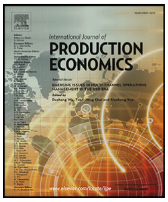
Int. J. Production Economics 278 (2024) 109426

Contents lists available at ScienceDirect

International Journal of Production Economics

journal homepage: www.elsevier.com/locate/ijpe



A sustainable semiconductor supply chain under regulation

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ARTICLE INFO

Keywords:
Semiconductor industry
Circular economy
Supply chain management
Subsidy
Endogenous return

ABSTRACT

Modern life would not exist without semiconductors as all electronic components used in computers, telecommunications, health care, transportation, and energy systems are equipped with chips. To examine both backward and forward activities in semiconductor industry, this paper formulates the industry as a closed-loop supply chain. It articulates how old semiconductors are processed and recycled to manufacture new silicon and chips, and examines the impact of a commonly applied subsidy scheme on the performance of semiconductor firms which operate in upstream and downstream layers of the industry. Specifically, the proposed semiconductor supply chain involves (i) a return function sensitive to monetary incentives; (ii) a subsidy legislation rewarding end-users for recycling; (iii) upstream industry where silicon is produced using virgin and scrap materials; (iv) downstream industry in which semiconductor manufacturers (such as TSMC, Samsung, Intel) buy silicon and other materials, hire workers, and then produce and sell chips. We characterize Stackelberg equilibrium silicon and semiconductor prices and outputs and calibrate model parameters using actual data to quantify the effects of subsidy and collection channels on silicon and semiconductor firms' performance. We find that the subsidy scheme neither distorts firms' strategies nor causes any inefficiency for the semiconductor industry. It stimulates circular economy activities and provides economic and environmental benefits.

1. Introduction

While semiconductors are indispensable components of electronic devices, the semiconductor industry brings about environmental problems. Semiconductor fabrication plants use a significant amount of water and energy and result in a large carbon footprint (Wang et al., 2023). Ruberti (2023) analyzed the environmental performance of leading semiconductor manufacturers (such as Taiwan Semiconductor Manufacturing Company (TSMC) and Semiconductor Manufacturing International Corporation (SMIC)) and found that as firms' revenues and their research and development expenses went up they generated more waste and greenhouse gas (GHG) emissions. Lev-Ram (2024) reports that, in addition to thousands of tons of chemical waste generated annually by the semiconductor industry, the large fabs owned by TSMC and Intel use as much as 100 MWh electricity, which is more than what big oil refineries demand, and can consume more than 1 million gallons of water daily per a fab to rinse chips and cool equipment.[2] In fact, the top chip manufacturer TSMC alone used over 7% of the electricity generated in Taiwan in 2022 and its power consumption was more than doubled from 2017 to 2022.[3] Given that about 80% of Taiwan's electricity generation comes from fossil fuel, TSMC's carbon footprint is immense.[4] The CHIPS and Science Act signed in 2022 authorized nearly 280 billion dollar subsidies and tax credits of which nearly 53 billion dollars allocated to semiconductor firms for the purpose of semiconductor manufacturing and research and development in the US. Given these financial incentives, the increasing demand for semiconductors fueled by Artificial Intelligence (AI) products, and chips trade disputes and restrictions between China and the USA (and Europe), Intel and TSMC have started constructing new plants in Arizona, where underground water is limited. These events imply that the environmental implications of the semiconductor industry will be more pronounced than those of transportation, electricity, and oil and gas sectors which are heavily criticized and therefore have already initiated energy transition to reduce their carbon emissions. Consequently, the primary focus of this research lies in examining the impact of compensation policies on stimulating circular economy activities within the semiconductor industry.

Given the immense energy and resource consumption of the industry, a range of government policies (such as California Climate

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[1] This research was in part supported by a grant from the Social Sciences and Humanities Research Council of Canada.

[2] https://fortune.com/2024/01/29/chips-act-semiconductor-factories-environmental-impact-water-electricity-carbon-chemical-waste/.

[3] https://www.statista.com/statistics/1312965/tsmc-energy-consumption-by-source/.

[4] https://en.wikipedia.org/wiki/EnergyinTaiwan.

https://doi.org/10.1016/j.ijpe.2024.109426
Received 13 March 2024; Received in revised form 17 September 2024; Accepted 27 September 2024

Corporate Data Accountability Act and the European Union's Corporate Sustainability Reporting Directive) and financial incentives (such as the ones provided through the CHIPS Act) led the semiconductor companies to implement their own sustainability goals.[5] Many semiconductor firms increased their electricity consumption from renewables. For example, in 2022 NPX Semiconductors' 35% electricity consumption stemmed from renewable energy, while Nijmegen of the Netherlands used 100% renewable energy in its wafer fab. Samsung has been only using renewable energy in its plants in the USA since 2019. In addition, Intel's 93% of energy consumption has come from renewables as of its 2022–23 fiscal year.[6] The semiconductor companies have also engaged in reverse logistics activities. For instance, NVidia makes sure that its e-waste is properly decommissioned and recycled. Through Apple's trade-in program, Apple reuses or recycles precious metals such as gold, palladium, cobalt, and lithium from the returned devices. Similarly, AMD and Microsoft recover and recycle critical components and materials from their used products collected in Asia.[7]

Policy makers play critical roles in semiconductor supply chain operations and affect firms' performance through vertical restrictions, monetary incentives, and regulatory laws and enforcement. Governments often support high-tech industries through subsidies and tax brakes in order to spur innovation, increase economic activity, and achieve their own sustainability goals. Even though the semiconductor industry is highly profitable and worldwide sales are valued over a half trillion dollars, the industry is still subsidized. For example, according to an OECD (2018), governments provided over $50 billion to 21 large semiconductor firms during 2014–2018 in order to expand their research and development activities.[8] The CHIPS Act of the USA has provided $39 billion in subsidies for chip manufacturing in the USA, which mostly provided benefits to Intel with $19.7 billion for constructing Ohio facility, and Micron Technology with $10.3 billion for its fabrication plants (Howard, 2024).

This paper is motivated by a subsidy regulation applied to automotive sector that is relevant for the semiconductor reverse supply chain. Motor vehicles are equipped with hundreds of semiconductors; while an average car has approximately 1400–1500 chips, electric, luxury, and sports cars contain two times more chips. Semiconductors in vehicles furnish many performance and safety features such as providing infotainment functionality, adjusting air conditioning, monitoring tire pressure, triggering airbags in case of accident, adjusting seats, controlling ignition timing, managing fuel injection, distributing breaking force between the wheels, controlling the flow of hydraulic fluid for turning the steering wheel, providing advanced driver assistance systems and wireless connections.[9] During economic and financial crises governments implement subsidy programs such as "Scrappage Incentive Programs", "Automotive Stimulus Package", and "Vehicle Efficiency Incentive". In such programs, a subsidy is generally provided to consumers. The goals of these government programs are multifaceted and aim to increase economic activity, stimulate recycling, recovery, and reuse activities, save energy and virgin minerals and metals, and reduce air emissions. As part of these programs, old vehicle owners who returned their vehicles and bought new ones received subsidies of $4500, $1000, Euro 2500, and Euro 3500 from the governments of US, Canada, Germany and Italy, respectively. The amount of subsidy, the perception of consumers to these programs, and the structure of supply chains impact the success of these programs. In relation to these subsidy programs, this research articulates how old semiconductors in used cars should be collected, processed and recycled to manufacture new silicon and chips.

Given the complexity of chip manufacturing and industrial organization of semiconductor industry, we formulate a tractable semiconductor closed-loop supply chain (CLSC) to investigate a number of research issues. In the reverse supply chain, given the subsidy, we deliberate collection and recycling of used semiconductors. Specifically, we intend to address the following research questions and their ramifications.

- **(a)** What is the impact of subsidy on semiconductor supply chain outcomes (i.e., returns, silicon and semiconductor outputs and prices, and semiconductor firms' profits) in both upstream and downstream layers of the industry?
- **(b)** Does a subsidy provided through scrappage programs create economic loss in the semiconductor supply chain?
- **(c)** Does return behavior (either exogenous or endogenous) affect forward and reverse semiconductor supply chain operations in the presence of subsidy?
- **(d)** Does the collection channel matter in the semiconductor industry? If yes, what is the most profitable collection channel for the semiconductor industry in the nexus of subsidy and endogenous returns?

To the best of our knowledge, these questions are novel and have not been addressed in the literature. To assess the impact of subsidy regulation on the semiconductor industry, we formulate a CLSC structure incorporating silicon production from virgin material and used chips, a new semiconductor production by competitive chip makers, semiconductor labor market, collection and recycling of used semiconductors, and sophisticated consumers who are price, rebate, and subsidy responsive in returning their used items. We address the proposed research questions by characterizing Stackelberg equilibrium outcomes. Furthermore, using actual data we calibrate model parameters to semiconductor forward and reverse supply chains and offer numerical exercises to quantify and assess the impact of subsidy and collection channels in the industry.

This paper contributes to the semiconductor industry literature in a number of ways. It is the first paper in the literature formulating the semiconductor industry in a CLSC framework to study the impacts of subsidy and collection channel in the presence of endogenous return. It explicitly formulates production functions for silicon and semiconductors and explains how used items containing semiconductors are turned into new products. It embeds an efficient subsidy scheme to examine its role on the industry outcomes and returns. From reverse supply chain operations perspective it address the most profitable collection channel in the industry given endogenous return behavior. Most importantly, it uses actual firm and industry data to calibrate model parameters and quantify equilibrium silicon and semiconductor prices and industry profits.

Some of the findings are: **(i)** Semiconductor firms' CLSC strategies are not distorted by the proposed subsidy program. That is, no welfare loss is created in the supply chain. This is good news for silicon and semiconductor firms, consumers, and governments. A policy implication of this finding is that government subsidized car scrappage programs including electric vehicle subsidies and electronic items return programs are worthwhile to the society and provide incentives for semiconductor firms to close the supply chain loop. In addition, these kinds of subsidies spur economic activity, reduce pollution, and save virgin materials and energy. **(ii)** An upper bound for the number of scrap semiconductors to be collected and recycled in the reverse supply chain operations is also characterized. This upper bound is endogenous and should be used as a threshold by governments in order to determine the total subsidy to be allocated. Semiconductor and silicon producing firms can use this threshold to arrange their logistics operations along with their recycling and processing centers. A practical implication of this finding is that if recyclers and silicon manufacturing firms process more than the threshold quantity of chips, then they incur loss in profit

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[5] https://www2.deloitte.com/us/en/pages/consulting/articles/reducing-emissions-in-semiconductor-products.html.

[6] https://www2.deloitte.com/us/en/pages/consulting/articles/manufacturing-solutions-for-semiconductors.html.

[7] https://www2.deloitte.com/us/en/pages/consulting/articles/circularity-solutions-in-the-semiconductor-industry.html.

[8] https://www.oecd.org/trade/let-the-chips-fall-where-they-may/.

[9] https://www.icdrex.com/.

and governments waste tax revenue used for financing the subsidy. **(iii)** The most profitable collection channel in the semiconductor supply chain under subsidy involves silicon manufacturer or its subsidiary. The right choice of a collection channel positively contributes to the success of stimulus programs and improves the efficiency in the industry. This result is robust to both exogenous and endogenous return behaviors.

The structure of this paper is as follows. Section 2 briefly mentions the related papers about the semiconductor industry. Section 3 consists of a theoretical model which explains productions of silicon and semiconductors, recycling process of used chips, and endogenous consumer return behavior encompassing price, rebate and subsidy. Section 4 provides theoretical results with discussions. Section 5 explains the details of firm and industry data and explains how model parameters are calibrated using this data. Section 6 offers numerical outcomes and their implications. Section 7 extends the paper in a number of directions in order to assess the impacts of labor, production technology, backward activity, and vertical integration. Section 8 provides managerial implications for the semiconductor firms. The final section concludes with a brief summary.

2. Related literature and research gap

This section briefly reviews the literature which has studied the environmental and sustainability issues germane to the semiconductor industry. A set of papers related to economic regulations applied to CLSC frameworks has also been discussed, compared and contrasted to the current research.

2.1. Research pertinent to semiconductor industry

Academic studies on the semiconductor industry have been growing. Recent papers have emphasized the importance of this industry on other sectors and the broader economy, which heavily rely on microchips to function (see Eliaa et al., 2020; Varshney and Jain, 2023). During the pandemic era, demand for many consumer electronic devices and automobiles were not met due to chip shortages. This caused significant vehicle price hikes and years of waiting from order-to-delivery. Automakers lost billions of dollar, and potential new car buyers reverted to used car market and paid excessive prices for used cars. This and related supply chain bottleneck issues in both upstream and downstream semiconductor industries have urged governments and semiconductor producers to and resilient.

The carbon footprint of silicon production and semiconductor manufacturing is high and the industry is responsible from a significant amount of greenhouse gas emissions (Lee et al., 2022). In fact, silicon smelting requires a large amount of energy so that electricity consumption per metric-ton of silicon production is about 12–13 MWh, depending on smelting process and purity of silicon. Most silicon is produced in China, where high-carbon energy sources such as coal, oil and natural gas are burnt for power generation and industrial processes. Using renewable energy in the industry can reduce air pollution levels to help achieve social responsibility and satisfy the environmental targets (Genc and Reynolds, 2019; Lin et al., 2022).

The semiconductor industry is one of the most polluting sectors compared to others as significant amount of water, virgin elements, and energy are used in silicon and chip fabrications (Wang et al., 2023). Therefore, a number of studies focused on energy and material sustainability issues in the industry (Sueyoshi and Ryu, 2020; Lin et al., 2022; Swain et al., 2022; Santharm and Ramanathan, 2022; Yu et al., 2024). These issues include reduction in usage of resources and rare metals, regulatory controls, measures to prevent environmental degradation and air pollution, and social responsibility and carbon neutrality objectives of the semiconductor firms.

To contribute to sustainability initiatives in the semiconductor industry, circular economy models should be designed to address resource scarcity issues, critical raw elements conservation, and recycling and reusing of scrap silicon and chips through effective backward supply chain management strategies. These measures will provide immense environmental benefits, conserve virgin elements and resources, reduce energy consumption, decrease production costs, and increase profitability in the industry. To our knowledge, a study on semiconductor circular economy involving silicon and chips recovery and manufacturing along with effective reverse logistics operations and regulations has not been examined in the semiconductor literature. Therefore, this research intends to fill an important research gap in the semiconductor industry.

A recent paper by Dou et al. (2024) examined a CLSC model relevant to the semiconductor industry to study the impacts of production and interruption costs and reliability on the supply chain network design. A number of papers considered other important issues in the semiconductor industry including sustainability and resilience of semiconductor materials (such as gallium, germanium, and silicon) supply chain (Yu et al., 2024), forecasting demand for chips (Chien et al., 2010), capacity planning for semiconductor manufacturing under uncertainty (Karabuk and Wu, 2003; Chou et al., 2007; Rastogi et al., 2011; Chien et al., 2012; Romauch and Hartl, 2017), measuring productivity of semiconductor packaging and testing firms (Liu and Wang, 2008), and the impact of Covid-19 on semiconductor shortages (Ramani et al., 2022). Compared to these papers which address specific semiconductor industry issues, our research focuses on the semiconductor CLSC forward and backward activities along with equilibrium pricing of silicon and semiconductors in the presence of subsidy and endogenous returns.

