d + t))$ and $W^{SR(ii)}(r_{SR}, t) = \frac{1}{4}(\frac{1}{\alpha} + \frac{1}{\beta} - 2(2\epsilon_e + \epsilon_s + 2o_d) + 2(\epsilon_e + \epsilon_s - k)r_{SR})$, where $\frac{\partial W^{SR(ii)}(r_{SR},t)}{\partial r_{SR}} = \frac{\epsilon_e+\epsilon_s-k}{2}$. If $k \geq \epsilon_e + \epsilon_s$, $t^* \in [0, \bar{t})$ and $r_{SR}^* = 0$, leading to $W^{EC(i)}(r_{SR}^*, t^*) = \frac{1}{4}(\frac{1}{\alpha} + \frac{1}{\beta} - 2(2\epsilon_e + \epsilon_s + 2o_d))$; and if $k < \epsilon_e + \epsilon_s$, $t^* \in [0, \bar{t})$ and $r_{SR}^* = 1$, leading to $W^{SR(i)}(r_{SR}^*, t^*) = \frac{1}{4}(\frac{1}{\alpha} + \frac{1}{\beta} - 2(2\epsilon_e + k + 2o_d))$. Comparing the total welfare under problems (i) and (ii): If $k \geq \epsilon_e + \epsilon_s$, $W^{SR(ii)}(r_{SR}^*, t^*) > W^{SR(i)}(r_{SR}^*, t^*)$ only when $\epsilon_e < \frac{3}{8\alpha} + \frac{3}{8\beta} - \frac{2\epsilon_s - 2o_d - u_p}{3} = \bar{\epsilon}_e^{SR}(\epsilon_s, u_p, o_d, \alpha, \beta, ) \doteq \bar{\epsilon}_e^{EC}$, where $\frac{\partial \bar{\epsilon}_e^{SR}}{\partial \epsilon_s} = -\frac{2}{3} < 0$; and if $k < \epsilon_e + \epsilon_s$, $W^{EC(ii)}(r_{EC}^*) > W^{EC(i)}(r_{EC}^*)$ only when $\epsilon_e < \frac{9}{8\alpha} + \frac{9}{8\beta} - 2k - 6o_d - 3u_p = \bar{\epsilon}_e^{EC}(u_p, o_d, \alpha, \beta, k) \doteq \bar{\epsilon}_e^{EC}$, where $\frac{\partial \bar{\epsilon}_e^{SR}}{\partial \epsilon_s} = 0$. Summarizing the above; there exists a environmental externality threshold $\bar{\epsilon}_e^{EC}$ ($\bar{\epsilon}_e^{SR}$) such that if $\epsilon_e < \bar{\epsilon}_e^{EC}$ ($\epsilon_e < \bar{\epsilon}_e^{SR}$), $W^{EC(ii)}(r_{EC}^*) > W^{EC(i)}(r_{EC}^*)$ ($W^{SR(ii)}(r_{SR}^*, t^*) > W^{SR(i)}(r_{SR}^*, t^*)$), i.e., the total expected welfare is higher when the outcome is over-prescription. Moreover, $\frac{\partial \bar{\epsilon}_e^{EC}}{\partial \epsilon_s} \leq 0$.This proves Proposition 13.

