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Carbon taxation in Singapore's semiconductor sector: a mini-review on GHG emission metrics and reporting

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Abstract

The threat of climate change has catalyzed global endeavors to curb greenhouse gas emissions, with carbon taxation emerging as a pivotal policy instrument. Singapore, akin to Taiwan, has embraced this tool, and its ramifications on their semiconductor industry are both profound and multifaceted. At the outset, the imposition of carbon taxes inevitably escalates production costs for semiconductor firms, compelling them to offset their carbon footprint financially. This escalation, in turn, poses a risk of eroding the industry's competitive edge, nudging firms to contemplate the prospect of migrating to locales with more lenient carbon taxation regimes. However, in juxtaposition to these challenges, carbon taxation unveils a silver lining. It instigates semiconductor entities to recalibrate their operations, infusing energy-efficient technologies and pivoting towards renewable energy avenues. Such transitions not only attenuate their carbon emissions but also curtail their financial burden arising from carbon taxation. This manuscript elucidates a panoramic landscape of both policy innovations and technological strides specific to Singapore's semiconductor arena. It aims to be an instrumental compass for stakeholders, delineating pathways for achieving optimal eco-financial equilibrium in the sector.

Highlights

- Singapore's carbon emissions standards set a global benchmark for competitive practices.
- The review identifies cutting-edge carbon reduction methodologies prevalent in the semiconductor industry.
- There's a discernible gap in literature examining the confluence of carbon tax policy with industry practices.
- Highlighting this lacuna, our review serves as a potential catalyst for driving sustainable advancements in the semiconductor domain.

Keywords Singapore, Semiconductor industry, Carbon tax, Technology development, GHG policy

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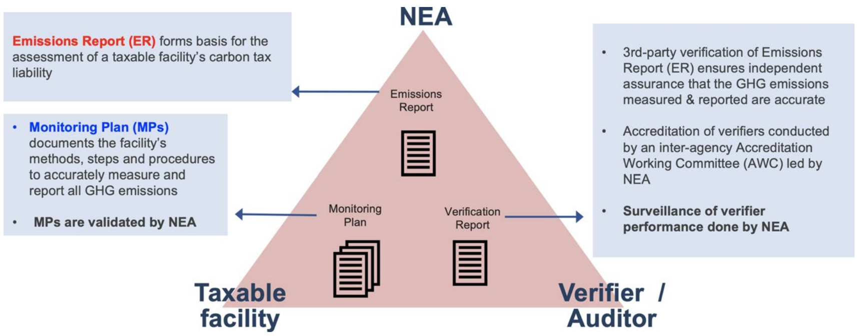
Graphical Abstract



Emissions Report (ER) forms basis for the assessment of a taxable facility's carbon tax liability

- **Monitoring Plan (MPs)** documents the facility's methods, steps and procedures to accurately measure and report all GHG emissions
- **MPs are validated by NEA**

- 3rd-party verification of Emissions Report (ER) ensures independent assurance that the GHG emissions measured & reported are accurate
- Accreditation of verifiers conducted by an inter-agency Accreditation Working Committee (AWC) led by NEA
- **Surveillance of verifier performance done by NEA**

1 Introduction

The alarming rate of climate change and its impending adverse effects have necessitated global actions. Consequently, carbon tax emerges as a pivotal tool embraced by nations, seeking to attenuate greenhouse gas emissions. Its intent is not solely to levy charges but also to motivate industries to adopt sustainable practices and technologies (Lee and Chang 2018). Despite its ubiquitous implementation, the rationale for its introduction, especially concerning its impact on industries like semiconductor production, needs clear elucidation.

In 2019, Singapore, in alignment with its commitment under the United Nations Framework Convention on Climate Change (UNFCCC), embarked on its carbon taxation journey. The nation aspires to curtail its greenhouse gas emissions by 36% below the business-as-usual projection by 2030 (Lin and Chiang 2019). Targeting the top 30 greenhouse gas emitters, the tax is predicated on the carbon dioxide equivalent emissions of facilities. Notably, revenues from this tax are earmarked for climate-centric projects, underpinning Singapore's transition towards a low-carbon paradigm (National Climate Change Secretariat 2019). Conversely, Taiwan, housing the world's foremost semiconductor factories, has proclaimed its carbon tax policy rollout in 2023. This strategy focuses on substantial emitters spanning energy, transportation, and industrial sectors, with a goal to diminish greenhouse gas emissions by 20% below 2005 standards by 2025 (Tan and Tan 2019). The tax's yield is slated for propelling low-carbon innovations and pioneering green technologies. An intricate juxtaposition of these two regions' carbon taxation architectures is presented in Table S1 (Wang and Lin 2020).

Significantly, the semiconductor domain is a cardinal carbon emission source in Singapore and Taiwan, drawing attention to the potential ramifications of carbon taxation on it. While such a tax may inflate operational expenditures in Singapore, potentially hampering competitiveness, it concurrently paves the avenue for semiconductor entities to spearhead and monetize low-carbon technological marvels (Wong and Tan 2021). Remarkably, both regions' carbon tax frameworks overlook emissions emanated from land-centric activities as stipulated by the UNFCCC, alongside transportation emissions and indirect emissions (Scope 2 and Scope 3) linked to electricity consumption. This omission is especially salient given Singapore's reliance on grey electricity, as opposed to green, nullifying carbon credit offset possibilities (Tietenberg 2013; Metcalf 2009).

Navigating through this backdrop, this review endeavors to furnish a meticulous panorama of Singapore's carbon taxation industrial modus operandi and its repercussions on the semiconductor landscape. Furthermore, it delves into the opportunities and challenges bequeathed by carbon taxation to semiconductor ventures, accentuating the imperative of a robust GHG emissions surveillance and reporting mechanism within the industry (Li et al. 2020).

2 Singapore Greenhouse Gas (GHG) protocol and carbon taxation

A carbon tax is a policy that puts a price on carbon emissions by taxing the amount of carbon dioxide or other greenhouse gases emitted by a company or organization (Tietenberg 2013). The idea behind a carbon tax is to create an economic incentive for companies to reduce their emissions by making it more expensive to pollute. The effectiveness of a carbon tax as a policy tool to reduce emissions and mitigate climate change is a matter of debate. Some experts argue that a carbon tax is an efficient and effective way to reduce emissions because it creates a financial incentive for companies to invest in cleaner technologies and practices (Metcalf 2009).

By making emissions more expensive, a carbon tax can encourage companies to find ways to reduce their emissions in order to save money. On the other hand, critics of carbon taxes argue that the tax is regressive and disproportionately affects low-income households, and it is difficult to implement and enforce. Additionally, it may not be sufficient to reduce emissions to the level required to mitigate the effects of climate change (Gautier 2019).

The Singaporean government, acknowledging the need to mitigate greenhouse gas (GHG) emissions, implemented a carbon tax in 2019, as depicted in Fig. 1(a). Initially set at SGD\$5/tCO_2e spanning from 2019 to 2023, it's slated to escalate to SGD\$25/tCO_2e in 2024 and 2025 and SGD\$45/tCO_2e during 2026–2027, and aims to achieve SGD\$50–80/tCO_2e by 2030. Facilities emitting 25,000 tCO_2e or above annually are considered taxable, while those emitting a minimum of 2,000 tCO_2e are designated as reportable. The tax encompasses a spectrum of GHGs, including CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6. However, GHGs from minor emissions sources unrelated to the main production activity and NF_3 are tax-exempt. GHG emissions tied to transport fuels are subsumed under Customs & Excise duties.