2.2. Related closed-loop supply chain research

A number of papers have extended circular economy models in a number of directions. Examples include coordination problems and environmental measures (Bazan et al., 2017), component reuse in manufacturing (Chen, 2017), take-back legislation (Esenduran et al., 2017), optimal rebate and return mechanisms (Genc and De Giovanni, 2018), subsidy for remanufactured products (Chai et al., 2021; Nie et al., 2021), innovation-led lean programs and sustainability in supply chains (Genc and De Giovanni, 2020), sales channel choice and subsidy (He et al., 2019), subsidy offerings in logistics operations (Chen and Hu, 2018), subsidy and environmental considerations (Dou and Choi, 2021; Yu et al., 2021). De Giovanni and Ramani (2024) have reviewed literature covering recent developments in supply chain studies.

Among these studies, a number of issues are highly relevant for the semiconductor industry and the remedies offered therein can provide benefits to the semiconductor firms. First, the coordination between upstream and downstream firms in the industry can facilitate forming effective recycling and component reuse policies. Second, return and rebate policies applied to consumer cyclical sectors can be extended to include technology sector, in particular the semiconductor industry. Third, subsidies provided to other remanufactured products could involve silicon and chips. In the literature, while subsidies are usually provided to the business firms in other sectors, which have been shown to cause inefficiencies, this paper argues that the subsidy provided to end-users in the semiconductor industry is efficient, and does not distort firms' strategies.

In the literature, there are a few applications of closed-loop supply chain (CLSC) frameworks relevant to other industries. De Giovanni and Ramani (2024) note that while the CLSC studies are mostly theoretical, only a small fraction of the papers included real data to examine some real-world CLSC issues. Examples of applications of CLSC models include Zhu et al. (2023) and Zaman and Zaccour (2021) who examined automotive industry, Chen and Hu (2018) who studied beer industry, Khorshidvand et al. (2023) who investigated garment sector, and Genc (2024) who examined steel industry. Given that applied papers in the CLSC context are rare, the current research is valuable as it uses actual data to examine the impact of compensation policies on stimulating circular economy activities in the semiconductor industry.

The optimal choice of channel distribution has been commonly studied in the literature, where most papers are theoretical in nature. However, the findings are divergent. For example, De Giovanni (2014) found that the best collection channel involved the manufacturer while Savaskan et al. (2004) observed that the channel distribution would be handled by the retailers but not the manufacturers. Note that these studies were theoretical and did not involve any specific industry analysis in contrast to ours. In the case of semiconductor industry, our paper asks first time who should collect the used semiconductors and shows that the collection should be handled by upstream sector.

In parallel with the recent studies, we consider the impact of government incentives on the semiconductor industry. In that regard, we examine the role of subsidy on silicon and chips production and recycling. In particular, we use actual industry and firm level data to quantify the effects of subsidy on profits, returns, and silicon and semiconductor prices. Different than other papers in the literature, such as Chen and Hu (2018), Chai et al. (2021), Nie et al. (2021), Dou and Choi (2021) and Yu et al. (2021), which examined the effects of subsidy on several issues such as environmental outcomes, remanufacturing, and logistics operations, we question whether subsidy offering is efficient or not (in the semiconductor supply chain), search for the upper bound of collection quantity, and investigate the best collection channel for the industry when end-users exhibit endogenous return behavior in the presence of subsidy. Behavioral considerations of end-users under subsidy regulation in circular economy models are uncommon in the literature. Most importantly, different than the above studies, we offer an efficient subsidy scheme which does not distort supply chain strategies. The same subsidy scheme can be implemented to other supply chains which exhibit similar structures as to the semiconductor industry.

3. Model: Production sectors and return behavior

There are lots of firms and research institutes which operate in the worldwide semiconductor supply chain.[10] The structure of the semiconductor industry has three main stages. The first involves inventions and innovations through research and development which is carried out by universities, firms, and governments. The well-known semiconductor companies such as Taiwan Semiconductor Manufacturing Company (TSMC), Intel, Nvidia, Texas Instruments (TI), and Samsung heavily engage in R&D. The second stage incorporates architectural (i.e., functional, logic, circuit, and physical) designs of semiconductors carried out by firms such as TSMC, Samsung, Intel, Advanced Semiconductor Materials Lithography (ASML), Qualcomm, Broadcom, Advanced Micro Devices (AMD), MediaTek, Nvidia, Micron, Apple. The third stage incorporates semiconductor fabrication performed by firms such as TSMC, Samsung, Intel, TI, and Sk Hynix. Among these firms, TSMC holds the largest market share of semiconductor manufacturing, followed by Samsung and Intel.[11] Once semiconductors are manufactured as intermediate products, they are utilized to make final products such as computers, cell phones, TVs, PV solar panels, refrigerators, furnaces, cars, trucks, missiles, rockets. On the other hand, many third-party firms or subsidiaries of well-known semiconductor firms (such as Nvidia and AMD) engage in reverse supply chain activities involving collection, reuse, and recycle processes of used final products incorporating semiconductors.

From silicon refining to a finished chip stage, there are over 1000 steps to follow and it can take up to four months from design to mass production phases. Nevertheless, the key steps are that silicon is turned into wafers using photographic sheets and chemicals, which are then converted into semiconductors using some metals.[12]

Semiconductors which are the building blocks of modern technology are broadly categorized into two segments: Integrated circuits (ICs such as CPU and GPU) and OSDs (Optoelectronics, Sensors, and Discrete semiconductors). Majority of semiconductors constitute integrated circuits which are also known as chips in short. For example, approximately 83% of all semiconductor sales in 2020 were chips.[13] Therefore, the terms chips and semiconductors are used interchangeably in the semiconductor industry. Chips can be classified into four groups which are logic circuits, memory circuits, micro circuits, and analog circuits. Logic circuits are electronic circuits which function as brains of computers and perform logical and binary operations. Memory circuits like USB flash drives, hard drives, and dynamic random access memories (DRAMs) store data. Micro circuits like central processing units (CPUs), graphic processing units (GPUs), and accelerated processing units (APUs) are microprocessors. Analog circuits like voice and video recordings convert data from analog to digital.

Assume that the semiconductor industry is organized as a CLSC involving upstream and downstream production sectors, and a recovery and recycling sector. Silicon is produced as an intermediate product by a manufacturer (M) (such as China Molybdenum or Zijin Mining Group Co., which are the largest silicon producers in the world) who combines virgin product (e.g., silica sand) with recycled materials (e.g., silicons in used electronic devices such as cell-phones, computers, and TVs) in upstream sector of the supply chain.[14] A semiconductor such as a computer chip or an infotainment system integrated circuit is produced and sold as a final product in downstream industry.

In downstream, there are competitive firms (denoted by R) such as TSMC, Samsung, Intel, Micron, AMD, TI, Nvidia, Qualcomm, SK Hynix, LG, Hitek, MediaTek, Microchip, STM, UMC, Broadcom, Applied Materials, Lam Research, NXP, Toshiba, Sony, Elpida, Nanya, and many others which buy silicon from upstream manufacturer M and combine it with labor (and many other elements and components) to produce and sell semiconductors.[15]

Semiconductor labor market is competitive such that workers are hired at a competitive wage. For the reverse logistics of returns, two collection channels are examined: either M's or R's subsidiaries handle the collection of used items encompassing significant amount of semiconductors. Alternatively, a third-party firm contracted by one of these firms collects the used items. When end-users return their old items they get paid a subsidy from a (local and/or federal) government (G) and receive a refund from the collector. The old items incorporating semiconductors are utilized as inputs by upstream manufacturer M to produce a new silicon.

Fig. 1 exposes the sequence of events in the semiconductor CLSC. A complete and perfect information structure is assumed in this strategic game. The upstream silicon producer decides its wholesale price k and silicon production quantity K. After observing the upstream decision, each downstream semiconductor firm chooses to produce q_i units of semiconductors, leading to total quantity $Q = \sum_i q_i$ which determines the market price $P[Q]$ for a particular chip. After consuming products incorporating semiconductors, the end users return them for a refund f and subsidy s. The used products are collected by collectors and then recycled in upstream.

Fig. 2 illustrates the supply chain structure under upstream (M) collection channel.[16]. For any collection channel, the unit cost of collection including shipping and handling is constant and is represented by $g > 0$.

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[10] https://www.statista.com/statistics/1287789/semiconductor-companies-by-stage/.

[11] Raboresearch at https://www.rabobank.com/.

[12] https://www.asml.com/en/technology/all-about-microchips/how-microchips-are-made.

[13] See Rabobank report at https://www.rabobank.com/knowledge/d011371771-mapping-global-supply-chains-the-case-of-semiconductors.

[14] Used electronic devices such as computers, smart phones, LED TVs are important source of silicon recycling.

[15] In 2021 there were over 465 firms which have been operating in the downstream semiconductor industry. Even in the fabrication stage, there are over 30 companies which intensely compete. See https://www.statista.com/statistics/1287789/semiconductor-companies-by-stage/ for details.

[16] The supply chain under downstream (R) collection channel is similar to the one in Fig. 2. The only difference is the upstream silicon producer makes a fixed payment per return to the downstream collectors.

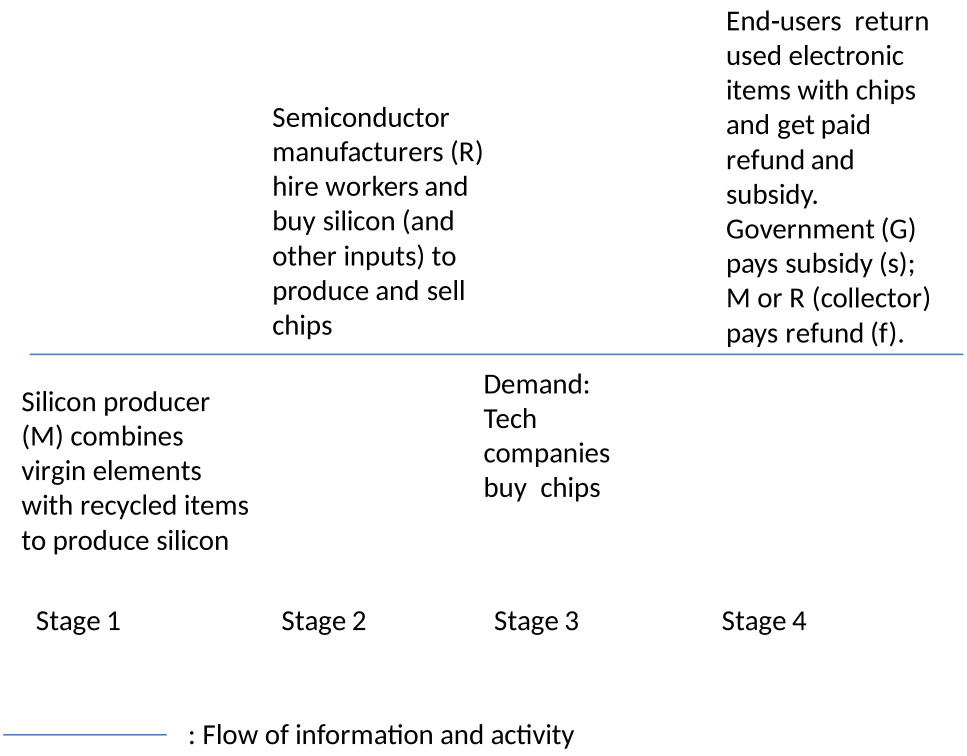

Fig. 1. The sequence of events in the semiconductor CLSC.

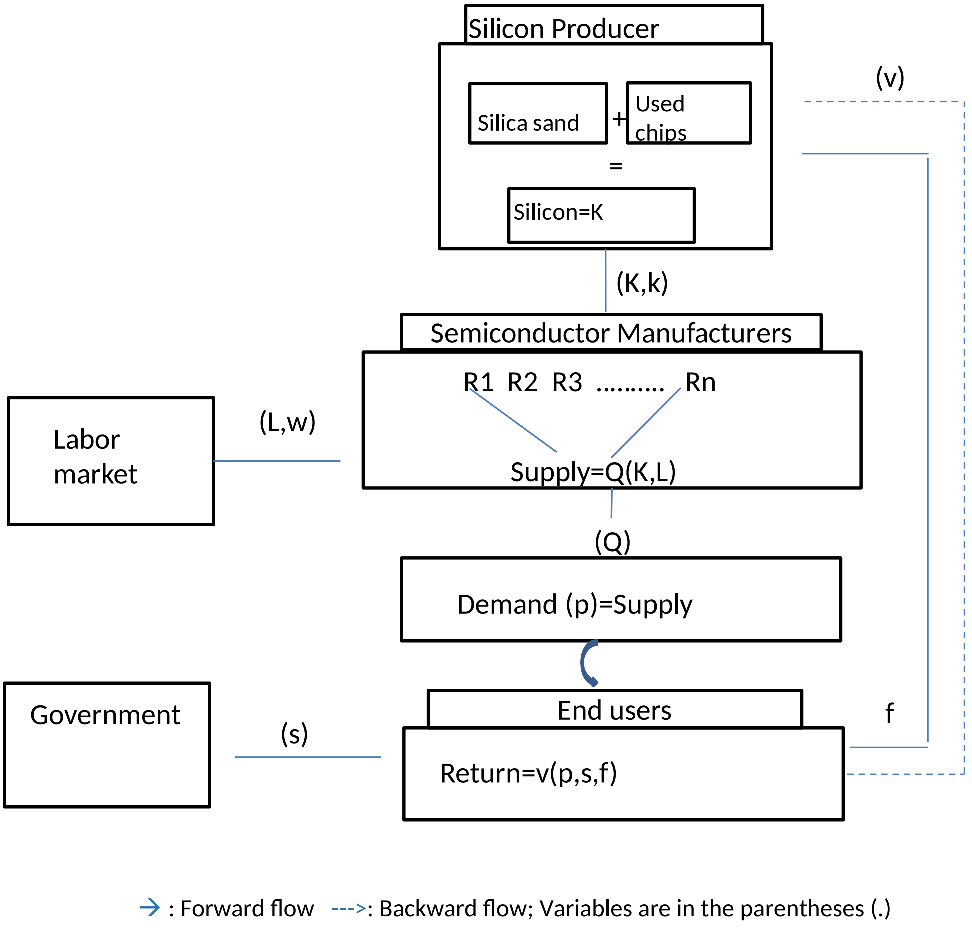

Fig. 2. The Semiconductor CLSC structure with endogenous return and the silicon producer (or its subsidiary) collects the used items.

Downstream semiconductor makers (such as TSMC, Samsung, Intel, and TI) optimally choose the number of workers or work hours required for production. Therefore, labor and wages will impact silicon and semiconductor prices and outputs.

The used items incorporating semiconductors are recycled linearly:

$$m[v] = \beta v, \tag{1}$$

where v represents the amount of used items and βv denotes the amount recovered in recycling process. For example, if v is the number of old cell-phones collected for recycling, then only βv units of silicon is recovered.