We now calculate the total welfare under each policy at the equilibrium and compare them to obtain the welfare-maximizing policy. Based on Proposition 11, the producer's profit depends on $u_p$ vs. $\bar{u}_p$. Hence, first assume that $u_p < \bar{u}_p$. The producer always obtains higher profit with inducing over-prescription of the doctor, hence both policies result in over-prescription. Following the proof of Proposition 13, under the $SR$ policy, the planner solves the problem given by $\max_{r_{SR},t} W^{SR(ii)}(r_{SR}, t) = \frac{1}{48}(\frac{3}{\alpha} + \frac{3+8\beta(-3\epsilon_e-\epsilon_s+(\epsilon_e+\epsilon_s-k)r_{EC}+3u_p)}{\beta})$, such that $0 \leq r_{SR} \leq 1$ and $0 < t < t^{ii}$. Note that any $t$ satisfying $0 < t < t^{ii}$ can be considered as the equilibrium fee. On the other hand, under the $EC$ policy, the planner solves the problem given by $\max_{r_{EC}} W^{EC(ii)}(r_{EC}) = \frac{1}{4}(\frac{1}{\alpha}+\frac{1}{\beta}-2(2\epsilon_e+\epsilon_s+2o_d)+2(\epsilon_e+\epsilon_s-k)r_{EC})$, such that $0 \leq r_{EC} \leq \min\{r^{ii}, 1\}$. When $k < \min\{\hat{k}, \tilde{k}\} = \hat{k}$, $r^{ii} > 1$ and both problems become equivalent. Therefore, when $u_p < \bar{u}_p$ and $k < \bar{k}$, both policies leads to same level of total welfare at the equilibrium. When $k \geq \min\{\hat{k}, \tilde{k}\} = \hat{k}$, $r^{ii} \leq 1$, implying that $r^*_{SR} \geq r^*_{EC}$. Therefore, when $u_p < \bar{u}_p$ and $k \geq \bar{k}$, $SR$ leads to same or higher level of total welfare at the equilibrium. Second assume that $u_p \geq \bar{u}_p$. The $SR$ policy still results in over-prescription and the planner solves the same problem: $\max_{r_{SR},t} W^{SR(ii)}(r_{SR}, t) = \frac{1}{4}(\frac{1}{\alpha}+\frac{1}{\beta}-2(2\epsilon_e+\epsilon_s+2o_d)+2(\epsilon_e+\epsilon_s-k)r_{SR})$, such that $0 \leq r_{SR} \leq 1$ and $0 < t < t^{ii}$. However, in this case, the $EC$ policy may or may not avoid over-prescription based on the unit collection cost $k$, as Proposition 12 states. When $k < \tilde{k} = \min\{\hat{k}, \tilde{k}\} = \bar{k}$, $\bar{r}_{EC} > 1$ and the producer always obtains higher profit with inducing over-prescription of the doctor, hence both policies result in over-prescription. In this case, the planner solves the problem given by $\max_{r_{EC}} W^{EC(ii)}(r_{EC}) = \frac{1}{4}(\frac{1}{\alpha} + \frac{1}{\beta} - 2(2\epsilon_e + \epsilon_s + 2o_d) + 2(\epsilon_e + \epsilon_s - k)r_{EC})$, such that $0 \leq r_{EC} \leq 1$, which is equivalent to the problem under $SR$. Therefore, when $u_p \geq \bar{u}_p$ and $k < \bar{k}$, both policies leads to same level of total welfare at the equilibrium. When $k \geq \tilde{k} = \min\{\hat{k}, \tilde{k}\} = \bar{k}$, $\bar{r}_{EC} \leq 1$ and the producer can avoid