In 2023, Singapore's commitment to curbing GHG emissions sees a continuation of the Carbon Pricing Act 2018 (CPA 2018). As per Fig. 1(b), third-party verification becomes imperative for taxable facilities. This verification, conducted by a National Environment Agency (NEA) accredited entity, scrutinizes the Emissions Report's (ER) accuracy in accordance with the Monitoring Plan (MP). Once verified, the ER must be submitted to NEA by 30th June following each reporting period.

Third-party verification is done to give the verifier confidence to sign off the ER with a reasonable level of assurance. NEA provides templates for Notice of Verification, Verification Plan Summary, and Verification Report that accredited verifiers must use for the conduct of verification and the final verification report (Fig. 2). Companies wishing to provide third-party verification services must be accredited by NEA through an independent assessment to carry out the verification of GHG emissions reporting in line with the Carbon Pricing Act (CPA) and its accompanying regulations. A site visit is conducted to ensure the implementation of the MP (including the QMF) (Table S2) is reflective and to check the pressure gauge/weigh scales on-site. Emissions data/supporting documents are to be kept beyond the acquisition date so that the verifier can check the records and for NEA to duplicate the verification if needed (Fig. 3).

The Monitoring Plan (MP) serves as a detailed account of the methodologies and procedures deployed by companies to report GHG emissions accurately, functioning

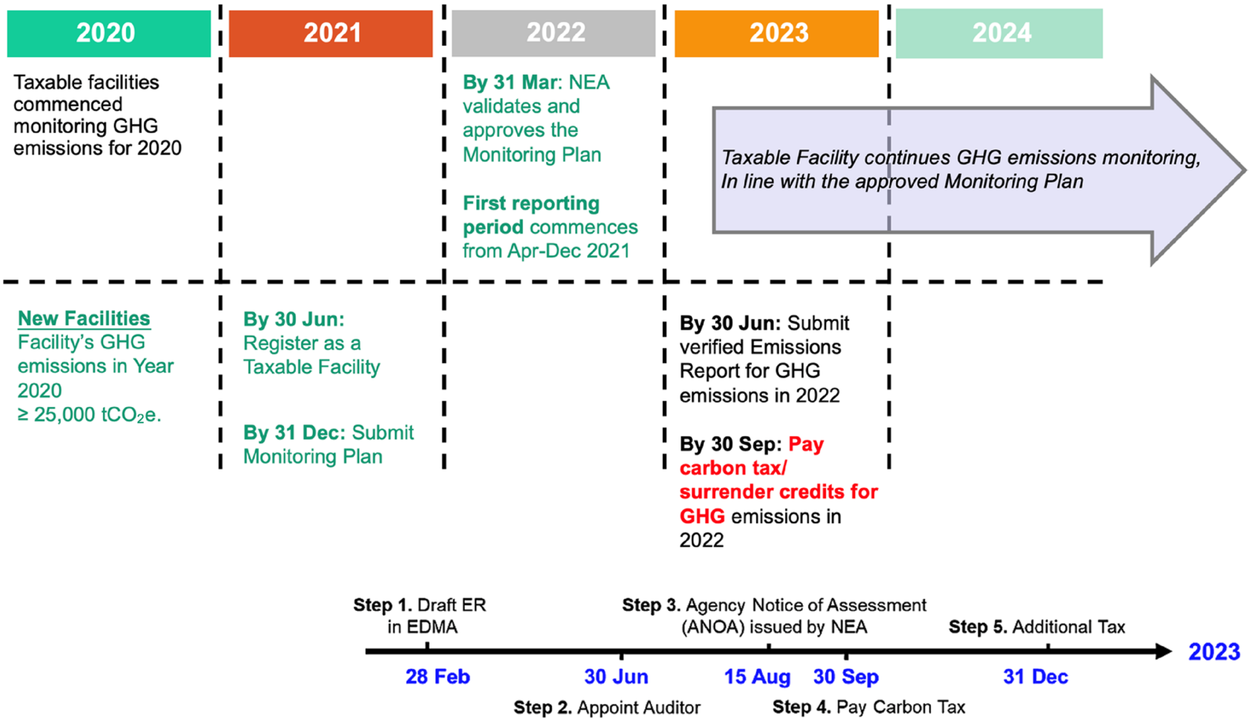
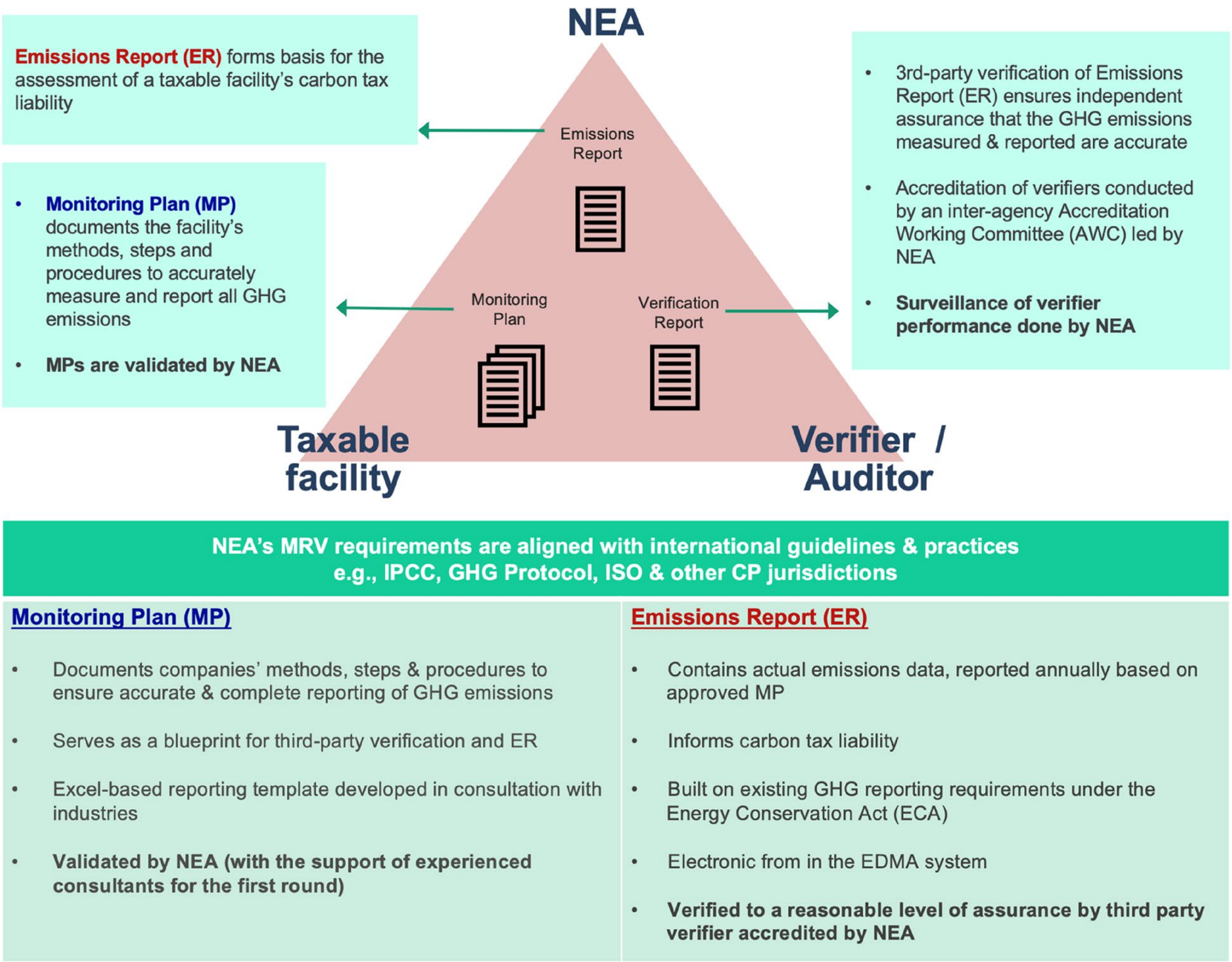