The recycling rates of semiconductors can vary from product to product. For example, photo-voltaic (PV) cycle's new process can bring recycling rates of silicon-based modules up to 95% (Lunardi et al., 2018). In this case, β equals 0.95 if the recycled product is a PV cell. By using multiple leaching reagents,insoluble silicon is separated from metals like silver and aluminum in the PV cells. Bogust and Smith (2020) showed that it is possible to have an 88% recovery rate of crystalline silicone particles in shredded solar panels using mechanical screening method. CPUs and GPUs in electronic items can be recycled for silicon using a similar process.

Electronics recycling is very common in the world. In fact, legislations such as the Waste Electrical and Electronic Equipment Directive of the European Union and the United States National Computer Recycling Act require sustainable disposal of items, and separation and reuse of raw materials in old or end-of-use products. For example, in the US in 2009, 38% of computers and 25% of total electronics waste were recycled. Many raw materials and precious metals such as silicon, tin, copper, iron, aluminum, silver, gold, and a variety of plastics in computers have been recycled to reduce the cost of making new ones.[17]

Silicon is amalgamated with some raw elements to improve the conductivity and obtain different grades of silicon. Note that most commonly used grades of silicon are 441, 553, 3303 and 2202, in addition to other lesser known grades. Silicon is utilized to make chips used in mobile phones, TVs, vehicles, rockets, PV-cells, bio-medical devices, and other electronics as final products.

Silicon as an intermediate product is produced as a mixture of recycled silicon and virgin silica sand. Let K be the amount of silicon. Assume that $1-\alpha$ portion comes from raw material (i.e., silica sand) and α portion comes from recycled semiconductors, where $\alpha \in (0, 1)$.

$$K = \alpha K + (1-\alpha)K. \tag{2}$$

This function indicates how virgin and recycled materials are processed together to produce silicon. The proportion α is fixed due to chemical and physical properties of silicon's grade. Only a fixed proportion of collection is useful to produce a given grade of silicon. Therefore, the rate α is fixed in production process.[18]

Let $c_1 > 0$ be a unit cost of silicon production when the recycled silicon is used to produce a new silicon for a microchip, and $c_2 > 0$ be a unit cost of production when the raw material, that is silica sand, is used in making silicon. Assume that $c_1 < c_2$ holds. This assumption is justifiable because manufacturing from used-product in general costs less than manufacturing from a virgin material. This assumption is based on the observations that on top of obvious savings from energy costs and virgin materials, silicon and microchip makers obtain carbon offset credits by recycling used products. These credits can be traded to generate cash and hence reduce production costs. Furthermore, in the semiconductor industry, recycling of semiconductor materials can raise brand values and improve social and environmental governance ratings of semiconductor companies like Samsung, Intel, AMD, TSMC. These factors help the companies negotiate better terms of trade with their clients, increase their share prices, and reduce their financial and economic costs.

Table 1
Silicon cost structure.

Inputs used to produce silicon	Costs
Silica	5%–7%
Petroleum coke	8%–10%
Charcoal	8%–10%
Graphite electrode	10%–12%
Electrical power	55%–60%
Others	10%–15%

On the other hand, for some cases the opposite could be true, so $c_1 > c_2$ may hold, say due to high recycling costs. However, the actual relationship between c_1 and c_2 is an empirical question and does not change our analyses or results. This is because both used and virgin materials are mixed together to produce a new silicon. Therefore, we obtain a weighted average cost of silicon denoted c, which is a linear combination of c_1 and c_2. All equilibrium outcomes in the propositions below will be a function of c irrespective of the relation between c_1 and c_2.

The cost of producing K units of silicon is

$$C[K] = c_1 \alpha K + c_2(1-\alpha)K. \tag{3}$$

The weighted average cost is denoted c and $c \equiv \alpha c_1 + (1-\alpha)c_2$. So, silicon production cost function boils down to $C[K] = cK$.

Table 1 presents unit production cost of silicon which is associated with unit costs of silica, petroleum coke, charcoal, graphite electrode, electrical power, and others such as phosphorus or boron elements.[19] This shows that the main input to produce silicon other than energy is silica, which we take into account in cost function (3).

There are a large number of competitive firms (R) in downstream sector which produce semiconductors such as microprocessors (CPUs), memory chips, graphical processing units (GPUs), and commodity integrated circuits (CICs). Downstream semiconductor producing firms (such as TSMC, Samsung, Intel, Micron, AMD, and TI) buy K units of silicon supplied by M (such as China Molybdenum) and hire L units of labor to produce a final product (e.g., a computer chip). Note that in the context of semiconductor, labor could also mean robot which may substitute actual human in microchip fabrication. Alternatively, both robots and humans could be used simultaneously and their costs can be taken into account separately.

Downstream firms (R) use a Leontief production function, which is suitable to represent production process in manufacturing sectors. In the extensions section, we will discuss implications of utilizing different production technologies. R firms use silicon as a critical capital input at the amount of K and employ labor at the amount of L with a fixed proportion to produce Q units of semiconductors in the following fashion:

$$Q[K, L] = min\{e_1 K, e_2 L\} \tag{4}$$

Without loss of generality, rescale the coefficients and rewrite Eq. (4) as $Q[K, L] = min\{K/e, L\}$, where $e = e_2/e_1 > 0$. This implies that $K = eQ$ units of silicon and $L = Q$ units of labor are combined to produce Q units of chips. Note that, in reality, inputs K and L could involve several capital inputs and labor wages. However, for the sake of tractability, we assume that each variable is with 1×1 dimension.

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[17] https://en.wikipedia.org/wiki/Electronic/waste/recycling.

[18] This assumption can also be justified in other sectors in which only a certain portion of recyclables is allowed to make a new product. For example, in packaging industry, a fixed portion of a new Tetra Pak carton juice container stems from a recycled carton. It is often written on a carton box: "This carton box is made with 20% recycled content", in which $\alpha = 0.2$ holds.

[19] Source: https://finance.yahoo.com/news/16-largest-silicon-producers-world-212541541.html.

Let the unit wholesale price of silicon be $k > 0$ and the unit price of labor be $w > 0$. If robots are used as labor, then w may represent rental cost, if actual humans are used then w may represent a wage paid to a worker in an assembly line (or an engineer who designs a chip). If robots and humans are used in chip making as laborer, then w could be an average of rental rate and wage costs.

In addition, price of silicon k should satisfy the following condition: $k > \alpha c_1 + (1-\alpha)c_2 = c$. That is, its price should be greater than its unit cost of production.

Downstream semiconductor manufacturers (R) face a linear demand curve for chips. The inverse demand function is

$$p[Q] = a - bQ. \tag{5}$$

The coefficients a and b are positive and represent the maximum price and price sensitivity to output, respectively. In addition, the relation $a > ke + w > 0$ should hold because the maximum price cannot be smaller than the marginal cost of a semiconductor. Linear demand function is commonly implemented and offers computational comfort with high estimation power in practice (Cohen et al., 2021).

By minimizing the total cost function subject to production function, equilibrium condition $p = ke + w$ is obtained. To see this, first note that the total cost function is equal to $kK + wL$. The objective is to minimize this cost function subject to production function, which is formulated as $min\ kK + wL$ subject to $Q(K, L) = min[K/e, L]$ to choose the optimal K and L. Then the solution of this problem is $K = Qe$ and $L = Q$ so that the minimized cost becomes $C(Q) = keQ + wQ$. This implies that the marginal cost of production, that is the first derivative of the total cost with respect to output, is $MC(Q) = ke + w$. Because downstream market is competitive price equals marginal cost holds, that is, the cost minimization in downstream industry leads to the equilibrium condition $p = ke + w$.[20] Each semiconductor maker produces q_i amount of chips where its marginal cost of production equals the competitive price, and $Q = \sum q_i$ holds.

A referee pointed out that the assumption of competitive downstream sector was a strong one. First, there are dominant players in the semiconductor industry depending on the type of chips that they produce. For example, Nvidia and AMD are dominant players in the GPU market, TI is the leading company in analog chips, and Samsung, SK Hynix and Micron dominate memory chip market. Even in the GPU market, Nvidia has a monopoly pricing power in a new flagship GPU called B200. However, in demand formulation in expression (5) we do not specify the type of semiconductor. Given that over 932 billion chips were sold in 2020 (see Footnote 33 for this estimate of ASML), our demand formulation for chips may refer to demand for logic and memory chips which comprise the majority of integrated circuits produced. If the objective of the paper would be modeling strategic interactions in the GPU market, we would consider a duopoly market with differentiated products. If the objective would be understanding about pricing in memory chips, we would consider a 3-player oligopoly model. However, the primary goal of this paper is not to perfectly model competition in a given layer of the industry, but it is about understanding the impact of compensation policies on stimulating circular economy activities within the semiconductor industry via a tractable model. Second, according to a report by Semiconductor Industry Association (2015), the U.S. semiconductor industry with the NAICS code 334413 is the second most competitive manufacturing industry out of 288 U.S. manufacturing industries. This result was obtained by using the United Nations' Competitive Industrial Performance (CIP) index.[21] Third, according to Statista report, there were about 470 semiconductor companies operated worldwide in 2021.[22] Consequently, given these reasons and for the sake of tractability of the forward and backward activities in the CLSC semiconductor industry, we assume perfect competition in downstream semiconductor industry.

We consider two types of return behavior for used products containing chips. The first one is a commonly assumed approach and is called passive return policy or waste stream return (e.g., Ferrer and Swaminathan, 2006), in which the return quantity is exogenous. The second return behavior takes into account of consumer response to incentives. It is endogenous and is called active return approach (Genc and De Giovanni, 2017, 2018). Namely,

$$v_1[p] = \sigma, \tag{6}$$

where the end-users voluntarily return $\sigma > 0$ amount of used products which contain semiconductors and are paid a rebate f per return. For example, σ may refer to the total number of chips in the end-of-life cellular phones or laptops which are collected and processed for recycle. Each and every of these products includes valuable parts and metals.

Next, we assume the following endogenous return function:

$$v_2[p] = \sigma - \delta(Ap - f - s), \tag{7}$$

where $A > 1$, and Ap may represent price of a finished product (such as a cell phone, a PC, or other electronic devices incorporating semiconductors) that consumers return to collectors who will recycle them for silicon. The coefficient A can change from product to product and p is the price of a specific semiconductor such as a CPU chip used in computers.[23]

The end-users evaluate the difference between the value of its product Ap, rebate f, and subsidy s before they decide whether to get rid of the used product or not.[24] The end-users in (7) are paid a fixed rebate by a collector and a subsidy by a government. Observe that the return decision intrinsically depends on the market price p of semiconductor. The more expensive the semiconductor is, the higher the price of consumer product (such as computer, smart phone or TV) is.

Observe that the function in (7) representing the consumers' return behavior should be independent of the marginal cost of silicon production c. That is, consumers of electronic items determine their return decisions based on the monetary incentives such as subsidy and refund that they are offered as well as the price of new items. Consequently, c does not affect v directly. However, because p is a function of c in equilibrium (and therefore c may influence v indirectly via p), as noticed by a referee, there could be a weak endogeneity issue, if one runs a regression using Eq. (7). However, this is an empirical question rather than a theoretical one. Furthermore, the end-users of electronics items will respond to price rather than their cost of production. This

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[20] Alternatively, as pointed out by an observant referee, when deriving Stackelberg equilibrium the game could be solved directly with n semiconductor manufacturers. That is, first plug in Q with summation of q_i in Eq. (9). Then the derived equilibrium would result in the price function

$$p = \frac{a + nke + nw}{1 + n}.$$

When n approaches infinity, the value of p converges to $ke + w$.

[21] https://www.semiconductors.org/wp-content/uploads/2018/06/U.S.-Semiconductor-Industry-Competitiveness-White-Paper-Final-for-posting-08042015.pdf.

[22] https://www.statista.com/statistics/1287789/semiconductor-companies-by-stage/.

[23] As pointed out by a referee the return functions in (6) and (7) can be combined and written in a compact manner as $v[p] = \sigma - \delta(Ap - f - s)$, where $\delta \geq 0$. If $\delta = 0$ then the return function is exogenous as in (6), otherwise it is endogenous as in (7). However, because we compare equilibrium outcomes over return behavior as analyzed in Propositions 1–6, we distinguish and write them separately and use subscript 1 to obtain v_1 as in (6) and use subscript 2 to obtain v_2 as in (7).

[24] The rebate f paid by a collector provides an additional incentive. The recycler or collector usually gets e-waste disposal subsidy from government and can share this subsidy with consumers. For example, the US and Chinese governments provide such subsidy to e-waste collectors.

is because price is observable to the consumers (and costs are mostly private information for the producers) and the consumers know that price is a function of market structure, competition framework, and many market variables, so it makes sense to respond to price rather than a change in cost of a particular element, part, or component.

On the other hand, it is possible that the amount of collection v may affect the marginal cost c. If this is the case, then cost function in (3) should be non-linear. That is, the marginal production cost of silicon should not be a constant, but a convex function. However, it is an empirical question whether the cost function is linear or non-linear. In addition, a surge in returned semiconductors does not affect their proportion α because α is fixed regardless of the amount of collection quantity v. That is, no matter how many used semiconductors are collected, the manufacturer cannot use all but only its α portion in making a new silicon. This could generally be due to regulations or chemical properties of silicon which allow amalgamation of metals at certain rates only.

Also, s cannot change c in the current setting of the model. This is because subsidy is paid to the end-users, but not to the manufacturers. In a different model where subsidy provided to the manufacturers, equilibrium outcomes might change if subsidy would change their production costs. However, in real-world applications, usually subsidy is provided to firms in order to be used for R& D activities or to reduce their fixed costs or investments costs such as costs associated with capacity expansions or building new fabs, as outlined in the CHIPS Act of the USA. For such kind of subsidies, our equilibrium outcomes would be intact.

Note that returns increase in subsidy in the endogenous return function. However, we analytically and numerically show in our analyses in the following sections that this kind of subsidy will not distort supply chain equilibrium strategies of silicon and semiconductor manufacturers and it will not cause any economic loss (i.e. dead-weight loss) in the semiconductor industry.

In the case of cell phone, for example, there are millions of hibernating and idle phones which are not being used anymore by the owners. This return function suggests that if governments provide subsidy to the consumers, they can return these idle products, and therefore contribute to circular economy and help spur economic activity. As is the case with this return function, the subsidy can be attached to purchasing a new product. So, consumers can recycle more and buy more. This kind of subsidy will enhance the reverse supply chain activities and entail more essential elements/metals to be recycled and used in making low-cost semiconductors.

In this endogenous return function, the end-users react to subsidy s such that a higher subsidy results in higher returns. That is, $dv_2/ds > 0$ holds. Providing subsidy offers lots of economic and environmental benefits. By stimulating recycling of used electronic devices, utility companies and silicon and semiconductor manufacturers can save energy, reduce costs, create jobs, and protect the environment.

The objective functions of M and R which are formulated next will vary depending on collection channels and return functions.