over-prescription. In this case, the planner solves the problem given by $\max_{r_{EC}} W^{EC(i)}(r_{EC}) = \frac{1}{48}(\frac{3}{\alpha} + \frac{3+8\beta(-3\epsilon_e-\epsilon_s+(\epsilon_e+\epsilon_s-k)r_{EC}+3u_p)}{\beta})$, such that $\bar{r} < r_{EC} < \min\{r^i, 1\}$ to avoid over-prescription; and $\max_{r_{EC}} W^{EC(ii)}(r_{EC}) = \frac{1}{4}(\frac{1}{\alpha} + \frac{1}{\beta} - 2(2\epsilon_e + \epsilon_s + 2o_d) + 2(\epsilon_e + \epsilon_s - k)r_{EC})$, such that $0 < r_{EC} < \bar{r}$ to induce over-prescription. Based on Proposition 13, when $\epsilon_e < \bar{\epsilon}_e^{EC}$, the total welfare is higher with the over-prescription outcome, i.e., $W^{EC(ii)}(r^*_{EC}) > W^{EC(i)}(r^*_{EC})$. As the $SR$ policy induces over-prescription and $r^*_{SR} \geq r^*_{EC}$, $W^{SR(ii)}(r^*_{SR}, t^*) > W^{EC(ii)}(r^*_{EC})$, i.e., the total welfare at the equilibrium is equal or higher under $SR$. When $\epsilon_e \geq \bar{\epsilon}_e^{EC}$, solution under the $EC$ policy gives $W^{EC(ii)}(r^*_{EC}) \leq W^{EC(i)}(r^*_{EC})$. Solution under the $SR$ policy gives $W^{SR(ii)}(r^*_{SR}, t^*) = \frac{1}{4}(\frac{1}{\alpha} + \frac{1}{\beta} - 2(2\epsilon_e + \epsilon_s + 2o_d))$ if $k \geq \epsilon_e + \epsilon_s$

and $W^{SR(ii)}(r_{SR}^*, t^*) = \frac{1}{4}(\frac{1}{\alpha} + \frac{1}{\beta} - 2(\epsilon_e + k + 2o_d))$ if $k < \epsilon_e + \epsilon_s$. Comparing the welfare under each policy: if $k \geq \epsilon_e + \epsilon_s$, $W^{EC(i)}(r_{EC}^*) > W^{SR(ii)}(r_{SR}^*, t^*)$ only when $\epsilon_e > -\epsilon_s + 3k + \frac{16\alpha\beta(\epsilon_s - 9k)k}{9\beta + 3\alpha(3+8\beta(2k-2o_d-u_p))} = \tilde{\epsilon}_e(\epsilon_s, u_p, o_d, \alpha, \beta, k) \doteq \tilde{\epsilon}_e$, where $\tilde{\epsilon}_e = \bar{\epsilon}_e$; if $k < \epsilon_e + \epsilon_s$ and $k < \frac{\alpha+\beta-4\alpha\beta o_d}{2\alpha\beta}$, $W^{EC(i)}(r_{EC}^*) > W^{SR(ii)}(r_{SR}^*, t^*)$ only when $\epsilon_e > \frac{9}{8\alpha} + \frac{9}{\beta} - 2k - 6o_d - 3u_p = \tilde{\epsilon}_e(u_p, o_d, \alpha, \beta, k) \doteq \tilde{\epsilon}_e$, where $\tilde{\epsilon}_e > \bar{\epsilon}_e$; and if $k < \epsilon_e + \epsilon_s$ and $k \geq \frac{\alpha+\beta-4\alpha\beta o_d}{2\alpha\beta}$, $W^{EC(i)}(r_{EC}^*) > W^{SR(ii)}(r_{SR}^*, t^*)$ only when $\epsilon_e > -\epsilon_s + \frac{4k(3\beta+\alpha(3+2\beta(\epsilon_s-3k-6o_d)))}{3(\alpha+\beta+8\alpha\beta u_p)} = \tilde{\epsilon}_e(\epsilon_s, u_p, o_d, \alpha, \beta, k) \doteq \tilde{\epsilon}_e$, where $\tilde{\epsilon}_e > \bar{\epsilon}_e$. Therefore, when $u_p \geq \bar{u}_p$ and $k \geq \bar{k}$, the $EC$ policy leads to higher total welfare at equilibrium only when $\epsilon_e > \tilde{\epsilon}_e$, otherwise the $SR$ policy leads to higher total welfare. This proves Proposition 14.