Fig. 1 Timeline for compliance by taxable facilities for the implementation of Singapore's Carbon Pricing Act (CPA) and verification schedule for the 1^{st} year in 2023



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NEA's MRV requirements are aligned with international guidelines & practices e.g., IPCC, GHG Protocol, ISO & other CP jurisdictions

Monitoring Plan (MP)

- Documents companies' methods, steps & procedures to ensure accurate & complete reporting of GHG emissions
- Serves as a blueprint for third-party verification and ER
- Excel-based reporting template developed in consultation with industries
- **Validated by NEA (with the support of experienced consultants for the first round)**

Emissions Report (ER)

- Contains actual emissions data, reported annually based on approved MP
- Informs carbon tax liability
- Built on existing GHG reporting requirements under the Energy Conservation Act (ECA)
- Electronic from in the EDMA system
- **Verified to a reasonable level of assurance by third party verifier accredited by NEA**

Fig. 2 Singapore National Environment Agency (NEA)'s Measurement, Reporting and Verification (MRV) framework aligned with international guidelines & practices (IPCC, GHG Protocol, ISO14064, Code of Practice, etc.)

as a foundational document for third-party verification and ER. As an effort to ensure reported GHG emissions' integrity and adherence to the ratified MP, an unbiased assessment of the ER is mandated. As delineated in Fig. 3, these verification parameters echo the practices embraced by pioneering carbon pricing jurisdictions, such as the EU, California, and Korea. These measures also align with international protocols and are enhanced with feedback garnered from industry consultations with prospective third-party verifiers. The inaugural list of accredited verifiers was made public on NEA's official platform in July 2019 (Ambec et al. 2013).

As indicated in Fig. 4, companies that are subject to the carbon tax are required to purchase fixed-price credits (FPCs) from the National Environment Agency (NEA) for each tonne of CO_2e they emit. The FPCs are priced at SGD $5 per credit, and companies must purchase enough credits to cover their verified emissions for the reporting year. For example, if a facility emits 68,000 tCO_2e in a year, the facility owner must buy 68,000 credits from NEA at a cost of SGD $340,000 (68,000 credits x SGD $5 per credit) (Chen 2019). Once the credits are purchased, the facility owner must surrender them to NEA by 30 September of each year. This process helps companies build up experience in dealing with carbon credits and lays the groundwork for potentially allowing companies to use properly monitored, reported and verified (MRV-ed) international offsets to pay part of their carbon tax liability in the future.

The Singapore carbon tax is a market-based mechanism that encourages companies to reduce their emissions and transition to a low-carbon economy while providing flexibility in how they comply with the tax. The FPC approach allows companies to manage their carbon tax liability while also contributing to the government's efforts to mitigate climate change. Singapore's carbon tax is also considered as a model for other countries and regions, as it demonstrates that

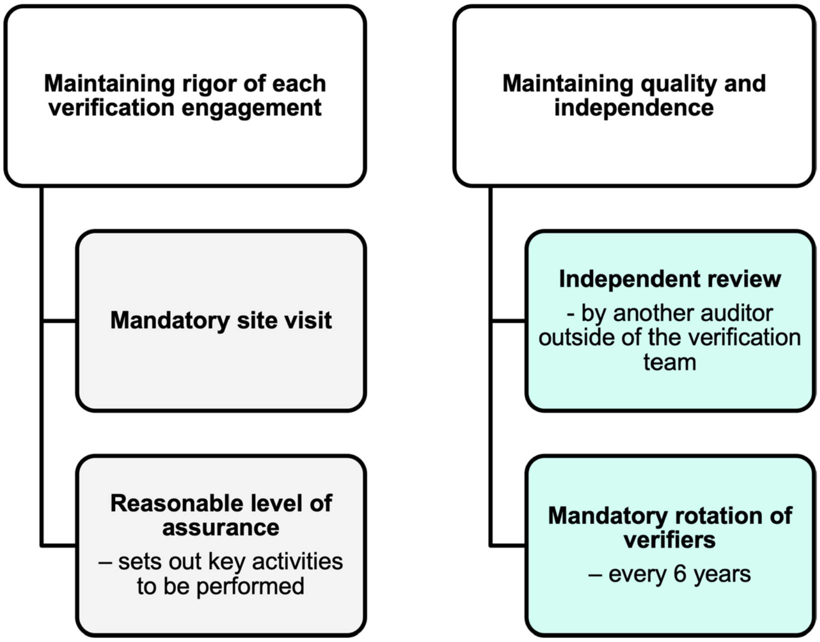

Fig. 3 Third-party verification requirements aligned with practices in leading carbon pricing jurisdictions

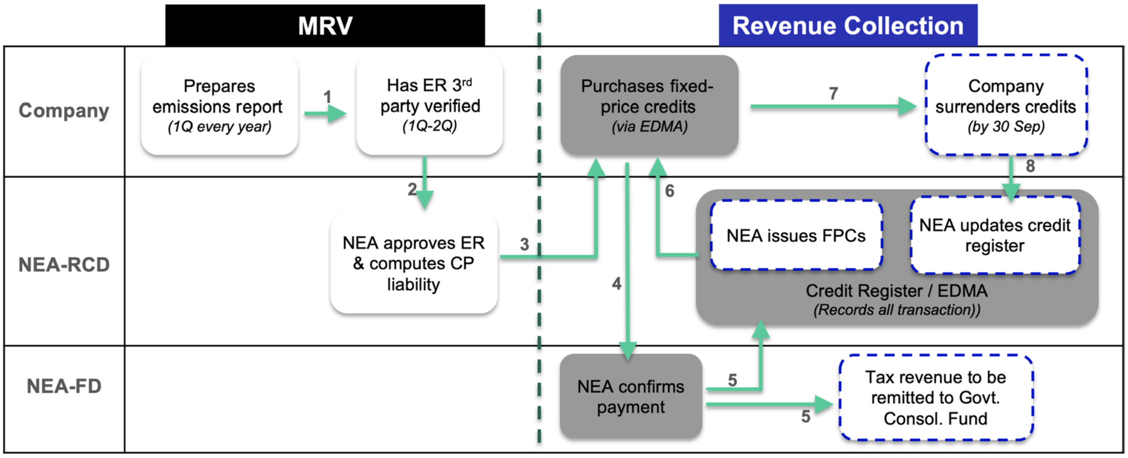

Fig. 4 Overview of credit registry and revenue collection

it is possible to implement a carbon tax quickly, without causing significant economic disruption, and with support from business and the public in the following aspects (Chu 2019):