When return function is endogenous and the collection is carried out by silicon producer M or its subsidiary, its objective function is

$$\Pi^{s,M}_{M,2}[k] = (k - c)K[k] - (\sigma - \delta(Ap - f - s))(g + f), \tag{8}$$

where $c = \alpha c_1 + (1 - \alpha)c_2$, g represents the shipping and handling cost per return, subscript M refers to the manufacturer, subscript 2 refers to endogenous return, and superscript s denotes subsidy and superscript M denotes collection by the manufacturer or its subsidiary.

Each downstream semiconductor firm's profit is independent of subsidy,

$$\Pi^{s,M}_{R,2}[q] = (p - ke - w)q_i. \tag{9}$$

On the other hand, when downstream semiconductor firms or their subsidiaries make the collection or third party firms do it on their behalf, the silicon manufacturer's profit is

$$\Pi^{s,R}_{M,2}[.] = (k - c_1)\alpha K[k] + (k - c_2)(1 - \alpha)K[k] - (\sigma - \delta(Ap - f - s))F, \tag{10}$$

where the total collection cost per return is represented by F, which is the summation of what is paid to the end-user (f), and a shipping and handling cost (g), and a transfer fee from the manufacturer to the collector (l) so that $F = f + g + l$ holds. Under this collection channel, each downstream semiconductor firm's profit is

$$\Pi^{s,R}_{R,2}[.] = (p - ke - w)q_i + (\sigma - \delta(Ap - f - s))(F - f - g)/n. \tag{11}$$

Firms in the supply chain strive to maximize profit functions to obtain their optimal strategies. The solution paradigm employed in this paper is Stackelberg equilibrium because of the following reasons. Stackelberg equilibrium concept takes into account of sequential decision making process in the supply chain, compared to Nash equilibrium which describes the simultaneous decision making process between the firms. In the context of the semiconductor industry, a silicon supplier produces a grade of silicon in upstream and a semiconductor manufacturer produces a type of semiconductor in downstream using the silicon provided by the upstream supplier. Downstream semiconductor manufacturers observe price of silicon, buy silicon at an optimal quantity, hire works, and use other inputs, and then produce a semiconductor product and post their price. That is, there is a lag between the decisions of upstream and downstream firms. Consequently, the decision making process is sequential which warrants Stackelberg equilibrium approach appropriate in the semiconductor industry. Furthermore, Stackelberg solution yields more competitive outcomes than Nash equilibrium; lower prices and higher outputs are obtained under Stackelberg approach than under Nash solution. Because of these reasons most papers in the literature, including the current paper and the ones cited in the reference list, assume Stackelberg solution rather than Nash approach.

Also, note that the difference between profit expressions in (8) and (10) is not just the last term, representing the total cost of collection. It is not clear that upstream silicon producer will be better off by collecting the used semiconductors, even if the shipping and handling cost g is the same irrespective of the collection channel. In Stackelberg equilibrium, the quantity K (i.e., the amount of silicon production) and the prices k and p (i.e., silicon and semiconductor prices) will be different over collection channels when the return function is endogenous, as shown in Propositions 1 and 2.[25]

In the appendix, Table 7 presents the model notation.

4. Theoretical results

This section examines the role of subsidy on silicon and semiconductor prices and production strategies and determines the most profitable collection channel under different return behaviors in the semiconductor supply chain.

Because of economic and environmental reasons, governments support recycling programs and provide monetary incentives in the form of subsidies to businesses and consumers (e.g., the CHIPS Act of the US provided subsidies to Micron and Intel corporations). Asian, European, and North American countries and states have been subsidizing consumers of electronic items, electric cars, and appliances for a long time. This section will show that the subsidy mechanism applied to these products does not distort production and pricing strategies. However,

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[25] In the current setting of the model, the shipping and handling cost represented by g could easily be changed depending on who the collector is. The reason is it linearly enters into the total collection cost F per return, which is the summation of what is paid to the end user (f), and the shipping and handling cost (g), and a transfer fee from the manufacturer to the collector (l) so that $F = f+g+l$ holds. For example, one may let shipping and handling cost be g_1 if upstream producer or its subsidiary collects, and it be g_2 if downstream manufacturers or their subsidiaries collect. However, in this case one needs to define the relation between g_1 and g_2. Because this relation is an empirical question, we simply assume that $g_1 = g_2 = g$. In any case, it is a linear function of F that renders the model solution tractable.

we will show that it will impact the optimal collection channel choice and hence profitability in the semiconductor closed-loop supply chain.

When a government (G) issues a cheque valued s euros or dollars per used item it will spend in total

$$\Pi^s_G[.] = sv[.]. \tag{12}$$

This expenditure function can be exogenous or endogenous depending on the total number of returns in (6)–(7).

When a silicon manufacturer or its subsidiary collects the used products, Stackelberg equilibrium solution under exogenous returns in (6) is independent of subsidy because the objective functions of M and R do not include subsidy.

On the other hand, when the return function is endogenous and sensitive to subsidy as in (7) the silicon manufacturer's objective function depends on subsidy and is formulated as in (8) and (10).[26] The semiconductor manufacturers' (R) objective functions under two collection channels are provided in expressions (9) and (11).

We obtain the following result in the semiconductor supply chain with subsidy.

Proposition 1. *When the silicon manufacturer or its subsidiary collects the used items incorporating semiconductors, Stackelberg equilibrium outputs and prices under the subsidy are characterized as follows.*

(i) *If the return function is exogenous, equilibrium outcomes are*

$$k_1^{s,M} = \frac{(a+ec-w)}{2e},\ p_1^{s,M} = \frac{(a+ec+w)}{2},\ Q_1^{s,M} = \frac{(a-ec-w)}{2b},$$
$$K_1^{s,M} = \frac{e(a-ec-w)}{2b},\ L_1^{s,M} = \frac{(a-ec-w)}{2b}.$$

(ii) *If the return function is endogenous, equilibrium outcomes are*

$$k_2^{s,M} = \frac{(a+ec-w+\delta Ab(f+g))}{2e},\ p_2^{s,M} = \frac{(a+ec+w+\delta Ab(f+g))}{2},$$
$$Q_2^{s,M} = \frac{(a-ec-w-\delta Ab(f+g))}{2b},\ K_2^{s,M} = \frac{e(a-ec-w-\delta Ab(f+g))}{2b},$$
$$L_2^{s,M} = \frac{(a-ec-w-\delta Ab(f+g))}{2b}.$$

The proofs are presented in the Appendix.

This proposition shows that subsidy does not distort equilibrium strategies in the semiconductor industry whether consumer return behavior is exogenous or endogenous. However, the silicon manufacturer's profit decreases in subsidy because the number of returns increases in subsidy.

We obtain the following equilibrium outcomes when collection is carried out in downstream industry.

Proposition 2. *When downstream semiconductor firms or their subsidiaries collect the used semiconductor products, Stackelberg equilibrium prices and outputs under subsidy are as follows.*

(i) *If the return function is exogenous, equilibrium outcomes are*

$$k_1^{s,R} = \frac{(a+ec-w)}{2e},\ p_1^{s,R} = \frac{(a+ec+w)}{2},\ Q_1^{s,R} = \frac{(a-ec-w)}{2b},$$
$$K_1^{s,R} = \frac{e(a-ec-w)}{2b},\ L_1^{s,R} = \frac{(a-ec-w)}{2b}.$$

(ii) *If the return function is endogenous, equilibrium outcomes are*

$$k_2^{s,R} = \frac{(a+ec-w+\delta AbF)}{2e},\ p_2^{s,R} = \frac{(a+ec+w+\delta AbF)}{2},$$
$$Q_2^{s,R} = \frac{(a-ec-w-\delta AbF)}{2b},\ K_2^{s,R} = \frac{e(a-ec-w-\delta AbF)}{2b},$$
$$L_2^{s,R} = \frac{(a-ec-w-\delta AbF)}{2b}.$$

The impact of subsidy on collection channels and equilibrium strategies is stated as follows.

Proposition 3. *Given the subsidy program in the semiconductor industry, the following holds.*

(i) *The amount of subsidy does not distort equilibrium strategies in the supply chain. Whether collection is carried out by upstream or downstream firms, equilibrium pricing and output decisions with subsidy will be identical to the ones without subsidy.*

(ii) *Regardless of who handles the collection channel, prices (outputs) are higher (lower) under endogenous returns than under exogenous returns.*

(iii) *Under downstream collection channel, while the silicon manufacturer's profit decreases in subsidy, each semiconductor firm's profit increases in subsidy.*

(iv) *When collection is handled by the silicon producer or its subsidiary, its profit decreases in subsidy, but each semiconductor firm's profit is independent of subsidy.*

These results are obtained when findings in Propositions 1 and 2 are directly compared. From (i) we learn that CLSC strategies are not distorted by the subsidy. This is good news for the entire the semiconductor industry stakeholders, including firms and governments. Most importantly, this result is robust to collection channels and return behaviors. From (ii) we understand that consumers will be paying higher prices for the new products under endogenous return behavior irrespective of the collection channel. The findings in (iii) and (iv) suggest that the subsidy program diminishes profitability in silicon industry for any collection channel.

Note that although the subsidy provided to consumers diminishes the CLSC profitability, firms in the semiconductor industry have incentives and profit motives to participate into the CLSC and recycle chips. To see this, we carry out additional analysis in Section 7.4, titled "What if there were no backward activities?", where we characterize equilibrium outcomes when there were no backward activities, that was the case in the absence of collection, recycling, and subsidy. We show in Proposition 6 that under a mild condition on the upper bound of the returns (that is, when the number of return is not "too high", the silicon producer's profit (and hence the total CLSC profit) is higher in the CLSC than its profit without backward activities. In addition, in real life, firms are offered side payments and/or tax breaks by governments to expand their operations and take part in backward activities. For example, chip manufacturing firms such as Micron, Intel and TSMC have obtained grants, subsidies, and tax breaks through the CHIPS Act of the USA. Consequently, the semiconductor firms can increase their profitability by participating into the CLSC activities and getting paid through financial incentives offered by governments.[27]

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[26] If the objective is to determine the socially optimal subsidy one should maximize a comprehensive social welfare function involving enterprise profit, consumer surplus, environmental cost, and government expenditure. This could be a useful benchmark to characterize the most efficient outcomes. By calculating the first-best as the benchmark, one could compare it with the results under the current setting and measure the total dead-weight loss in the industry. This could be an interesting theoretical and applied exercise. In fact, by assuming competitive downstream industry we have already obtained results closer to the first-best. However, the socially optimal subsidy would not be a very realistic implementation because governments usually choose subsidies exogenously, based on their budgets in a fiscal year.

[27] The subsidy provided to the consumers satisfies government's objectives in order to stimulate recycling activities, conserve energy and raw materials, and reduce landfills. The semiconductor firms are already part of supply chain with or without such subsidy. However, when a government incentive in the form of subsidy is provided to consumers, as is the case in this model, firms may ask for favorable legislation from the government in order to participate the CLSC given that they are job creators and provide tax revenues to the government. When they receive financial aid through, for example, the CHIPS Act of the US government, their profit function shifts up. Although these financial aspects do not show up in the model, such lump-sum payments or tax breaks will not affect equilibrium outcomes (outputs, prices, and returns) but will increase the firms' profits as they enter into their profit functions as constants.

The findings in this proposition also open up the following question: what is the best collection channel when subsidy is implemented?

While the previous studies investigated optimal collection choice for different sectors under various settings, excluding the semiconductor industry, they omitted the role of price regulations and endogenous return behavior on the channel choice. The literature does not offer unanimous answer for the optimal collection channel as explained in the literature review section.

As a measure of performance, we compare the total CLSC profits under upstream collection to the profits under downstream collection. There are several cases to examine depending on return behavior.

Case A: Subsidy provided to the end-users is positive and their return behavior is exogenous.

In this case, the total supply chain profit is $\Pi^{s,M}_{M,1} + \Pi^{s,M}_{R,1} \equiv \Pi^{s,M}_{1}$ under M's collection channel. When R firms collect the total supply chain profit is $\Pi^{s,R}_{M,1} + \Pi^{s,R}_{R,1} \equiv \Pi^{s,R}_{1}$. Because downstream firms are competitive, it is sufficient to compare the silicon manufacturer's profits over collection channels. We know that $\Pi^{s,M}_{M,1} = K^{s,M}_{1}(k^{s,M}_{1} - c) - \sigma(g+f)$ and $\Pi^{s,R}_{M,1} = K^{s,R}_{1}(k^{s,R}_{1} - c) - \sigma(g+f+l)$. From Propositions 1 and 2 we have $K^{s,R}_{1} = K^{s,M}_{1}$ and $k^{s,R}_{1} = k^{s,M}_{1}$. Therefore, $\Pi^{s,M}_{M,1} > \Pi^{s,R}_{M,1}$ holds. This means that M should be the collector when subsidy is offered and the return behavior is exogenous.

Case B: Subsidy is nil in the semiconductor CLSC and the return behavior is exogenous.

This is similar to Case A where subsidy is applied because Proposition 3 proves that the subsidy does not distort optimal strategies in the supply chain. Because $\Pi^{s,M}_{M,1} > \Pi^{s,R}_{M,1}$ holds, the total CLSC total profits are higher under M's collection when subsidy is zero and consumers are passive in their return behavior.

Case C: Subsidy is nil in the semiconductor CLSC and the return behavior is endogenous.

This is a benchmark case to show the impact of endogenous return behavior. In this case, $\Pi^{M}_{M,2} = K^{M}_{2}(k^{M}_{2} - c) - (\sigma - \delta(Ap^{M}_{2} - f))(g+f)$ and $\Pi^{R}_{M,2} = K^{R}_{2}(k^{R}_{2} - c) - (\sigma - \delta(Ap^{R}_{2} - f))(g+f+l)$ hold. From Propositions 1–2 we know that $K^{R}_{2} < K^{M}_{2}$ and $k^{R}_{2} > k^{M}_{2}$ and $p^{R}_{2} > p^{M}_{2}$ satisfy. Because of the price effect, $\Pi^{M}_{M,2} > \Pi^{R}_{M,2}$ holds. However, this profit differential diminishes as the number of returns goes down. As a result, the silicon manufacturer or its subsidiary should collect the used product.

Case D: Subsidy is positive and the return behavior is endogenous.

The profits are $\Pi^{s,M}_{M,2} = K^{s,M}_{2}(k^{s,M}_{2} - c) - (\sigma - \delta(Ap^{s,M}_{2} - f - s))(g+f)$ and $\Pi^{s,R}_{M,2} = K^{s,R}_{2}(k^{s,R}_{2} - c) - (\sigma - \delta(Ap^{s,R}_{2} - f - s))(g+f+l)$. From Propositions 1 and 2 we obtain $K^{s,R}_{2} < K^{s,M}_{2}$ and $k^{s,R}_{2} > k^{s,M}_{2}$ and $p^{s,R}_{2} > p^{s,M}_{2}$. These imply that $\Pi^{s,M}_{M,2} > \Pi^{s,R}_{M,2}$ holds.

These analyses lead us to the following results.