To obtain the preferred policy from the producer's perspective, we compare his profit at the equilibrium $\Pi_m^P[x_P^*]$ under each policy, where $P = EC/SR$ and $x_P = r_{EC}/r_{SR}, t$. Given the assumption $u_p < \bar{u}_p^{SR}$, the producer's profit is always higher with over-prescription under $SR$, hence $\Pi_m^{SR(ii)}[t^*] = \frac{1}{4}(\frac{1}{\alpha} + \frac{1}{\beta} - 4(o_d + t))$, where $0 \leq t \leq t^{ii}$. On the other hand, the producer's profit depends on $u_p$ w.r.t. $\bar{u}_p$ and $k$ w.r.t. $\bar{k}$, following Propositions 11-12. First consider $u_p < \bar{u}_p$ and $k < \bar{k} = \min\{\hat{k}, \tilde{k}\} = \hat{k}$. In this case, the producer's profit is higher with over-prescription, hence $\Pi_m^{EC(ii)}[r_{EC}] = \frac{1}{4}(\frac{1}{\alpha} + \frac{1}{\alpha} - 4o_d - 2kr_{EC})$, where $r_{EC} \in [0, 1]$. If $k < \epsilon_e + \epsilon_s$, then $r_{EC}^* = 1$ and $\Pi_m^{EC(ii)}[r_{EC}^*] > \Pi_m^{SR(ii)}[t^*]$ only when $t > \frac{k}{2} = \bar{t}(k) \doteq \bar{t}$. If $k \geq \epsilon_e + \epsilon_s$, then $r_{EC}^* = 0$ and $\Pi_m^{EC(ii)}[r_{EC}^*] > \Pi_m^{SR(ii)}[t^*]$. Second consider $u_p \geq \bar{u}_p$ and $k < \bar{k} = \min\{\bar{k}, \tilde{k}\} = \tilde{k}$. In this case, the producer's profit is higher with over-prescription, hence $\Pi_m^{EC(ii)}[r_{EC}] = \frac{1}{4}(\frac{1}{\alpha} + \frac{1}{\beta} - 4o_d - 2kr_{EC})$, where $r_{EC} \in [0, 1]$. If $k < \epsilon_e + \epsilon_s$, then $r_{EC}^* = 1$ and $\Pi_m^{EC(ii)}[r_{EC}^*] > \Pi_m^{SR(ii)}[t^*]$ only when $t > \frac{k}{2} = \bar{t}(k) \doteq \bar{t}$. If $k \geq \epsilon_e + \epsilon_s$, then $r_{EC}^* = 0$ and $\Pi_m^{EC(ii)}[r_{EC}^*] > \Pi_m^{SR(ii)}[t^*]$. Third consider $u_p < \bar{u}_p$ and $k \geq \bar{k} = \min\{\hat{k}, \tilde{k}\} = \hat{k}$. In this case, the producer's profit is higher with over-prescription, hence $\Pi_m^{EC(ii)}[r_{EC}]$, where $r_{EC} \in [0, r^{ii}]$. If $k < \epsilon_e + \epsilon_s$, then $r_{EC}^* = r^{ii}$ and $\Pi_m^{EC(ii)}[r_{EC}^*] > \Pi_m^{SR(ii)}[t^*]$ only when $t > \frac{1}{4}(\frac{1}{\alpha} + \frac{1}{\beta} - 4o_d)$, which contradicts with

$t < t^{ii}$. Therefore, $\Pi_m^{EC(ii)}[r_{EC}^*] < \Pi_m^{SR(ii)}[t^*]$. If $k \geq \epsilon_e + \epsilon_s$ where $r_{EC}^* = 0$ and $\Pi_m^{EC(ii)}[r_{EC}^*] > \Pi_m^{SR(ii)}[t^*]$. Finally consider $u_p \geq \bar{u}_p$ and $k \geq \bar{k} = \min\{\hat{k}, \tilde{k}\} = \tilde{k}$. In this case, the social planner can avoid over-prescription, hence producer's profit is $\Pi_m^{EC(i)}[r_{EC}] = \frac{1}{48}(\frac{3}{\alpha} + \frac{3}{\beta} - 8kr_{EC} + 24u_p)$, where $r_{EC} \in [\bar{r}, \min\{r^i, 1\}]$. If $k \geq \epsilon_e + \epsilon_s$, then $r_{EC}^* = \bar{r}$ and $\Pi_m^{EC(i)}[r_{EC}^*] > \Pi_m^{SR(ii)}[t^*]$ only when $t > \frac{3}{32}(\frac{3}{\alpha} + \frac{3}{\beta} - 8(2o_d + u_p)) = \bar{t}(u_p, o_d, \alpha, \beta) \doteq \bar{t}$. If $k < \epsilon_e + \epsilon_s$, $r_{EC}^* = \min\{r^i, 1\}$. When $k < \bar{\bar{k}}$, $r_{EC}^* = 1$ and $\Pi_m^{EC(i)}[r_{EC}^*] > \Pi_m^{SR(ii)}[t^*]$ only when $t > \frac{1}{48}(\frac{9}{\alpha}+\frac{9}{\beta}+8(k-6o_d-3u_p)) = \bar{t}(u_p, o_d, \alpha, \beta, k) \doteq \bar{t}$. When $k \geq \bar{\bar{k}}$, $r_{EC}^* = r^i$ and $\Pi_m^{EC(i)}[r_{EC}^*] = 0$, hence $\Pi_m^{EC(ii)}[r_{EC}^*] < \Pi_m^{SR(ii)}[t^*]$. This proves Proposition 15.

To obtain the preferred policy from the environmental and public health perspectives, we compare the total environmental and social disutility at equilibrium $DU^P[x_P^*]$ under each policy, where $P = EC/SR$ and $x_P = r_{EC}/r_{SR}, t$. With the $SR$ policy, the planner can set any collection rate, $r_{SR} \in [0, 1]$. On the other hand, with $EC$ policy, the range for collection rate $r_{EC}$ depends on $u_p$ w.r.t. $\bar{u}_p$ and $k$ w.r.t. $\bar{k}$, following Propositions 11-12. First consider $u_p < \bar{u}_p$ and $k < \bar{k}$. In this case, both policies result in over-prescription; $DU^P[x_P] = \epsilon_e(\frac{1}{2} + \frac{1-r_P}{2})$ for any $x_P$, where $r_{EC} \in [0, 1]$ under $EC$ and $r_{SR} \in [0, 1]$ under $SR$. Therefore, both policies lead to same level of total disutility at the equilibrium. Second consider $u_p \geq \bar{u}_p$ and $k < \bar{k} = \min\{\hat{k}, \tilde{k}\} = \tilde{k}$. In this case, both policies result in over-prescription, where $r_{EC} \in [0, 1]$ under $EC$ and $r_{SR} \in [0, 1]$ under $SR$. Therefore, both policies lead to same level of total disutility. Third consider $u_p < \bar{u}_p$ and $k \geq \bar{k} = \min\{\hat{k}, \tilde{k}\} = \hat{k}$. In this case, both policies result in over-prescription, where $r_{EC} \in [0, r^{ii}$ under $EC$ and $r_{SR} \in [0, 1]$ under $SR$. If $k \geq \epsilon_e + \epsilon_s$, $r_{EC}^* = r_{SR}^* = 0$, hence $DU^{EC(ii)}(r_{EC}^*) = DU^{SR(ii)}(r_{SR}^*, t^*)$. If $k < \epsilon_e + \epsilon_s$, $r_{EC}^* = r^{ii} < 1 = r_{SR}^*$, hence $DU^{EC(ii)}[r_{EC}^*] > DU^{SR(ii)}[r_{SR}^*, t^*]$. Finally consider $u_p \geq \bar{u}_p$ and $k \geq \bar{k} = \min\{\hat{k}, \tilde{k}\} = \tilde{k}$. In this case, the $SR$ policy results in over-prescription whereas the $EC$ policy avoids over-prescription; $DU^{EC(i)}[r_{EC}] = \epsilon_e(\frac{1}{3} + \frac{1-r_{EC}}{6})$ and