1. Political will: the government of Singapore had a strong desire to address the issue of climate change and was committed to implementing a carbon tax as part of its efforts to reduce emissions.
2. Simplicity: Singapore's carbon tax is relatively simple. It applies to only large emitters and the rate is fixed at $5 per tonne of CO_2. This simplicity makes it easier to implement and less controversial than more complex systems.
3. Economic considerations: Singapore has a strong economy and a well-developed infrastructure, which made it easier for the government to implement a carbon tax without causing significant disruption to the economy (Tietenberg 2013; Lee 2019).
4. Small size: Singapore is a small country which simplifies the administration of the carbon tax, allowing for faster implementation and enforcement.
5. International cooperation: Singapore was part of the Under 2 Coalition, an international agree-

ment among cities, states and countries to limit the increase in global average temperature to below 2 degrees Celsius. This helped them to have a framework for their carbon tax (Ministry of the Environment and Water Resources 2019).

6. Proactivity: Singapore has already taken several steps to address climate change such as investing in renewable energy, energy efficiency, and electric vehicles. This made the implementation of a carbon tax easier as it aligns with the already existing plan.

3 Emission sources identification in semiconductor production

The GHG emission stream identification process in Singapore's semiconductor industry involves several steps (Table 1). The first step is to identify the sources

Table 1 GHG emission in carbon tax extract from Greenhouse Gas (GHG) emissions measurement and reporting guidelines

Items	Description
Emission Source	**Fuel combustion** 1. Manufacturing process 2. Kitchen **IPPU** 1. Integrated circuit or semiconductor production 2. Use of greenhouse gases in fire protection equipment 3. Use of HFCs or PFCs in refrigeration and air-conditioning equipment 4. Use of SF_6 in electrical equipment 5. Fugitive emissions*
Emission Stream Type	**Fuel combustion** 1. Liquefied Petroleum Gas 2. Diesel **IPPU** **1. Integrated circuit or semiconductor production** 1.1 Plasma etching thin film 1.2 Cleaning chemical vapour deposition (CVD) tool chambers 1.3 Furnace (diffusion) 1.4 Nitride removal (etching) 1.5 Cleaning of low-k CVD reactors **2. Use of greenhouse gases in fire protection equipment (Facility)** 2.1 Carbon dioxide (CO_2) 2.2 HFC-227EA (CF_3CHFCF_3) **3. Use of HFCs or PFCs in refrigeration and air-conditioning equipment (Facility)** 3.1 R-404A 3.2 R-410A **4. Use of SF_6 in electrical equipment (Facility)** 4.1 Use – Sealed Pressure (MV Switchgear) 4.2 Use – Closed Pressure (HV Switchgear) 4.3 Gas Insulated Transformers
Emissions Quantification Method	**Method 1: Calculation Approach** Calculation of emissions from activity data (e g amount of fuel or process input) and appropriate conversion factors (e g emission factors and net calorific value) **Method 2: Material Balance** Determination of CO_2 emissions based on the balance of the carbon content entering the process through feedstock and the amount exiting the process through products **Method 3: Direct Measurement** Measurement of GHG emissions directly at the point of release, e.g., a Continuous Emissions Monitoring System (CEMS) that measures the exhaust gas flow rate and the concentration of the GHG emissions at an exhaust stack
Type of Measurement Instrument or Technique	1. Invoice 2. Pressure gauge 3. Weigh scales 4. Measurement 5. Accurate measurement
Tier	Tier 2a and 2b (before Y2024) and Tier 2c (after Y2024)
Greenhouse Gas to be Reported	1. Plasma etching thin film CH_4, SF_6, CHF_3, CH_2F_2, CH_3F, CF_4, C_2F_6, C_4F_8, C_5F_8, CO 2. Cleaning Chemical Vapour Deposition (CVD) tool chambers N_2O, NF_3, CF_4, C_2F_6 3. Furnace (Diffusion) N_2O

of emissions, including direct emissions from the manufacturing process and indirect emissions from energy consumption (Fig. 5):

1. Raw material acquisition: the semiconductor manufacturing process begins with the acquisition of raw materials. Silicon, the primary material for most semiconductors, is extracted from quartzite gravel or crushed quartz (Chu 2019). The extraction process requires significant energy, typically sourced from non-renewable resources, resulting in GHG emissions. Other materials, such as gallium and arsenic for compound semiconductors, also have their respective extraction emissions.
2. Silicon wafer production: pure silicon is derived from the raw material and then melted with a small portion of boron in a crucible. This process requires substantial heat, typically sourced from carbon-emitting energy sources. The molten mixture is then drawn into a single crystal ingot, which is then sliced into thin wafers (Ministry of the Environment and Water Resources 2019; Xiao et al. 2023).
3. Wafer processing: this is the heart of semiconductor device fabrication, where actual circuits are created on the wafers:

    - Oxidation: silicon dioxide is grown on the wafer surface. This step involves exposing the wafer to a mixture of high-temperature steam and oxygen, which can result in emissions if not controlled effectively.
    - Photolithography: a light-sensitive photoresist is applied to the wafer, exposed to UV light through a mask, and then developed to leave a patterned photoresist on the wafer. The solvents and chemicals used in this step have associated emissions.
    - Etching: unprotected parts of the wafer are subjected to chemical or plasma etch processes to remove material. This step releases GHG emissions, especially when using potent greenhouse gases like sulfur hexafluoride (SF6) in plasma etching.
    - Ion implantation: ions are implanted in the silicon wafer to modify the properties of the silicon. This requires energy-intensive equipment.

4. Assembly and packaging: after wafer processing, the wafer is sliced into individual chips, which are then assembled into packages (Gautier 2019). This involves the use of lead or gold for connections, and the soldering process can result in GHG emissions.
5. Energy consumption and distribution: indirect emissions stem from the electricity consumed in manufacturing, cooling, distribution, and other auxiliary processes. Considering the energy-intense nature of semiconductor manufacturing, this is a significant source of GHGs.
6. Waste management and disposal: the semiconductor production process generates waste, from defective chips to spent chemicals and solvents. The treatment, transportation, and disposal of these wastes contribute to the industry's GHG emissions.