Proposition 4. *The characterization of optimal collection channel facilitating the highest total profits in the semiconductor CLSC is the following.*

i) *When subsidy is implemented, if the return behavior is exogenous, then the silicon producer or its subsidiary should collect the used products. This result also holds true when subsidy is nil.*

(ii) *When subsidy is implemented, if the return behavior is endogenous, then the most profitable collection channel involves upstream firm's collection. This result also holds true when subsidy is reduced to zero. Moreover, equilibrium chain profitability in the industry decreases in the number of returns.*

Note that, as pointed out by a referee, in an alternative model where one would consider a setting such that market demand would be a function of subsidy and semiconductor manufacturers would be offered subsidies to invest in new technologies and expand production capacities. In fact, the CHIPS Act of the US signed in 2022 aimed those objectives and provided subsidies and tax incentives to semiconductor companies operated in the US. Intel, TSMC, and Micron have already benefited from this law and received sizeable subsidies. Note that under such a model, where demand was affected by the subsidy our results would change. In particular, equilibrium strategies would be affected by the amount of subsidy. On the other hand, if the subsidy would be a lump-sum payment to the semiconductor companies without affecting demand for chips or end-products, as is the case with the Act, our results would still remain intact.

However, in the current setting of the model, subsidy must be independent of market demand formulated in expression (5). The reason for that is demand expression in (5) indicates demand for semiconductors by electronics producers who manufacture products such as smartphones, PCs, vehicles, and bio-medical devices. Furthermore, in our model subsidy is provided to consumers of those electronic devices. The current setting of this paper is realistic and is parallel to "Scrappage Incentive Programs" and "Automotive Stimulus Package" applied all over the world, and in particular congruent with "the Waste Electrical and Electronic Equipment Directive of the European Union" and "the United States National Computer Recycling Act".

5. Data and model calibration

This section provides data used for calibrating the model parameters for semiconductor recovery, silicon price and production, and semiconductor fabrication and sale.

Silicon prices: Silicon is a sophisticated metalloid with excellent chemical and mechanical properties. It is extracted from sand which is abundantly available on the surface of earth and in the sea. It is a very versatile rubbery product. Although silicon is the main element to manufacture semiconductors used for making electronic items, it has also been used in making explosives, ceramics, tiles, cement, and alloys like aluminum-silicon and ferro-silicon. To give a glimpse of silicon grades and its locational prices, Table 2 presents the Shanghai Metals Market (SMM) silicon prices at the top three (out of ten) ports in China.[28] The SMM is the largest silicon market in the world. On the supply side, China is the world's largest silicon manufacturer. Its production in 2022 was 6 million metric tons (mmt). Russia, the second largest producer, produced 640,000 metric tons in the same year. On the demand side, the USA is the largest importer of silicon, followed by India.[29]

Table 3 presents the commonly produced silicon grades with its metalloid composition.

The weight of a silicon chip depends on a number of factors including size and chemical composition. As can be seen from the SSM wholesale silicon price list, its price greatly varies with its chemical composition which determines purity of silicon. It also depends on size as well as where it is sold, and whether it is for export or domestic markets.

Silicon cost: The cost of silicon production also changes due to its location, chemical composition, and carbon intensity. However, some estimates are available. For example, it is estimated that the marginal cost of silicon carbide (SiC) which is used in high-end electronic devices operating at high temperatures and/or voltages is in the interval of \$1500/ton with 5 tons/ton CO2 intensity and \$30M/ton with 200 tons/ton CO2 intensity. The most expensive ones are utilized to make SiC wafers which are used in expensive electronic devices (such as chips used in space shuttles, rockets, high-end vehicles, and bullet proof vests).[30] Fabrication of SiC wafers also requires large scale plants with large furnaces whose operational and maintenance costs also add up to the cost of production. Note that SiC is one of the hardest metals with melting point of 2700 Celsius. SiC is obtained by heating high-grade

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[28] See https://news.metal.com/newscontent/102515293/SMM-industrial-silicon-metal-price-list-.

[29] See www.statista.com statistics for silicon.

[30] https://thundersaidenergy.com/downloads/silicon-carbide-production-costs/.

Table 2
SMM industrial silicon metal price list on Dec 7, 2023.
Source: https://news.metal.com.

Transaction place	Specification	Price	Average price	Previous week price
East China (yuan/mt)	Standard 553#	14 200–14 400	14 300	14 220
	Above standard 553#	14 600–14 800	14 700	14 660
	521#	15 000–15 100	15 050	15 050
	441#	15 000–15 200	15 100	15 070
	421#	15 500–15 600	15 550	15 550
	3303#	15 600–15 800	15 700	15 700
	2201#	20 000–21 000	20 500	20 500
Huangpugang port (yuan/mt)	Standard 553#	14 100–14 300	14 200	14 120
	Above standard 553#	14 700–14 800	14 750	14 730
	441#	15 000–15 200	15 100	15 070
	421#	15 500–15 800	15 650	15 650
	411#	15 700–16 000	15 850	15 850
	3303#	15 500–15 700	15 600	15 700
	2202#	20 000–21 000	20 500	20 500
	Standard 553#	14 100–14 300	14 200	14 120
Export (FOB $/mt)	Above standard 553#	1990–2020	2005	1993
	441#	2110–2150	2130	2130
	421#	2200–2260	2230	2230
	3303#	2200–2240	2220	2220
	2202#	2830–2880	2855	2855

Table 3
Silicon Grades.
Source: RomgSheng Refactory (www.rsef.com).

Brand	Chemical composition %			
	Si ≥	Impurity ≤		
		Fe	Al	Ca
Si-2202	99.5	0.2	0.2	0.02
Si-3303	99.3	0.3	0.3	0.03
Si-411	99.3	0.4	0.1	0.1
Si-421	99.2	0.4	0.2	0.1
Si-441	99.0	0.4	0.4	0.1
Si-553	98.5	0.5	0.5	0.3

silica (Si02) with coke using electric furnaces for days. This process requires a lot of energy and results in high carbon emissions.[31]

Given these cost figures, the marginal cost of silicon production is assumed to be $1500/ton in model simulations, which is a lower bound of the reported cost estimates. Given that a silicon used in a chip approximately weighs 0.23 grams, it holds that $c = \$0.000345$ per silicon in the expression (3). Alternatively, given that a typical chip weighs around 2 grams, $0.00345 becomes the approximate unit cost of silicon used in making a typical chip.

Demand for semiconductors: Demand for semiconductors is unprecedented and has been growing over years. The Dutch semiconductor designer ASML estimated that 932 billion chips in 2020 and 1.15 trillion chips in 2021 produced and sold globally. Over 80% of semiconductors are manufactured in Asia and TSMC is the largest producer in the world with 54% market share. Also, TSMC and its subsidiaries manufacture over 90% of the world's most advanced semiconductors.[32] In terms of revenue, the Fortune magazine reports that the market size for semiconductors was $527.88 billion in 2021 and $573.44 billion in 2022, and it will increase to $1.4 trillion in 2029.[33] The recent statistics show that 2023 prices were higher than 2022 prices. For example, according to the World Semiconductor Trade Statistics (WSTS) the average selling price was $0.568 per unit in the third quarter of 2023, compared to the price of $0.509 in 2022. In addition, the total revenue in the third quarter of 2023 (in short, 3Q23) increased by 6.3% from the second quarter of 2023 but declined by 4.5% from 3Q22 to $134.7 billion. Meanwhile 237.1 billion units were sold during 3Q23, up 2.6% quarter on quarter but down 14.4% year-on-year.[34]

To be able to formulate demand equation for semiconductors, we first explain what is meant by semiconductors in the industry. Often times, semiconductors and chips are interchangeably used in the news and the literature. However, the Organization for Economic Cooperation and Development (OECD) categorizes semiconductors into two groups. Group 1 includes integrated circuits (ICs) which are simply known as chips. They are formed by logic circuits (e.g., encoders and decoders), memory chips (such as DRAM and NAND), microchips (such as GPUs, CPUs, and APUs), and analog circuits (e.g., video and voice recorders). Group 2 covers optoelectronics, sensors, and discrete semiconductors (OSDs). Among those, logic and memory chips form the largest share of semiconductors. For instance, chips comprised of 83% of semiconductor sales in 2020.[35]

Given that semiconductors span a variety of products with subcategories and classifications, it becomes a daunting task to define demand for semiconductors. However, we will define it as general as possible and keep in mind that chips form the majority of semiconductor sales and there is available data for chips sales and prices.

Demand for semiconductors is estimated using price elasticity, production, and price figures. Given that inverse demand in Eq. (5) is $p = a - bQ$, demand becomes $Q = a/b - p/b$. The goal is to estimate the coefficients a and b. The elasticity information will be used to predict these coefficients. By definition, the price elasticity of demand equals $\varepsilon = -\frac{1}{b}\frac{p}{Q}$.

As can be seen from the Federal Reserve Economic Data (FRED) in Fig. 3, semiconductor prices have trended downwards over the years due to technological advancements. We will use a recent average selling price of $0.568 per unit and the ASML's estimate of 932 billion chips production and sale worldwide in 2020 to estimate demand coefficients.[36] Flamm (2017) provides the price elasticity estimate of

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[31] Another cost estimate is provided by the RadioChemistry report, which indicates that silicon with 99.9% purity costs about $50/lb; hyperpure silicon may cost as much as $100/oz. This report is available at https://www.radiochemistry.org/periodictable/elements/14.html.

[32] https://www.power-and-beyond.com/10-facts-about-the-semiconductor-industry-a-c0e3bb177357fbf8e30b284877f88364/.

[33] https://www.fortunebusinessinsights.com/semiconductor-market-102365.

[34] https://evertiq.com/news/54733.

[35] See Rabobank report at https://www.rabobank.com/knowledge/d011371771-mapping-global-supply-chains-the-case-of-semiconductors.

[36] See https://evertiq.com/news/54733 and https://www.power-and-beyond.com/10-facts-about-the-semiconductor-industry-a-c0e3bb177357fbf8e30b284877f88364/.

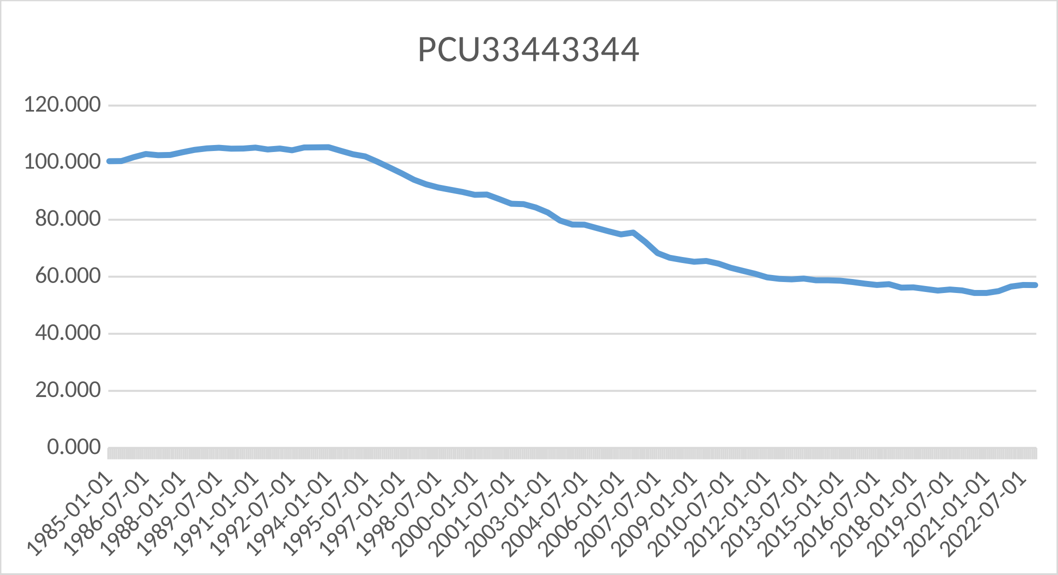

Fig. 3. Producer Price Index Semiconductor Manufacturing, Index Dec 1984 = 100, Semiannual, Not Seasonally Adjusted, provided by Federal Reserve Economic Data. The industrial code for semiconductors is PCU33443344.

-0.77 for chips using linear and logarithmic demand functions. So, we assume $\varepsilon = -0.77$.

Using these elasticity figure and price-output data points it is obtained that $b = 0.00079148$ holds. Next, using demand formula and the same price and output pair, it is obtained that $a = 1.3057$ holds. Therefore, the worldwide inverse demand for semiconductors (mainly logic and memory circuits) is estimated as

$$p[q] = 1.3057 - 0.00079148q, \tag{13}$$

where q is in billions ($\times 10^9$).

While Samsung and Intel design and manufacture semiconductors and are among the top manufacturers of chips, TSMC is the world's largest foundry which makes chips under contract for Samsung, Intel, AMD, Nvidia, Qualcomm, and many others. TSMC has factories in Taiwan, China, Singapore, and the US.[37] In addition, TSMC manufactures about 90 percent of the world's advanced chips used in smart phones, artificial intelligence, electric vehicles, space shuttles, air planes, medical devices, etc.[38] TSMC's top-ten customers include Apple, Qualcomm, AMD, Broadcom, Nvidia, MediaTek, Intel, Marvell, NXP and Unisoc, which accounted for 80 percent of TSMC's revenue in 2022.[39] Therefore, in demand function q incorporates quantity demanded by these top customers as well.

Wages in the semiconductor industry: According to ZipRecruiter intelligence report which is based on employer job postings and third party data sources, as of November 2023 the average hourly pay in semiconductor manufacturing in the US is $24.95. Most of the workers' hourly wages are in between $34.62 and $13.94, depending on skill, location, and experience.[40]

Also, based on this report, the average annual pay for a Samsung Semiconductor worker in the US is $66,185 a year, as of November 2023. This translates into approximately $31.82 per hour which is equivalent to $1272 per week or $5515 per month. Also, the maximum and the minimum salaries at Samsung are $153,500 and $21,500, respectively. Similarly, the average hourly pay for a TSMC worker in the US is approximately $23.25. Most wages at TSMC are in between $31.73 and $17.07 per hour.

Table 4
TSMC highly qualified personal earnings in Nov 2023.
Source: ZipRecruiter.

Job title	Annual salary	Monthly pay	Hourly wage
Semiconductor product engineer	$144,072	$12,006	$69.27
Director semiconductor	$136,380	$11,365	$65.57
Engineer semiconductor	$115,864	$9655	$55.70
Semiconductor contract	$101,781	$8481	$48.93
Semiconductor equipment engineer	$100,599	$8383	$48.36

Because TSMC is the market leader in semiconductor fabrication, we assume that the average wage paid at TSMC represents the wage in the model. So, $w = \$23.25$/hour holds in profit equations (9) and (11). Essentially, it takes more than 1000 steps-including deposition (of a silicon wafer), resist (i.e., coating), lithography (i.e., mapping of transistors), etch (i.e., baking and developing), ionization (i.e., tuning electrical conductivity), packaging (i.e., slicing, dicing, foiling, covering)-and requires more than 3 months from designing to fabrication stages to finally obtaining a semiconductor in working condition.[41] Assume that a worker can help fabricate 100 semiconductors per hour in mass production stage. Given the labor wage per hour is $23.25, $w = \$0.2325$ represents labor cost per semiconductor.

Table 4 shows wages and salaries paid at TSMC design and production facilities in 2023 in the US.