$DU^{SR(ii)}[r_{SR}, t] = \epsilon_e(\frac{1}{2} + \frac{1-r_{SR}}{2})$, where $r_{EC} \in [\bar{r}, \min\{r^i, 1\}]$ under $EC$ and $r_{SR} \in [0, 1]$ under $SR$. If $k \geq \epsilon_e + \epsilon_s$, $r^*_{EC} = \bar{r} > r^*_{SR} = 0$, hence $DU^{EC(i)}[r^*_{EC}] < DU^{SR(ii)}[r^*_{SR}, t^*]$. If $k < \epsilon_e + \epsilon_s$, $r^*_{EC} = \min\{r^i, 1\}$ and $r^*_{SR} = 1$. When $k < \frac{3(\alpha+\beta+8\alpha\beta u_p)}{8\alpha\beta} = \bar{\bar{k}}(u_p, \alpha, c) \doteq \bar{\bar{k}}$, $r^*_{EC} = 1 = r^*_{SR}$, hence $DU^{EC(i)}[r^*_{EC}] < DU^{SR}[r^*_{SR(ii)}, t^*]$. When $k \geq \bar{\bar{k}}$, $r^*_{EC} = r^i < 1 = r^*_{SR}$, hence $DU^{EC(i)}[r^*_{EC}] < DU^{SR(ii)}[r^*_{SR}, t^*]$ only when $\epsilon_s < \frac{3\epsilon_e(\alpha+\beta+8\alpha\beta u_p)}{-3\beta+\alpha(-3+8\beta(k-3u_p))} = \bar{\epsilon}_s(\epsilon_e, u_p, \alpha, \beta, k) \doteq \bar{\epsilon}_s$. This proves Proposition 16. Combining the conditions obtained from Proposition 15 gives similar structure as in Table 5, proving Proposition 17.

**A3.3. Patient's Consumption Behavior.** In our base model, we assume that the patient uses his desired quantity if it is available, which is not necessarily equal to the need of the patient. In this section, we assume that the patient realizes his need as he is using the prescription medicine and uses this amount of medicine, i.e., $q_u = \theta_n$. As the doctor bases his prescribing on the need of the patient, his problem remains same. However, this assumption eliminates the effect of external influential factors, implying that pharmaceutical overage is only due to doctor's over-prescription. This does not affect the producer's problem under the $SR$ policy, and changes his problem under the $EC$ policy in the following way. In problem (i), his problem is given by $\max_{p,\eta_d,\eta_p} \Pi_m^{EC(i)}(p, \eta_d, \eta_p) = E_{\theta_n,\theta_u}[p\ \theta_n - k\ r_{EC}\ (\theta_n - \theta_n) - \alpha\ \eta_d^2 - \beta\ \eta_p^2] = p\ \frac{1}{2} - \alpha\ \eta_d^2 - \beta\ \eta_p^2$, such that $-u_p \leq \eta_d - p < o_d\ (1 - \eta_p)$, $0 \leq \eta_d \leq 1$, and $0 \leq \eta_p \leq 1$. (The problem (ii) remains same as $\max_{p,\eta_d,\eta_p} \Pi_m^{EC(ii)}(p, \eta_d, \eta_p) = E_{\theta_n,\theta_u}[p\ 1 - k\ r_{EC}(1 - \theta_n)^+ - \alpha\ \eta_d^2 - \beta\ \eta_p^2] = p - k\ r_{EC}\frac{1}{2} - \alpha\ \eta_d^2 - \beta\ \eta_p^2$ such that $o_d\ (1 - \eta_p) + p \leq \eta_d$, $0 \leq \eta_d \leq 1$, and $0 \leq \eta_p \leq 1$.) This shows that the producer's profit is higher as compared to before in problem (i) under the $EC$ policy. As the structure of the producer problems is same as before, our structural results and insights remain valid. Further details are available on request.

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