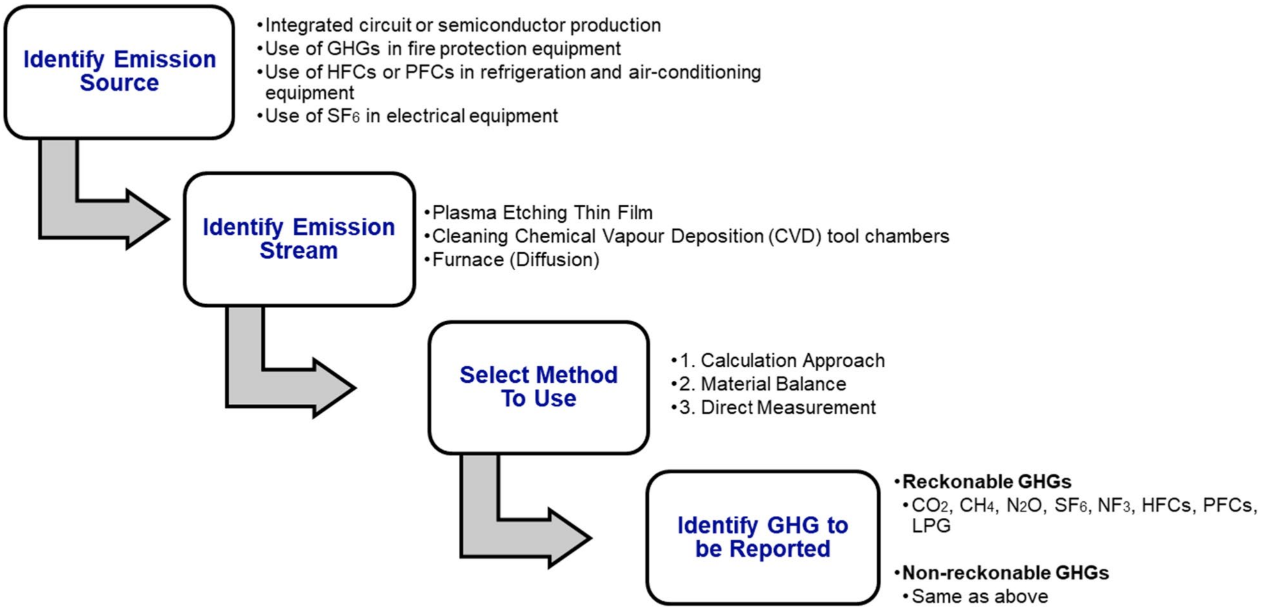

Fig. 5 Greenhouse Gas (GHG) Emission Stream identification process in Singapore's semiconductor industry

Once the emission sources are identified, the next step is to quantify the amount of emissions from each source. This involves collecting data on the energy consumption and production processes, and using emission factors to calculate the amount of GHG emissions associated with each process (Tables S3 and S4). The emission factors are based on the type of equipment used, the efficiency of the equipment, and the type of fuel or energy source used. These factors are determined by industry standards and best practices, as well as by government regulations and guidelines. After quantifying the above mentioned emissions from each source, the next step is to prioritize the emission streams based on their contribution to the overall GHG emissions. This helps to focus efforts on the most significant sources of emissions and identify opportunities for emissions reduction. Finally, once the emission streams are identified and prioritized, companies can develop and implement strategies to reduce their emissions. This may include process improvements, equipment upgrades, energy efficiency measures, and the use of renewable energy sources (Li et al. 2021).

The Singapore Carbon Pricing Act 2018 and the ISO 14064–1:2018 standard both focus on measuring and reporting greenhouse gas (GHG) emissions. However, there are some key differences between the two frameworks (Table 2): one major difference is that the Singapore Carbon Pricing Act 2018 focuses specifically on direct emissions (Scope 1) of CO_2, CH_4, N_2O, SF_6, HFCs, and PFCs from fuel combustion and industrial processes and product use (IPPU). It includes some exceptions, such as emissions from the combustion of certain biofuels and biomass, as well as diesel with a sulfur content of more than 10 ppm. In contrast, the ISO 14064 Standard includes all three scopes of emissions—direct (Scope 1), energy indirect (Scope 2), and other indirect (Scope 3)—in its guidelines (National Development Council 2019).

Table 2 Comparison between Singapore's carbon pricing act 2018 and ISO14064 standard Greenhouse Gas (GHG) emissions measurement and reporting guidelines

Singapore's Carbon Pricing Act 2018 (NEA Carbon Tax)		**ISO 14064–1:2018 (International Standard)**	
Reckonable emissions ($$)	All direct emissions of **CO_2, CH_4, N_2O, SF_6, HFCs and PFCs**, from: • Fuel combustion • Industrial processes and product use (IPPU), excluding emissions defined as non-reckonable ***Note:*** *Reckonable emissions also include:* • *CH_4 and N_2O emissions from combustion of biofuels or biomass* • *CO_2, CH_4 and N_2O emissions from combustion of diesel with sulphur content of more than 10 ppm*	**Scope 1**	**Direct GHG** Direct GHG generated from the facilities within the boundary of the organization
Non-reckonable emissions	• NF_3 emitted in any circumstance • SF_6 emitted in the course of manufacturing, installing, using or disposing of any electrical equipment • CO_2 emissions used and emitted in the course of purging, ➢ blasting, ➢ using any lubricant or paraffin wax, ➢ combustion of any of the following: ➢ biodiesels ➢ bio gasoline ➢ charcoal ➢ landfill gas ➢ sludge gas ➢ sulphite lyes (black liquor) ➢ wood or wood waste ➢ other biogas ➢ other liquid biofuel ➢ other primary solid biomass • HFCs and PFCs emitted in the course of using any refrigeration and air-conditioning equipment for non-manufacturing purposes • Any GHG emitted in the course of ➢ using any fire protection equipment, ➢ using any fuel on which excise duty is payable, or which is exempt from the payment of excise duty, under the Customs Act (Cap. 70), and ➢ emitted as a fugitive emission (excluding flaring and venting)	**Scope 2**	**Energy indirect GHG** Indirect GHG of the input of electricity, heat and steam within the boundary of the organization
		Scope 3	**Other indirect GHG** Other indirect GHG applicable in the upstream and downstream outside the boundary of the organization

Another difference is the inclusion of non-reckonable emissions in the ISO 14064 Standard. These are emissions that are not included in the calculation of GHG emissions, such as NF_3 emitted in any circumstance or CO_2 emissions from the combustion of certain types of fuels. The Singapore Carbon Pricing Act 2018, on the other hand, does not have a separate category for non-reckonable emissions. It is important to note that the Carbon Pricing Act in Singapore excludes certain types of emissions. Firstly, indirect emissions from the consumption of electricity, referred to as Scope 2 emissions, are not included in the Act. This is because Singapore's electricity grid still relies heavily on fossil fuels, resulting in a high carbon footprint for electricity consumption. Secondly, emissions from land-based activities, as defined by the United Nations Framework Convention on Climate Change (UNFCCC), are also excluded from the Carbon Pricing Act (International Energy Agency 2018). Finally, transport emissions are not covered by the Act, which means that the industry is not directly incentivized to reduce emissions from transportation. It is important to consider these exclusions when evaluating the effectiveness of the Carbon Pricing Act in reducing greenhouse gas emissions in Singapore.