Semiconductor recycling and Silicon Recovery: There are hundreds of semiconductors in vehicles that serve many critical purposes. They are used for enhancing performance and safety, and provide a number of conveniences such as infotainment functionality, adjusting air conditioning, monitoring tire pressure, triggering airbags in case of accident, and automatically adjusting seats. In terms of performance and efficiency of a vehicle, semiconductors manage fuel injection and control ignition timing. They facilitate optimal stopping in breaking

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[37] https://en.wikipedia.org/wiki/Semiconductor-device-fabrication.

[38] https://www.washingtonpost.com/world/2023/10/09/taiwan-tsmc-chip-manufacturer-fab/.

[39] https://exploresemis.substack.com/p/tsmcs-top-10203040-customers-who.

[40] https://www.ziprecruiter.com/Salaries/Semiconductor-Manufacturing-Salary.

[41] https://www.asml.com/en/news/stories/2021/semiconductor-manufacturing-process-steps.

system via distributing breaking force between the wheels. In addition, semiconductor chips are helpful in turning the steering wheel by controlling the flow of hydraulic fluid. In terms of safety functionality, semiconductors are used in advanced driver assistance systems (ADAS) such as adaptive cruise control and lane departure warning. Moreover, microchips used in the infotainment systems process and store data, and provide wireless connections and entertainment through audio, video, and other multimedia features.[42]

In terms of semiconductor recovery, we use data with regard to a motor vehicle scrappage program called "Vehicle Stimulus Package" which was enacted by the US government through which used-car owners were paid subsidy. Used vehicles were recycled for parts, precious metals, and elements through this subsidy program. Silicon extracted from the semiconductors was utilized by upstream silicon manufacturer in order to produce new silicon with various grades.

There are two reasons why this used vehicle program with subsidy is chosen in connection to semiconductor recovery. First, motor vehicles contain a lot of semiconductors. According to DRex, a global electronic components distributor, an average modern vehicle contains about 1400 to 1500 semiconductor chips, and luxury and sports vehicles have upto 3000 chips.[43] On the other hand, typical old internal-combustion-engine (ICE) cars contain about 500–600 chips. Second, chips in cars are more durable than chips in other electronics items as regulations require those chips to be resistant to severe temperatures and be conformable with reliability and security requirements. So, silicon recovered from chips in vehicles can be reused to make new silicon more effectively. For example, chips in automobiles can function in temperatures between −40 Celsius and 155 Celsius and are resistant to outside factors such as vibration, dust, and electromagnetic interference. In addition, they are made to last about 15 years or up to 200,000 km due to safety, reliability, and security standards (such as TS 16949, ISO 26262).[44]

When a used-car owner returned his/her car to a dealer, he/she was paid $f = \$100$ for a scrap value of the car. The dealer sold the old car for \$150, gave \$100 to the owner, and retained the difference. At Gary Rome Hyundai Inc. in Holyoke, each new vehicle buyer was offered \$50 credit towards the purchase of a new car. Cliff Dexheimer, the general sales manager of Gary Rome Hyundai, said that "It cost more than \$50 per car to transport clunkers and kill them, but we still gave every customer the scrap value".[45] Given this information, the model parameters g and f become \$50 and \$100, respectively. Also, $l = \$50$ holds because the dealer received \$50 per car from a recycling company on top of its cost of shipping and handling. Note that parameter values for (f, g, l) do not change our results qualitatively and their values may vary from dealer to dealer. In addition, based on the "Car Allowance Rebate System" legislation, old vehicle owners received a fixed subsidy of \$4500 per return from the federal government.

Through the used vehicle return program of the "Car Allowance Rebate System", 690,000 vehicles were collected (see https://en.wikipedia.org). Because an average used ICE car contains about 500–600 chips, multiplying the number of returned vehicles with the average number of chips (i.e., 550) leads to $v = 379,500,000$ in Eq. (1), representing the number of semiconductors collected for recycling.

Given that recycling rate of microchips is high and is above 90%, a lower bound of it is assumed. So $\beta = 0.9$ is used in simulations, which is a conservative recovery rate for semiconductors. Therefore, the number of recovered semiconductors is $\beta v = 341,550,000$.[46] This implies that upstream silicon manufacturer will process $341,550,000$ chips and extract a certain amount of recycled silicons to make new ones.

Given the recycled semiconductors, the following question arises. How much silicon can be recovered from old chips for the purpose of making new silicons? Based on studies by Bogust and Smith (2020) and Rahman et al. (2021), the recovery of crystalline silicon particles from shredded solar panels is at the rate of 88%. While Bogust and Smith suggested using a physical recycling method comprised of nitrogen dilution combined with pyrolysis and mechanical screening methods, Rahman et al. applied environmentally friendly chemical method to obtain a similar recovery rate.[47] Therefore, using these findings it is assumed that $\alpha = 0.88$ holds in Eq. (2).

Because silicon is an intermediate product to be turned into a semiconductor, it is safe to assume that $e_1 = 1$ and $e_2 = 1$ hold in production function (4). In fact, this assumption is not critical because equilibrium strategies will exhibit similar characteristics with other combinations of labor and capital in Leontief technology.

New car buyers are sensitive to a subsidy (s) they receive from the government, to a refund (f) they receive per clunker, and to a price of new car before they decide whether to get rid of their old vehicles. Assume, without loss of generality, that the sensitivity rate is low and $\delta = 0.1$ holds.[48]

In addition, assume that the average selling price of a new car is \$20,000. Given that the parameter A which is equal to the price of car divided by the average price of a semiconductor (which equals \$0.568), we calculate $A = 35,211.27$. Essentially, A represents a conversion rate between car price and semiconductor price in Eq. (7).

Subsidy: Subsidy programs for used cars have been commonly applied by governments in many countries. Table 5 displays car scrappage programs implemented in selected countries.[49] These programs are still popular as part of the "Green Economy" initiatives. For example, "Scrappage Incentive Program" of Canada in 2020 offered \$1000 for an old car and additional \$1000 towards purchase of an electric vehicle (https://electricautonomy.ca/2020/01/23/). In Italy, the scrappage program has aimed to reduce air emissions, and cars running on electricity, hydrogen or LPG are offered better incentives. In the US, the car scrappage program commonly referred as "Cash for Clunkers" was devised as part of the automotive stimulus package. It intended to stimulate car industry and the maximum voucher at \$4500 was handed over to consumers who bought better fuel efficient cars than their old ones.[50]

The subsidy monies reported in Table 5 are exogenously determined by the governments. This is similar to the quantity regulation of the European Waste Electrical and Electronic Equipment (WEEE) Directive's (2005) minimum collection target of 4 kg per capita for the EU countries. This target has also been exogenously set by the EU governments.

In this table, the maximum incentive corresponds to subsidy s, and the last column-cost to government-represents the value of expression (12).

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[42] https://www.icdrex.com/.

[43] https://www.icdrex.com/how-many-semiconductor-chips-in-a-modern-car/.

[44] https://www.diskmfr.com/how-many-chips-are-there-in-a-car/.

[45] For example, the car dealer-Atlantic Toyota Scion in Lynn- paid \$100 for each trade-in to new car buyers. See http://archive.boston.com/business/articles/2010/01/02/seeking_more_cash_for_their_clunkers/?page=full.

[46] Of course, the sizes of silicons used in each semiconductor for a given vehicle can vary, however, we do not make such distinction here, and due to limited information about the contents of chips in returned vehicles (which can change based on make and model of vehicles) we just count the number of chips and map it to the number of silicon in one-to-one relation.

[47] https://www.azom.com/article.aspx?ArticleID=21424.

[48] The model can be solved for any δ to examine its impact on semiconductor prices.

[49] This table is available at the Economist (2009) website http://www.economist.com/node/14205513 The article is entitled "Car scrappage schemes: Jump-starting the car industry".

[50] The details of car scrappage programs in other countries are available at https://en.wikipedia.org/wiki/Scrappage_program.

Table 5
Car scrappage programs for selected countries.

Country	Maximum incentive	Age requirement	Emissions requirement	Cost to government
United states	$4500	Under 25 years old	No	$3 billion
Germany	Euro 2500	Over 9 years old	No	$7.1 billion
United Kingdom	Euro 2000	Over 10 years old	No	$500 million
France	Euro 1000	Over 10 years old	Yes	$554 million
Italy	Euro 3500	Over 10 years old	Yes	N/A

N/A: Not available.

Table 6
Simulation data for silicon and semiconductors.

		Value
Demand:	b	0.0007915
	a	$1.30566
	ε	−0.77
Recycling:	α	0.30
	β	0.90
Production:	e_1	1
	e_2	1
Cost:	c	$1500/ton
Wage:	w	$23.25/hour
Subsidy:	s	$\{0, 1000, 1100, 1200, 1300, 1400, \ldots, 4500/car\}$
Collection:	f	$100/car
	g	$50/car
	l	$50/car
	σ	690,000 cars
	m	341,550,000 semiconductors
	A	35,211.27
Return sensitivity:	δ	0.1

Model parameters: Consequently, Table 6 is formed to exhibit the parameter values that will be used for model simulations in the numerical results section.

Given all these model parameters, we will vary subsidy, s = (0, 1000, 1100, 1200,1300, 1400, 1500, 1600, 1700, 1800, 1900, 2000, 2100, 2200, 2300, 2400, and 4500), to quantify its impact on Stackelberg equilibrium outcomes.

6. Numerical results

Given the theoretical predictions and the calibrated model parameters in the semiconductor supply chain, we can now quantify the effects of subsidy and collection channel on firms' strategies and performance. Specifically, the numerical analysis is based on cases involving semiconductor recovery, silicon production, and chip fabrication and sale. For the sake of briefness, we only demonstrate equilibrium returns, silicon and semiconductor price changes and silicon manufacturer's profit variation across collection channels to show the impact of subsidy.

Fig. 4a exhibits the variation in equilibrium number of returns $v_2[p] = \sigma - \delta(Ap - f - s)$ as subsidy changes incrementally. In this example, when subsidy is nil, the total number of used-car return is 687,280, which implies that at least 378 million semiconductors are collected for recycling when the vehicles are old and rather mechanical, and over 1 billion chips are recycled when the vehicles are rather modern. As subsidy increases more vehicles are recycled. Given the model parameters such as recycling capacity (σ), used car monetary incentives (f and s), and new car price (Ap), for every $100 subsidy increase, over 5500 additional chips will be processed for silicon and precious metals recovery under the US vehicle stimulus program.

Fig. 4b shows that equilibrium prices (similarly, all other equilibrium strategies such as the amount of new silicon, the quantity of semiconductor sales, the number of workers) are not distorted by the amount of subsidy. Irrespective of the amount of subsidy, Stackelberg equilibrium silicon and semiconductor prices will remain the same. This figure quantifies and testifies the findings in Propositions 1–2 that whether there is a subsidy or not, Stackelberg equilibrium strategies (k, p, Q, L, K) are intact.

Fig. 4c demonstrates the silicon manufacturer's profit difference as a function of subsidy when its subsidiary handles collection of used cars for silicon recovery versus when the collection is carried out in downstream. This profit difference is represented by the expression $\Pi_{M,2}^{s,M} - \Pi_{M,2}^{s,R}$, which is positive and increases in subsidy. Additionally, Fig. 4c quantifies the change in profits as subsidy varies. The rate of change of profit is about 50 times the incremental increase in subsidy. Consequently, the optimal collection channel involves upstream silicon firm's collection in the presence of subsidy.

7. Extensions and discussions

This section extends the model into several directions. First, we pose the following question: what would happen to outcomes if governments would not provide subsidies in the semiconductor supply chain? Second, to assess the implications of backward activities under subsidy, we ask: what would happen if there would not be any returns and/or recycling of chips? Furthermore, we discuss the impacts of production technology and labor in the semiconductor supply chain, and explain why vertical integration does not payoff in this industry whilst it is a profitable strategy for some CLSC models examined in the literature.

7.1. The role of labor in the semiconductor supply chain

This section emphasizes the role of labor and wages as they significantly affect the semiconductor CLSC outcomes.

First, observe that downstream semiconductor makers have to optimally choose how many workers (or work hours) they have to hire (or use), given the labor cost. They combine labor and capital at fixed proportions with Leontief technology. This signifies the importance of labor in production. If a different production technology were used, say Cobb–Douglas technology, then chip makers would have some flexibility of substituting capital for labor when the wages would rise. However, downstream firms would still need labor for production as capital and labor are not perfect substitutes.

Second, observe from the results in propositions that there exists one-to-one relationship between labor and the amount of chips produced. This stems from scaling of input coefficients in Leontief production. With Cobb–Douglas technology the optimal amount of labor would also be a fixed fraction of the final output. Specifically, labor would be equal to the number of chips times a term, which would be a function of input prices of capital and labor. Because input prices matter in optimal choice of labor, both labor and capital are substitutable at a certain degree under Cobb–Douglas technology. In any case, whether the technology is Leontief or Cobb–Douglas, quantity demanded for labor goes down as wage goes up, which can be seen from Propositions 1 and 2. However, the optimal amount of labor is independent of subsidy, which can also be observed from the propositions.

Third, while wage rate is fixed and determined in a competitive labor market, it impacts all production and pricing decisions at a constant rate. Whether there is subsidy or not, all silicon and semiconductor outputs decrease in wage at a fixed rate. The price of semiconductor increases in wage, but the price of silicon decreases in wage. This implies that silicon manufacturer should realize the impact of number of workers employed and wages paid in downstream chip industry. It should reduce silicon production when the wages go up in chip making industry. Furthermore, regardless of who collects, the wage rate impacts equilibrium strategies equally over different collection channels.

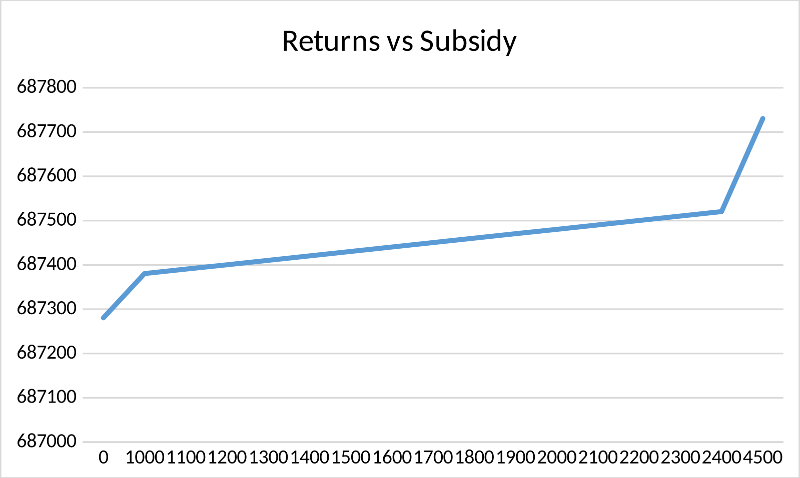

Fig. 4a. The impact of subsidy on the equilibrium number of returns of (v). The subsidy is affecting returns positively.