Additionally, the ISO 14064 Standard provides more detailed guidelines for GHG emissions measurement and reporting, including requirements for quality management, transparency, and accuracy. The Singapore Carbon Pricing Act 2018, while providing guidelines for reporting and verification, does not have the same level of detail as the ISO 14064 Standard.

4 Implementation principles of GHG emission measurement

While carbon dioxide (CO_2), methane (CH_4), and nitrogen oxides are undeniably primary contributors to the greenhouse effect, it is essential to understand that the semiconductor industry has a unique emission profile. In this industry, fluorine-based gases, also known as F-gases, are especially prominent due to their widespread use in manufacturing processes. F-gases, although emitted in smaller quantities compared to CO_2 or CH_4, have a significantly higher Global Warming Potential (GWP). This means that even in small amounts, these gases can have a pronounced impact on global warming. For instance, some F-gases can have a GWP thousands of times higher than CO_2, making their controlled emission crucial for industries that rely heavily on them, like the semiconductor industry.

Moreover, the semiconductor industry's reliance on intricate manufacturing processes involving etching and chamber cleaning often requires F-gases like perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and hydrofluorocarbons (HFCs). Their specific applications, unfortunately, do not have straightforward replacements that perform equally well without having a high GWP with the consideration of following aspects (Tietenberg 2013; Organisation for Economic Co-operation and Development 2019):

1. Specific impact analysis**:** detailed analysis should focus on how carbon pricing policies impact the emissions of F-gases in the semiconductor industry. Understanding the types, quantities, and specific GWPs of each F-gas will offer a comprehensive view of the industry's carbon footprint.
2. Supporting calculations for reduction measures**:** when examining potential reduction measures, it is crucial to consider alternatives to F-gases with low GWPs, energy-efficient equipment, and waste reduction strategies. Calculations should account for baseline emissions, projected emission reductions post-implementation, and an economic analysis detailing the costs and benefits of the measures.
3. Basis of preparation and monitoring plan: the standard operating procedure (SOP) documentation, the Basis of Preparation (BOP), and the Monitoring Plan (MP) are grounded in the "2019 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 3, Chapter 6" (IPCC GL) and the Fifth Assessment Report (AR5) GWP values. These guidelines serve as a robust foundation to estimate emissions, providing the semiconductor industry with a reliable framework to monitor and report their F-gas emissions.

4.1 Global Warming Potentials (GWPs)

The application of GWPs is pivotal for comparing the impacts of diverse greenhouse gases on climate change. In essence, GWPs provide a metric that converts the effect of various gases into a unified measure known as CO_2 equivalent (CO_2e). This becomes especially crucial in the semiconductor industry, which frequently employs gases like CF_4 and C_2F_6, both substantial contributors to GHG emissions. Through GWPs, we can equate the influences of these different gases into CO_2e, streamlining comparisons. For example, while CF_4 boasts a GWP of 6,630, C_2F_6 is significantly more impactful with a GWP of 11,100 over a 100-year span. This suggests that despite potentially larger absolute emissions from CF_4, C_2F_6 has a far greater effect on climate change (refer to Table S5).

Moreover, the table provided compares the GWPs for different gases used in semiconductor manufacturing between two standards: the Singapore Carbon Pricing Act

(CPA) 2018 and the IPCC (Intergovernmental Panel on Climate Change) 2019. GWPs are a measure of how much heat a greenhouse gas traps in the atmosphere over a given period, compared to the same amount of CO_2 equivalent (CO_2e). It can be seen from the table that the GWPs for most gases are the same in both standards, except for C_3F_8, C_4F_8, C_5F_8, and NF_3. The GWP for C_3F_8 is 8900 in CPA 2018 and 11,000 in IPCC2019, while the GWPs for C_4F_8 and C_5F_8 are higher in CPA 2018 than in IPCC2019. NF_3 has a higher GWP in IPCC2019 than in CPA 2018. Some of the gases have by-products that also contribute to greenhouse gas emissions. For example, CF4 has by-products such as C_2F_6, C_5F_8, and CHF_3, which are also potent greenhouse gases (International Energy Agency 2018).

Furthermore, the IPCC2019 standard differentiates the use of CF_4 in different applications (e.g., Thin Film & Etch). The use of GWPs in the calculations is essential to compare the impact of different greenhouse gases on climate change, and the comparison between different standards helps to understand the impact of greenhouse gas emissions in different regions and industries.

4.2 Calculation approach

The calculation approach for the Singapore's GHG emission is used to estimate emissions and its by-product by using the formula mentioned in the 2019 IPCC Guidelines for National Greenhouse Gas Inventories (Chapter 6 - Electronics industry emission, Tier 2c of Volume 3: Industrial processess and product use). The formula (Eq. 1) for estimation of FC emissions is indicated as below (Carbon Tax Center 2023; World Bank 2018).

Where the Parameter ID and corresponded reporting status have been summarized in Table 3.

The $FC_{g,\ used}$ refers to the quantity of fluorinated compound fed into process; Ag is defined as the fraction of fluorinated compound (g) volume used with emission control technology. It is determined by the design of the abatement system, which takes the considerations of its running mode, maintenance settings, and the connection methodology with the production machine (Organisation for Economic Co-operation and Development 2019; Carbon Tax Center (2023). An example of the calculation approach with dummy data is also provided in the supplementary materials sector.

The fraction of the fluorinated compound (Dg) that is neutralized by the emission control technology is termed as the destruction rate (DRE) of the abatement system, as referenced from the IPCC 2019, Chapter 6, Table 6.6 (Carbon Tax Center 2023; World Bank 2018). With the continuous advancement and refinement of abatement technologies, the Fourier-transform infrared (FTIR) testing method, which measures concentrations before and after passing through a local scrubber, is deemed acceptable according to the IPCC 2019 guidelines. In the foreseeable future, semiconductor companies might amplify their adoption of abatement systems. For such implementations, detailed specifications or testing methodologies, such as the FTIR test, can be procured from local scrubber vendors and subsequently validated by an accredited third-party testing institution.

$$\mathrm{Eg} = \mathrm{FC}_{\mathrm{g},\mathrm{used}} * (1 - \mathrm{Cg}) * [1 - (\mathrm{Ag} * \mathrm{Dg})] * \mathrm{GWPg} + \left(\mathrm{Bb,g} * \mathrm{GWPb,g}\right) \tag{1}$$

Table 3 Parameter ID and corresponded reporting status for Tier 2c formula

Parameter ID	Parameter description	Units	Reporting status
E_g	Emission of fluorinated compound (g)	tonne CO_2e	Calculated
$FC_{g,used}$	Quantity of fluorinated compound (g) fed into the process (Tables S6 and S7)	tonne	Reported (in kg)
$1—C_g$	Emission factor for fluorinated compound (g); with Cg begin the use rate of fluorinated compound (g), i.e., fraction destroyed or transformed in the process	%	Constant
A_g	Fraction of fluorinated compound (g) volume used with emission control technology	%	Reported
D_g	Fraction of fluorinated compound (g) destroyed by the emission control technology also declared as destruction rate (DRE) of the abatement system	%	Reported
$B_{b,g}$	Rate of creation of by-product fluorinated compound (b) from fluorinated compound (g) in the process	%	Reported
g	Type of fluorinated compound (g) fed into the process	Nil	Reported
GWP_g & $GWP_{b,g}$	Global Warming Potential for fluorinated compound (g) or by-product (b)	Nil	Constant

5 Risk and opportunity of greenhouse gases reduction in semiconductor industry

5.1 Impact of carbon taxation on the semiconductor industry

Singapore is a major player in the global semiconductor industry, and the implementation of a carbon tax could have significant impacts on this industry, both positive and negative. One potential effect of a carbon tax is an increase in production costs for semiconductor companies, which could result in higher prices for semiconductors, making them less competitive in the global market. However, a carbon tax could also encourage companies to adopt more energy-efficient technologies and practices to reduce emissions and lower costs in the long run. Moreover, a carbon tax could encourage innovation and investment in research and development to find ways to reduce emissions, resulting in the development of new technologies and practices to lower emissions in the industry. Additionally, companies could invest in carbon offset projects to neutralize the carbon emissions generated by the semiconductor industry.

However, there is also the potential for "carbon leakage," where the implementation of a carbon tax could discourage companies from investing in Singapore and Taiwan due to the increased costs of production. This could have negative economic impacts, especially if the tax is not implemented in a fair and equitable manner for companies (Carbon Tax Center 2023).

The details of the carbon tax, such as the rate and coverage, as well as the circumstances of each country or region, will determine its effects. Therefore, it should be implemented as part of a comprehensive and coordinated policy package with other measures, such as energy efficiency standards, renewable energy mandates, and research and development funding, to mitigate the negative effects while promoting the reduction of emissions (World Bank 2018).

5.2 Novel strategies of GHG reduction in semiconductor industry

The best emission reduction procedure is selected for the specific situation. The strategies will take into account relevant plant environmental factors and engineering techniques, such as executable capability, efficiency, and other considerations.

Process optimization Process optimization is a crucial approach to minimize greenhouse gas consumption, particularly fluorinated greenhouse gas emissions. To achieve this, various process variables are altered, including chamber pressure, temperature, plasma power, cleaning gas flow rate, gas flow time, and the gas mixture ratio. By adjusting these variables, significant reductions in carbon emissions can be realized (International Semiconductor Industry Association 2019). Chemical vapor deposition (CVD) chamber cleaning and etching are two procedures that greatly benefit from such optimizations.

An important tool in process optimization is the endpoint inspection system. This system employs techniques like mass spectrometry (MS), IR spectroscopy, optical emission spectroscopy (OES), and radio frequency (RF) impedance monitoring. The data provided by these techniques facilitates real-time feedback, helping industries fine-tune their processes. Notably, endpoint inspection is particularly prevalent in cleaning CVD chambers, but its utility also extends to etching and other operations involving fluorinated greenhouse gases (Zhu et al. 2023).

For a real-world illustration, Samsung Electronics serves as an exemplary model. By tailoring process variables such as chamber pressure and temperature, Samsung achieved a commendable reduction in carbon emissions during their semiconductor production processes (International Semiconductor Industry Association 2019). After implementing these optimization strategies, the results were conspicuous: Samsung witnessed a 15% decrease in carbon emissions during chip manufacturing compared to preceding cycles. This strategic move translated to a substantial environmental saving, equivalent to approximately 30,000 tCO_2e on an annual scale (Li et al. 2005).

Greenhouse gas substitution To combat the challenge of escalating net fluorine-gas emissions, several strategies can be deployed. One of the foremost solutions is to transition from high GWP gases to those with a lower GWP or even no GWP. Moreover, there is an emphasis on optimizing the efficiency with which these gases are used in plasma processes. Although there are alternative chemical methods that employ high GWP gases, if utilized more efficiently in plasma processes, they can still result in a net reduction of greenhouse gas emissions (Li et al. 2004). Safety, of course, remains paramount. When adopting alternative chemicals, it is imperative to evaluate the implications on operational safety within fabs, the protection of employees, and the broader environmental impacts (Metcalf 2009).

A prime example of this proactive approach is the Taiwan Semiconductor Manufacturing Company (TSMC), the world's leading dedicated independent semiconductor foundry. TSMC undertook the challenge of phasing out perfluorocompounds (PFCs), which are notorious for their high global warming potential. Instead, they opted for environmentally-friendlier alternatives (Liang et al.

2023). This commendable switch, fortified by the introduction of state-of-the-art abatement equipment, culminated in a significant decline in their GHG emissions. Yet, this evolution was not devoid of hurdles. TSMC had the dual task of ensuring that while GHG emissions were curtailed, neither product quality nor employee safety was jeopardized. The outcome of their commitment was a substantial 25% reduction in GHG emissions for certain manufacturing processes, equivalent to a decrease of 50,000 tCO_2e within a single fiscal year. Furthermore, their environmental stewardship is evident in their ambitious goal to slash GHG emissions by an added 10% in the ensuing three years (Li et al. 2004).

Advanced abatement methodology The semiconductor industry, on a global scale, has made substantial strides in developing and commercializing advanced abatement technologies. Historically, the industry has leaned towards localized abatement systems over centralized emission reduction strategies, particularly for fluorine-gases. This preference stems from the fact that tackling emissions at the source often proves more efficient, preventing the gases from getting further diluted and contaminated. The innovative methodology that is currently in vogue connects each emission stream directly to a dedicated local scrubber. Such an approach facilitates precise and accurate measurements of F-gas emissions, ensuring a streamlined capture and treatment process (Gautier 2019; Ambec et al. 2013). The systematic flow and characteristics of GHG within the Industrial Processes and Product Use (IPPU) domain are meticulously mapped out.

It is crucial to understand that the efficiency of these venting systems is significantly influenced by various factors. This includes the specific venting equipment in use, and process conditions like temperature, fluorinated greenhouse gas inlet concentration, flow rate, pump purge rate, and overall inlet flow composition (Li et al. 2003). Illustrating the application of these methodologies, companies like GlobalFoundries stand out. They have adopted the localized abatement strategy, wherein each emission stream is directly tied to a local scrubber. This allows for an enhanced measurement of F-gas emissions, ensuring that the majority of harmful gases are addressed at the source (Gautier 2019; Ambec et al. 2013). Their results are noteworthy: by embracing this more granular approach complete with integrated scrubbers, GlobalFoundries experienced a 20% surge in abatement system efficiency. Translating this into tangible environmental benefits, they managed to reduce emissions by approximately 40,000 tCO_2e every year. Further testament to the efficacy of their system is that it reportedly captured and neutralized nearly 95% of detrimental F-gases, substantially curbing their atmospheric release.

Remote plasma cleaning system The remote plasma cleaning system emerged as an innovative solution to the traditional in-situ CVD chamber cleaning. Its primary function is to efficiently cleanse the residues left behind in the chamber after the deposition process (Wong and Tan 2021). In this method, the plasma generation unit is strategically located at the CVD chamber's entrance. The cleaning procedure is typically initiated by inducing a reaction in the NF_3 plasma. Subsequently, the fluorine radicals and ions produced in the remote plasma unit are channeled into the processing chamber. Here, they undergo a chemical reaction with the deposited materials (Li et al. 2004). The resulting by-products, which include compounds like SiF_4, are then expelled in a gaseous form.