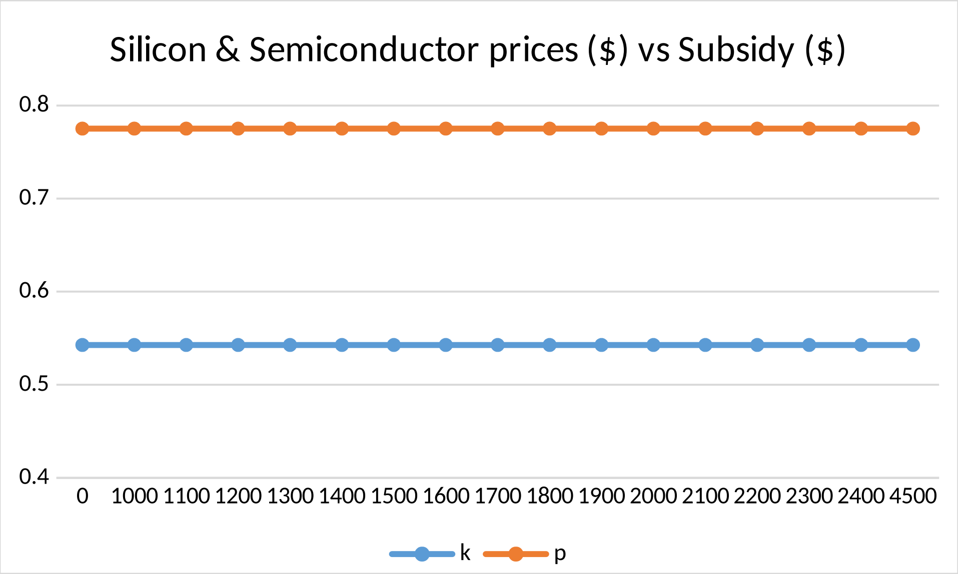

Fig. 4b. The impact of subsidy on equilibrium silicon and semiconductor prices (k,p). The subsidy is not affecting the prices.

7.2. The role of production technology in the semiconductor sector

Downstream chip makers combine capital and labor at fixed proportions with Leontief technology. When silicon price goes up semiconductor price also goes up at the same rate. Semiconductor manufacturers pass the change in silicon price onto final good customers without making any further impact on semiconductor price. Consequently, the silicon manufacturer controls semiconductor price without vertically integrating, and therefore captures the entire industry profit. On the other hand, if chip makers would operate with a different production function, say a variable-proportions process (e.g., Cobb–Douglas), in which they could substitute one input for another at a certain degree, then the silicon maker's profit without integration would be lower than its profit with integration. This is because silicon maker cannot have a full control over chip prices under Cobb–Douglas technology. If it intends to increase its wholesale price, then downstream chip manufacturers can substitute a high-cost input for a low-cost one.

7.3. Should the firms vertically integrate in the semiconductor supply chain?

Silicon manufacturer might wish to produce and sell semiconductors itself. Alternatively, it could apply vertical restraints on downstream chip makers, given that it is a monopolist and provides a critical input to downstream semiconductor sector. The previous research suggests that vertical integration between upstream and downstream firms enhances CLSC profitability. The outcomes are Pareto optimal when the firms merge or integrate. By coordinating production, silicon and semiconductor firms may reduce their costs and increase outputs and profits. Furthermore, they may eliminate the harm of double marginalization by means of integration. However, without resorting to these cost and chain power arguments, we show that vertical integration is not a profitable strategy in this studied semiconductor supply chain. This finding is explained by the characteristics of Leontief technology and is summarized as follows.

Proposition 5. *If firms in the semiconductor industry were to vertically integrate, then the total industry profit with integration would be equal to the total industry profit without integration.*

Importantly, this result holds for any type of return (exogenous or endogenous) behavior and any form of collection channel. Because downstream firms utilize a fixed proportions technology, upstream silicon manufacturer earns the same profit whether it integrates or not. As a Stackelberg leader, silicon manufacturer controls semiconductor

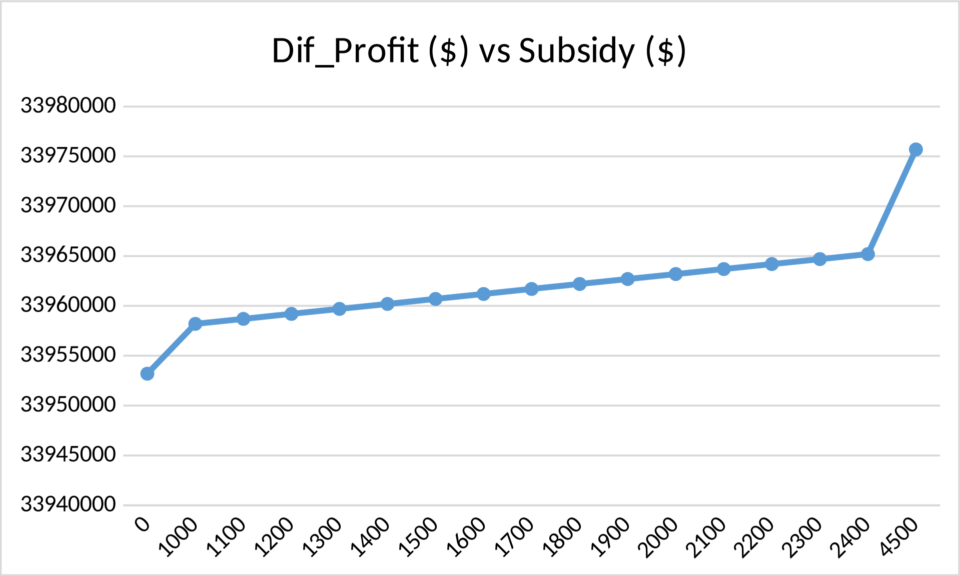

Fig. 4c. The impact of subsidy on profits over collection channels. Manufacturer is better off by collecting.

price, and hence the industry profit. Therefore, vertical integration will neither lead to any cost advantage nor facilitate substitution of capital for labor in downstream sector. On the contrary, it could be costly due to institutional restrictions or regulatory hurdle. Consequently, the silicon maker should not integrate with chip makers in the CLSC.

7.4. What if there were no backward activities?

A natural benchmark case involves when backward activities (i.e., collection and recycling) are totally discarded in the semiconductor supply chain.

Corollary 1. *In the absence of collection and recycling, Stackelberg equilibrium outcomes in the semiconductor industry are*

$$k_0 = \frac{(a + ec_2 - w)}{2e},\ p_0 = \frac{(a + ec_2 + w)}{2},\ Q_0 = \frac{(a - ec_2 - w)}{2b},$$
$$L_0 = \frac{(a - ec_2 - w)}{2b},\ \text{and}\ K_0 = \frac{e(a - ec_2 - w)}{2b}.$$

Above subscript 0 denotes equilibrium outcomes in the absence of backward activities. Specifically, this corresponds to $v_0[p] = 0$. The equilibrium outcomes in Corollary 1 are directly obtained from Proposition 1 by replacing the average cost c with c_2, assuming no returns ($\sigma = 0$) and no costs associated with collection ($f = g = l = 0$).

Comparing these outcomes to the ones with backward activities with v_1 return function, we obtain $k_0 > k_1$ and $p_0 > p_1$, and $Q_0 < Q_1$, $L_0 < L_1$, and $K_0 < K_1$. That is, prices are higher and quantities are lower in the absence of backward activities. This result holds because recycling of used products reduces production cost, and hence the product price. The result is also valid under endogenous return behavior as explained next.

Corollary 2. *Consumers are always better off under the collection programs implemented into the semiconductor industry. The maximum rebate that semiconductor firms should offer to consumers is* $\overline{f} = \alpha e(c_2 - c_1)/\delta Ab - g$.

When return function is exogenous, consumers pay lower price $p_1 < p_0$ and consume higher quantities $Q_0 < Q_1$ which holds for any value of rebate f. However, as silicon manufacturer's profit decreases in rebate, it will not choose a high rebate per return. It is not only environmentally beneficial for reducing landfills and emissions by returning the used products, but also consumers pay a lower price for the new product under any collection program. Furthermore, consumers earn an income for returning their used products. Therefore, collection programs improve consumer surplus. When the return function is endogenous $p_2 < p_0$ holds if and only if the rebate per item is not "too high". The upper bound of rebate, $\overline{f}$, should satisfy $f < \overline{f} = \alpha e(c_2 - c_1)/\delta Ab - g$. This is the maximum rebate that firms should offer to end-users in the semiconductor industry.

Given that consumers are better off with any collection program, the following question arises: What is the benefit for a firm to implement a collection program and utilize scraps or cores as inputs for production? Under what supply chain conditions should it initiate such program? The following proposition answers these questions.

Proposition 6. *The total profit in semiconductor supply chain with backward activities is higher than the profit earned without backward activities, if the number of returned products is not "too high". This holds when* $\overline{\sigma}_1 = e\alpha(c_2 - c_1)2(a - w - ec_2) + e\alpha(c_2 - c_1)/4b(f + g)$ *is satisfied for any return behavior.*

Denote the semiconductor industry profit in the absence of backward activities $\Pi_{M,0}$. We compare this profit to $\Pi_{M,1}$. As shown in the proof, the profit difference with and without collection program is $\Pi_{M,1} - \Pi_{M,0} = e\alpha(c_2 - c_1)2(a - w - ec_2) + e\alpha(c_2 - c_1)/4b - \sigma(f + g)$, where the first term is positive because $c_2 > c_1$.

$\Pi_{M,1} - \Pi_{M,0} > 0$ if and only if $\sigma < \overline{\sigma}_1 = e\alpha(c_2 - c_1)2(a - w - ec_2) + e\alpha(c_2 - c_1)/4b(f + g)$. To make the backward activities in the CLSC worthwhile so that they increase M's profit, the number of returns should not exceed the bound $\overline{\sigma}_1$. If the number of used items exceeds $\overline{\sigma}_1$, then silicon manufacturer becomes worse off by using too many recycled semiconductors. Alternatively, when the silicon manufacturer engages in backward activities, it should not process more than $\overline{\sigma}_1$ used chips.

When returns are endogenous as in $v_2[p]$, which involves subsidy, $\Pi_{M,2} - \Pi_{M,0} > 0$ implies $\sigma < \overline{\sigma}_2$, where $\overline{\sigma}_2$ is another upper bound for the returns. However, because $\Pi_{M,2} > \Pi_{M,1}$ holds, $\sigma < \overline{\sigma}_1 < \overline{\sigma}_2$ must satisfy. Therefore, the number of semiconductor collections should not exceed $\overline{\sigma}_1$ for any return function so as to make silicon producers participate into the CLSC and recycle chips.

8. Managerial and policy implications

This paper explains the impact of subsidy in the semiconductor supply chain under various consumer return behaviors and collection channels. The findings may be useful for managers who take part in silicon and semiconductor production and pricing decisions and organize their reverse logistics operations. It also provides policy implications in connection with subsidy regulations.

(1) The managers in the semiconductor industry should realize that although subsidy programs in general cause inefficiencies, their price, output, hiring, and purchasing decisions will not be distorted, if government initiated subsidy programs directly reward end-users who get incentivized to recycle their electronics or other items which incorporate semiconductors.

This result is based on Proposition 3 which shows that equilibrium outcomes in the semiconductor supply chain are intact under subsidy. While subsidy increases the number of returns of used items, it may decrease silicon manufacturer's profit. On the other hand, it provides benefits to downstream semiconductor makers when they collect, unless the number of downstream firms is "too large". However, their profits do not change if they do not deal with the collection.

As observed in car scrappage programs reported in Table 5, governments directly subsidized consumers. The US federal government offered $4500 for cars under 25 years old, Germany handed out 2500 Euro for cars older than nine years, Italy paid 3500 Euro, etc. These subsidy programs are still popular in developed countries and intend to stimulate consumer demand, create jobs, and provide environmental benefits. In addition, as part of circular economy initiatives, the scrappage programs enhance recycling, material recovery, product reuse and repair, and savings in energy and virgin mineral ores. We show that this kind of subsidy program does not distort supply chain strategies. On the contrary, they provide numerous economic benefits to silicon and semiconductor firms.

(2) The managers of silicon manufacturing companies should set the maximum quantity of used items containing chips to be processed and governments should determine their total subsidy funding based on this maximum. The managers and policy makers should realize that the maximum quantity to be processed is endogenous, therefore they should not offer monetary incentives to consumers who return "too many" used items. As a practical guideline, this paper provides a prescription for setting upper bound of chips collection quantity.

This is a result of Proposition 6, which endogenously provides optimal upper bound of returns to be processed. This finding may also explain a rationale for why managers and/or policy makers terminate used-product return programs after a while.

As an evidence to this finding, note that some governments eliminated their monetary incentives provided for car scrappage programs, because they exceeded their allocated budgets. For example, when the "Car Allowance Rebate System" was introduced by the US federal government, $3 billion was allocated to provide economic incentives to car buyers who traded in old and less fuel efficient vehicles and purchased new and more fuel efficient ones.

(3) When governments subsidize consumers who return their used items, the best collection channel involves upstream silicon manufacturer's collection of used items incorporating chips. This result is robust to consumer return behavior. In the case of endogenous returns, the total supply chain profitability in the semiconductor industry decreases in the number of returns. However, upstream silicon manufacturer should still collect and recover silicon from used electronics even if the number of returns is small.

This finding is a result of Proposition 4, which pinpoints the most profitable collection channel. When returns are exogenous, they do not impact the strategies in the semiconductor industry. Equilibrium strategies are identical irrespective of who handles the collection. In addition, because silicon manufacturer avoids paying to third party to collect the used items and utilizes them in producing new silicon, the system-wide processing costs of returns are lower under its collection. Therefore, the total chain profit is higher when silicon manufacturer collects. However, the impact of endogenous return behavior is less trivial for determining the optimal collection channel. When end-users are able to impact supply chain strategies through their return decisions, which happens with endogenous returns, optimal pricing and production strategies change over collection channels. This adds a complexity to calculate the total chain profits across collectors. However, because we are able to rank prices, outputs, and the total chain profits over collection channels, we can pinpoint the best collection channel.

(4) In the semiconductor industry, managers responsible from reverse supply chain operations should initiate collection programs for which end-users endogenously respond. Governments should subsidize these programs.

This finding is based on Propositions 1–4. A real-world example explaining this situation is that of used car scrappage programs implemented in the world (see Table 5). Most car owners surely evaluate the value of their old cars, prices of new cars, and subsidy to be received from governments before they decide whether to get rid of them. Therefore, it is reasonable to consider price, rebate, and subsidy sensitive return behavior in supply chains. For example, about two million cars are scrapped every year in the U.K.[51] The scrap value of car depends on its condition: whether it has come to the end of the road or has high mileage or significant repair costs (www.cartakeback.com). In addition, the scrap value depends on scrap metal and silicon prices that vary over time. The U.K. car owners can scrap their used cars through cartakeback.com and rewardingrecycling.co.uk, which are the largest scrap car recycling network. These companies follow the EU's "End of Life Vehicle Directive" to dispose the scrap cars following strict environmental rules.

Serving consumers with endogenous return behavior is also profitable for the industry because silicon and semiconductor manufacturers can increase their prices. The total supply chain profit is also higher under endogenous return. While consumers pay more, they are compensated through rebate and subsidy. For governments, while subsidy is costly, it can achieve different objectives such as satisfying environmental goals, avoiding landfills, reducing emissions, contributing to sustainability goals through recycling and remanufacturing from used products, and causing economic growth via new product creation.

(5) Collection programs in the semiconductor industry will likely be short-lived because of a limited amount of subsidy money. Therefore, recycling and sustainability departments in the semiconductor industry should organize their collection and processing centers accordingly.

The following example is offered to support this finding. According to the Financial Times (2018), due to China's ban on importing recyclables, the SA Recycling, one of the largest scrap metals traders in the USA, had to install a new line to wash and dissolve metals, which significantly increased the cost of recycling. Moreover, some recycling companies went bankrupt or left the industry due to cost increases in processing of the scraps.[52]

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[51] https://www.theguardian.com/money/2014/feb/14/getting-rid-old-car-scrap.

[52] See https://www.ft.com/content/360e2524-d71a-11e8-a854-33d6f82e62f8.

9. Concluding remarks

We study the semiconductor industry in a tractable closed-loop supply chain (CLSC) structure with novel ingredients involving (*i*) return function sensitive to monetary payments; (*ii*) subsidy legislation rewarding end-users for recycling; (*iii*) upstream sector producing silicon from virgin and used items; (*iv*) downstream sector hiring workers and buying silicon to produce and sell semiconductors.

To the best of our knowledge, this is the first paper in the literature formulating the semiconductor industry in a circular economy context and considering the impacts of subsidy regulation and collection channels in the industry. We characterize Stackelberg equilibrium strategies and quantify model predictions using data from sectors involving silicon recovery from old vehicles' electronics parts, silicon production from virgin elements and used items, and semiconductor manufacturing and sale in a competitive market. Using a car scrappage program in the US and end-user return behavior subject to monetary incentives and government subsidy, we formulate a reverse supply chain process in the semiconductor industry. We show that subsidy does not lead to distortions to silicon and semiconductor production and pricing strategies. Furthermore, subsidy enhances returns and contributes to the environment positively by reducing the use of virgin metals and energy. However, there are limits to the positive impacts of subsidy as subsidy programs are short-lived due to limited government budgets. From operational and logistics purposes, we determine an optimal upper bound of used-product quantity to be collected and processed in the semiconductor CLSC. Moreover, we pinpoint the most profitable collection channel under subsidy regulation in the industry. Our results are robust to exogenous and endogenous return behaviors. The findings of this research may be valuable for silicon and semiconductor manufacturers who price silicon and semiconductors, and for policy makers who provide subsidy in the semiconductor industry. The subsidy examined in this paper does not create inefficiencies in silicon and semiconductor production and pricing and does not cause welfare loss to the industry and society, while it provides a number of economic and environmental benefits.

Funding

This research was in part supported by a grant from the Social Sciences and Humanities Research Council of Canada.

CRediT authorship contribution statement

Talat S. Genc: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A

Appendix A presents the model notation.

See Table 7.

Table 7
The model notation.

Notation	Description
M	Silicon producer
R	Semiconductor manufacturers
v	Quantity of used product including semiconductors
β	Recycling rate
m	Quantity of recovered used product including semiconductors
K	Quantity of silicon
Q	Quantity of semiconductor
α	Rate of silicon production from used product
$1-\alpha$	Rate of silicon production from raw product
c_1	Marginal production cost based on used product
c_2	Marginal production cost based on raw product
c	Weighted marginal cost
e	The rate at which labor and silicon combined
σ	Maximum return quantity
a	Maximum price
b	Price sensitivity to output
ϵ	Semiconductor price elasticity of demand
δ	Return sensitivity to net price
f	Rebate per return
s	Subsidy per return
v_1	Exogenous return quantity
v_2	Endogenous return quantity
k	Wholesale price of silicon
w	Marginal cost of labor
g	Unit cost of shipping/handling
p	Retail price of a semiconductor
Ap	Retail price of a finished product (e.g., a cell phone or a PC)
F	Maximum cost of collection per unit
l	Collection payment from M to R
n	Number of downstream firms

Appendix B

Proof of Proposition 1. (i) The return function is passive: The profit maximization of a competitive downstream firm implies that marginal cost equals price. That is, $ke + w = p$ holds, where $p = a - bQ$. This implies that in equilibrium the number of sales of new product will be $Q_1^{s,M} = (a - ke - w)/b$. Using the production function, we can solve for optimal number of K and L needed for producing Q amount of new product. $K_1^{s,M} = eQ_1^{s,M}$ and $L_1^{s,M} = Q_1^{s,M}$ are the profit maximizing number of capital and labor required for production in the downstream. Then the relationship between demand for K and its price k becomes $K_1^{s,M}[k] = e(a-w-ek)/b$, with the usual demand property that demand decreases in price: $\partial K_1^{s,M}/\partial k < 0$.

Given that R firms will need the quantity K_1, M as a leader will choose its price k_1 to maximize its profit. This leads to the optimal intermediate good price $k_1^{s,M} = (a + ec - w)/2e$ in the upstream. In the downstream, the retail price will be $p_1^{s,M} = (a + ec + w)/2$. The total number of sales in the retail market will be $Q_1^{s,M} = (a - ec - w)/2b$, and the number sales in the intermediate good market will be $K_1^{s,M} = e(a - ec - w)/2b$.

(ii) The return function is active and endogenous: Given the return function $v_2[p] = \sigma - \delta(p - f - s)$, $ke + w = p$ holds, where $p = a - bQ$. This implies that in equilibrium the number of sales of in the retail market will be $Q_2^{s,M} = (a - ke - w)/b$. From the production function we obtain $K_2^{s,M} = eQ_2^{s,M}$ and $L_2^{s,M} = Q_2^{s,M}$ which are the profit maximizing number of capital and labor required for production by downstream firms. Then the relationship between demand for K and its price k becomes $K_2^{s,M}[k] = e(a - w - ek)/b$.

Given that the downstream firms will need $K_2^{s,M}$ amount of intermediate product, M will choose its price to maximize the profit by solving the game backwards. This leads to the optimal intermediate product price $k_2^{s,M} = (a + ec - w + \delta Ab(f + g))/2e$. Using the demand expressions for labor and capital, the optimum retail price will be $p_2^{s,M} = (a+ec+w+\delta Ab(f+g))/2$, and the outputs will follow immediately from the price expressions. □

Proof of Proposition 2. When the return behavior is $v_1(p) = \sigma$, the equilibrium price leads to $p_1^{s,R} = ke + w$, which is price equals marginal cost. The equilibrium number of sales of new product will be $Q_1^{s,R} = (a - ke - w)/b$, for which $K_1^{s,R} = eQ_1^{s,R}$ amount of capital and $L_1^{s,R} = Q_1^{s,R}$ amount of labor are needed by R firms. Given the demand for capital $K_1^{s,R}$, the M will choose its price to maximize its profit. This leads to the optimal price $k_1^{s,R} = (a + ec - w)/2e$. Then the retail product price charged to the customers becomes $p_1^{s,R} = (a + ec + w)/2$, the number of new retail sales is $Q_1^{s,R} = (a - ec - w)/2b$, and the number of intermediate good sales is $K_1^{s,R} = e(a - ec - w)/2b$.

Similarly, when the return behavior is $v_2[p] = \sigma - \delta(Ap - f - s)$, solving the game backwards for Stackelberg equilibrium yields the prices $k_2^{s,R} = (a + ec - w + \delta AbF)/2e$, and $p_2^{s,R} = (a + ec + w + \delta AbF)/2$. The optimal outputs are $K_2^{s,R} = e(a - ec - w - \delta AbF)/2b$ for the intermediate product, and $Q_2^{s,R} = (a - ec - w - \delta AbF)/2b = L_2^{s,R}$ for the new product. $\square$

Proof of Proposition 3. The first part is clear from the proofs of Propositions 1 and 2 that the equilibrium strategies do not involve subsidy s irrespective of the collector and return function. The second part is directly obtained by comparing the prices in Proposition 1 to the prices in Proposition 2. The proof of the third part is clear from the expressions (11) and (12) in that $\partial \Pi_M^{s,R}[s]/\partial s = -\delta AF < 0$ and $\partial \Pi_R^{s,R}[s]/\partial s = \delta A(F - f - g)/n > 0$. The proof of the last part is clear from the expressions (9) and (10) in that $\partial \Pi_M^{s,M}[s]/\partial s = -\delta A(f + g) < 0$ and $\partial \Pi_R^{s,M}[s]/\partial s = 0.\square$

Proof of Proposition 5. (a) Assume the endogenous return function $v_2[p] = \sigma - \delta(Ap - f - s)$. Denote the integration profit $\Pi_{I,2}$, which is maximized to choose retail price p:

$$\max_p \Pi_{I,2}[.] = Q[p]p - Q[p]w - \alpha c_1 Q[p]e - (1 - \alpha)c_2 Q[p]e - v[.](f + g)$$

where $Q[p]w$ is the total cost of labor because $L = Q$ holds by the production function, $\alpha c_1 Q[p]e$ is the cost of production from recycling the used products because $K = Qe$ by the production function. Similarly, $(1 - \alpha)c_2 Q[p]e$ is the cost of production from the raw material, and $v[.](f + g)$ is the cost of collection.

The first order derivative of profit function with respect to price yields $p_{I,2} = (a + w + ec + \delta Ab(f + g))/2$ which is the final product price under vertical integration. Observe that this price is identical to the price when there is no vertical integration in Proposition 1. That is, $p_I = p_2$. Therefore, final product prices will be identical whether industry is vertically integrated or not. Also, $Q_I = Q_2$ holds. The integrated profit can be written as

$\Pi_{I,2} = Q_I[p_I](p_I - w - ec) - v_2[p_I](f + g)$. The upstream M's profit in the supply chain without vertical integration is, as defined in the proof of Proposition 1, $\Pi_{M,2} = K_2(k_2 - c) - v_2[p_2](f + g) = eQ_2(p_2)(p_2 - w - ec)/e - v_2[p_2](f + g) = \Pi_{I,2}$ holds because $K_2 = eQ_2$, and $p_2 = ek_2 + w$, and $Q_{I,2} = Q_2$ and $p_{I,2} = p_2$. That is, vertical integration profit is equal to upstream M's profit under no integration. Since the downstream firms are perfectly competitive, their economic profits are zero. Therefore, the total industry profit in the closed loop supply chain when there is no integration equals to the total industry profit when industry is vertically integrated.

(b) Assume the return function $v_1[p] = \sigma$. Plugging this constant return function into the above integration profit, $\Pi_{I,1} = Q[p_{I,1}](p_{I,1} - w - ec) - \sigma(f + g)$, and taking the derivative of it yields the final good price under integration, $p_{I,1} = (a + w + ec)/2$.

Observe that this price is identical to the price when there is no vertical integration in Proposition 1. That is, $p_{I,1} = p_1$. Therefore, final product prices will be identical whether industry is vertically integrated or not. Also, $Q_{I,1} = Q_1$ holds. Using the arguments above in (a), it is clear that the profits are equal, that is $\Pi_{I,1} = \Pi_{M,1}$. $\square$

Proof of Proposition 6. When there is no collection, that is $v_0[p] = 0$, the manufacturer's profit is $\Pi_{M,0} = K_0(k_0 - c_2) = (a - ec_2 - w)^2/4b$. Its profit when there is exogenous collection, that is $v_1[p] = \sigma$, is $\Pi_{M,1} = (a - ec - w)^2/4b - \sigma(f + g)$.

(i) Observe that the difference of forward activity profits is positive. That is the difference of the first terms is $(a - ec - w)^2/4b - (a - ec_2 - w)^2/4b > 0$ because $c_2 > c$, because remanufacturing through used items reduces the average production cost. Then $\Pi_{M,1} - \Pi_{M,0} = e(c_2 - c)2a - 2w - e(c + c_2)/4b - \sigma(f + g) = e\alpha(c_2 - c_1)2(a - w - ec_2) + e\alpha(c_2 - c_1) /4b - \sigma(f + g)$. Therefore, $\Pi_{M,1} - \Pi_{M,0} > 0$ if and only if $\sigma < \overline{\sigma} = e\alpha(c_2 - c_1)2(a - w - ec_2) + e\alpha(c_2 - c_1)/4b(f + g)$. To guarantee higher profitability with the backward activities, the number of used products collected for remanufacturing should not exceed the upper bound $\overline{\sigma}$, defined above.

This bound is valid even if we assume the return function v_2, because $\Pi_{M,2} > \Pi_{M,1}$. This is because when the endogenous return function $v_2[p]$ is considered, $\Pi_{M,2} - \Pi_{M,0} > 0$ implies $\sigma < \overline{\sigma}_2$, where $\overline{\sigma}_2$ is another upper bound for the returned items. However, because $\Pi_{M,2} > \Pi_{M,1}$ holds (see Proposition 1) $\overline{\sigma}_1 < \overline{\sigma}_2$ must hold. Therefore, $\sigma < \overline{\sigma}_1 < \overline{\sigma}_2$ must satisfy. Consequently, the number of collected items should not exceed $\overline{\sigma}_1$ for any return function (v_1 or v_2).

(ii) From the profit difference $\Pi_{M,1} - \Pi_{M,0}$ above, it is clear that if there would not be any cost advantage of using recycled product in the production process, then the manufacturer should not do any backward activity. Mathematically, at $c_2 = c_1$, the profit difference would be $\Pi_{M,1} - \Pi_{M,0} = -\sigma(f + g) < 0$. Alternatively, if the cost of production does not go down in the remanufacturing process, then the firm M should not pay any fee per collection. That is $f = 0 = g$ must hold.

For the case of endogenous return function v_2, the M's profit is $\Pi_{M,2} = K_2(k_2 - c) - \sigma - \delta(Ap_2 - f)(f + g)$, where the equilibrium output and prices are obtained in the proof of Proposition 1. Also, as shown above, $\Pi_{M,2} - \Pi_{M,1} = K_1\theta/2e - \theta^2/4b - \theta e(k_1 - c)/2b + \theta(k_2 e - f + w)/b$ and $\Pi_{M,1} - \Pi_{M,0} = e\alpha(c_2 - c_1)2(a - w - ec_2) + e\alpha(c_2 - c_1)/4b - \sigma(f + g)$. Adding these two terms results $\Pi_{M,2} - \Pi_{M,0} = K_1\theta/2e - \theta^2/4b - \theta e(k_1 - c)/2b + \theta(k_2 e - f + w)/b + e\alpha(c_2 - c_1)2(a - w - ec_2) + e\alpha(c_2 - c_1)/4b - \sigma(f + g)$, where $\theta = \delta Ab(f + g)$. This can be simplified to $\Pi_{M,2} - \Pi_{M,0} = \theta(2p_1 - 2f + \theta/2)/2b + e\alpha(c_2 - c_1)2(a - w - ec_2) + e\alpha(c_2 - c_1)/4b - \sigma(f + g)$. Next the profit difference at $c_2 = c_1$ becomes $\Pi_{M,2} - \Pi_{M,0} \,|_{c_2=c_1} = -(f + g)\sigma - \delta(p_1 - f + \theta/4) \,|_{c_2=c_1} < 0$, as $p_1 - f > 0$ and $f, g, \theta, \sigma > 0$. $\square$

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