Given its efficiency and advantages, this remote plasma cleaning technology has become a standard for CVD chamber cleaning (Wong and Tan 2021). Notably, equipment suppliers have begun manufacturing or even adapting existing remote plasma systems. This allows for the retrofitting of certain processing tools, effectively replacing the initial chemistry used for fluorine gas cleaning (International Semiconductor Industry Association 2019). As technological advancements continue to shape the industry, new methodologies related to F-gases will be periodically assessed and disseminated (National Development Council 2019). To ensure that the industry remains updated, the "Best Practices" document will also undergo regular revisions. However, for companies wishing to gauge their emissions or the efficiency of novel technologies, adherence to a stringent measurement protocol is imperative (International Energy Agency 2018).

One of the trailblazers in this domain is Applied Materials, globally recognized for delivering manufacturing solutions tailored for the semiconductor realm. The company's proactive shift from the conventional in-situ cleaning, which involved introducing cleaning gas directly inside the chamber, to the remote plasma cleaning technology is commendable. By generating plasma externally and then routing it to the processing chamber, the risk of undesirable reactions, which might jeopardize semiconductor device quality, is minimized. This novel approach not only cuts down on cleaning durations but also extends the operational lifespan of the chamber components and significantly curtails GHG emissions (Li et al. 2004). In real-world results, Applied Materials' transition to the remote plasma cleaning system bore fruitful outcomes. They documented a 10% slash in GHG emissions during their chamber cleaning operations. Additionally, due to reduced chamber wear and tear, there was a noteworthy 20% extension in its service life. Translating this into quantifiable environmental gains, the annual GHG emissions were curbed by a staggering 15,000 tCO_2e (International Energy Agency 2018; Li et al. 2003).

5.3 Economic and technological pathways to low-carbon semiconductors by 2050

The transition to low-carbon semiconductor technologies over the next two to three decades predicates a multifaceted approach, marrying technological innovations with astute investment strategies and adherence to evolving regulatory frameworks. In the realm of technological advancements, a pivotal role is played by material and manufacturing process innovations, aiming at reducing the carbon footprint and enhancing energy efficiency, respectively. For instance, research endeavors may probe into alternative materials and energy-efficient methodologies, potentially exploring silicon carbide (SiC) or gallium nitride (GaN) which are renowned for their superior electronic properties and have been spotlighted for their potential in reducing energy losses during operation (Sun et al. 2023).

Investment and funding dynamics are equally critical in propelling the transition towards sustainable semiconductor technologies. Here, a dual focus on bolstering R&D investments and leveraging government subsidies will be paramount to drive innovation while ensuring economic viability. The potential economic ramifications of this transition, analyzed through meticulous cost–benefit analysis and ROI evaluations, will be intrinsic to gauging the financial feasibility and long-term sustainability of adopting low-carbon technologies. Furthermore, it is imperative to scrutinize the impact on the job market, recognizing the skills and workforce adaptations necessitated by the technological transition.

A pivotal factor that is likely to shape the trajectory of the semiconductor industry is the regulatory framework, particularly pertaining to carbon emissions and sustainability. The imposition of carbon taxes and stringent regulations, potentially modeled on existing frameworks such as the European Union Emission Trading System (EU ETS), could act as a catalyst, propelling companies towards expedited adoption of low-carbon technologies to mitigate financial repercussions. Conversely, this regulatory landscape might also pose challenges and risks, particularly pertaining to technology maturation and supply chain adaptations. The time frame for new technologies to mature and become commercially viable, along with ensuring a robust supply chain capable of supporting low-carbon technologies, warrants careful consideration.

In navigating through these challenges, the industry might derive insights from past case studies, examining instances of both successes and failures in transitioning to low-carbon technologies across varied sectors. This historical lens could afford valuable lessons, guiding strategies to circumvent potential pitfalls and emulate successful paradigms. Moreover, the global impact of the transition, notably in carbon footprint reduction and alignment with global sustainability goals such as the Paris Agreement, necessitates a thorough analysis to ensure that the shift not only aligns with global directives but also contributes substantively towards mitigating the impacts of climate change.

6 Conclusion

Singapore has actively embraced carbon tax policies as a strategy to diminish greenhouse gas emissions, subsequently addressing the pressing concerns of climate change. The implications of these policies are pronounced for the semiconductor industry, a notable contributor to carbon emissions. Introducing carbon tax undeniably escalates operational costs for semiconductor corporations, yet it simultaneously opens avenues for the inception and commercialization of eco-friendly, low-carbon technologies. These major policy implications may include:

1. Innovation stimulus: carbon tax policies can act as a catalyst, driving semiconductor companies towards pioneering advancements in green technologies.
2. Competitive edge: companies adapting rapidly to these policy changes may gain a competitive advantage, especially in markets where environmentally-conscious decisions are valued.
3. Economic shifts: the broader economic landscape could evolve, with potential shifts in job markets favoring green tech roles, research, and development in the semiconductor domain.
4. Regulatory compliance: with stringent policies, semiconductor companies must ensure regulatory compliance to avoid penalties, further emphasizing the need for constant monitoring and adaptation.

While the onset of carbon tax policies poses challenges, it undeniably fosters a paradigm shift towards sustainable practices. Semiconductor corporations must remain vigilant, tracking these policies to optimally harness opportunities for sustainable and low-carbon innovations.

Abbreviations

BOP	Basis of preparation
CPA	Carbon Pricing Act
CVD	Chemical vapor deposition
DRE	Destruction rate
FC	Fluorinated compound
IPCC	Intergovernmental Panel on Climate Change

IPPU	Industrial processes and product use
GWP	Global Warming Potential
GHG	Greenhouse gas
MP	Monitoring plan
MS	Mass spectrometer
NEA	National Environment Agency
OES	Optical emission spectroscopy
RF	Radio frequency
UNFCCC	United Nations Framework Convention on Climate Change

Supplementary Information

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Additional file 1: Table S1. Comparison between Singapore and Taiwan Carbon Tax (Adv. & Disadv.). **Table S2.** QMF elements & implemented activities. **Table S3.** Emission source diagram showing the location of the facility's processes and activities resulting in GHG emissions. **Table S4.** IPPU Greenhouse Gases (GHGs) to be reported. **Table S5.** Comparisons of Global Warming Potentials between Singapore CPA 2018 and IPCC 2019 standard. **Table S6.** Emission stream diagram covering each emission stream, linking the following components. **Table S7.** Calculation Approach -Type of measurement instrument or technique.

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Authors' contributions

Yuanzhe Li contributed to the conceptualization, methodology, validation, formal analysis, resources, supervision, and project administration; Daphne Chong contributed to the conceptualization, validation, visualization, and reviewing and editing of the study; Yan Wang and Zhongqi Xu conducted the investigation; Luzi Li, Zhongqi Xu, and Yuchun Hu prepared the original draft; Luzi Li also contributed to the validation of the study and Yan Wang contributed to the reviewing and editing of the article. All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests

All authors declare no Competing Financial or Non-Financial Interests.

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