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Wen Tien Tsai * and Chi Hung Tsai

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A Survey on Fluorinated Greenhouse Gases in Taiwan: Emission Trends, Regulatory Strategies, and Abatement Technologies

Wen-Tien Tsai [1,*] and Chi-Hung Tsai [2]

[1] Graduate Institute of Bioresources, National Pingtung University of Science and Technology, Pingtung 912, Taiwan; wttsai@mail.npust.edu.tw
[2] Department of Resources Engineering, National Cheng Kung University, Tainan 701, Taiwan; ap29fp@gmail.com
* Correspondence: wttsai@mail.npust.edu.tw; Tel.: +886-8-7703202

Abstract: Due to their excellent physicochemical properties, fluorinated greenhouse gases (F-gases), including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3), are used in a variety of applications, but they are potent greenhouse gases. Therefore, they have been blanketed into the list of phase-out under the international protocols or treaties. In this work, the updated statistics of the Taiwan's national inventory report (NIR) were used to analyze the trends of F-gases (i.e., HFCs, PFCs, SF_6 and NF_3) emissions during the period of 2000-2020. Furthermore, the regulatory strategies and measures for reducing the emissions of the four F-gases will be summarized to be in accordance with the national and international regulations. With the progressive efforts by the regulatory requirements and the industry's voluntary reduction, the total F-gases emissions indicated a significant increase from 2,462 kilotons of carbon dioxide equivalents (CO_{2eq}) in 2000 to the peak value (i.e., 12,643 kilotons) of CO_{2eq} in 2004, but sharply decreased from 10,284 kilotons of CO_{2eq} in 2005 to 3,906 kilotons of CO_{2eq} in 2020. It was also found that the most commonly used method for controlling the emissions of F-gases from the semiconductor and optoelectronic industries was based on the thermal destruction-local scrubbing technology.

Keywords: fluorinated greenhouse gas; emission trend analysis; regulatory policy; abatement technology

1. Introduction

Certain gases are called as greenhouse gases (GHGs) due to their abilities to absorb infrared (IR) radiation and bring out temperature enhancement in the lower (tropospheric) atmosphere, leading to the heating of the surface on earth. Naturally, the major GHGs include water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3) [1]. Although chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) were phased out under the Montreal Protocol on Substances that Deplete the Ozone Layer [2], the roaring emissions of these synthetically chemical alternatives, including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6) and nitrogen trifluoride (NF_3), were observed since the 1990s to be consistent with the enhancement of global warming or greenhouse effect due to their highly radioactively active features [3]. More importantly, the temperature rise of 1.5℃ on earth could be negatively affected on climate system and ecosystem, causing extreme weather events, shifting wildlife populations and habitats, rising sea level, and disease/epidemic risks increased [4].

To mitigate the emissions of GHGs from anthropogenic activities, the third session (COP3) of the United Nations Framework Convention on Climate Change (UNFCCC) was held in Kyoto in December 1997, where HFCs, PFCs and SF_6 were included into the basket of the major GHGs for negotiation based on their high global warming potential (GWP), often several thousand times stronger than CO_2. Furthermore, NF_3 was also mandated to be included in national inventory report (NIR) in the eighteenth session (COP18) of the UNFCCC (held in Dec. 2012) [5]. These fluorinated GHGs (F-gases) are man-made gases which were mostly used as industrial and commercial products like refrigerant, etchant, blowing agent and cleaning solvent [5-8]. To further reduce the emissions of F-gases, the Kigali Amendment, which signed on 15 October 2016 and entered into force on 1 January 2019 [9, 10], added HFCs to the list of controlled substances under the Montreal Protocol. For the developed countries, they are committed to reducing the use of HFCs by 45% by 2024 and by 85% by 2036, compared to their use between 2011 and 2013. On the other hand, the European Union (EU) has promulgated the new F-gases regulation, which applied since 1 January 2015 for replacing its original regulation adopted in 2006 [5, 7, 11]. The current regulation focused on limiting the total amounts of the most used F-gases (i.e., HFCs) sold, using low global warming potential (GWP) alternatives, and banning the use of F-gases in many new types of equipment.

In response to the international regulations and protocols, the Taiwan government has taken initiatives to prepare the national GHG inventory reports since 1998 in accordance with the guidelines of the Intergovernmental Panel on Climate Change (IPCC). Currently, the statistical data on national GHGs emissions has been established by ranging the period from 1990 to 2020 [12]. Table 1 summarized the main environmental properties (i.e., atmospheric lifetime, radiative efficiency and global warming potential) of fluorinated greenhouse gases (F-gases) [3], which were mainly used in a variety of Taiwan's industries [13]. Herein, radiative efficiency is a measure of greenhouse strength based on the change in radiative forcing per change in atmospheric concentration of a gas (Watts per meter square per part per billion, $Wm^{-2}ppb^{-1}$). Global warming potential (GWP) is defined as a comparative measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time (e.g., 100 years), relative to the emissions of 1 ton of carbon dioxide (CO_2). According to the data in atmospheric lifetime, most of F-gases are long-lived GHGs, especially in PFCs, SF_6, NF_3, and few of HFCs like HFC-23. On the other hand, the regulatory establishment may be the most important and efficient tool for mitigating GHGs emission. In this regard, the central competent agency (i.e., Environmental Protection Administration, also abbreviated as EPA) promulgated the regulations governing the climate change issues [14]. These regulations included the Air Pollution Control Act, the Climate Change Response Act of 2023 (the former act called Greenhouse Gas Reduction and Management Act), and the Waste Management Act. The relevant central government agencies also promoted GHGs emission reduction. For example, the Ministry of Economic Affairs (MOEA) promulgated the ban on the domestic production of HCFC-22 ($CHClF_2$, one of refrigerants), thus reducing the production of HFC-23 (CHF_3, a by-product in the HCFC-22 manufacturing process) [15]. In addition, the Taiwan government announced "*Taiwan's Pathway to Net-Zero Emissions in 2050*" on 30 March 2022 [16], which will put emphasis on the climate-related legislations as a fundamental base.

Based on the survey by the database like Web of Science, few works on the description about the emission trends and regulatory measures of F-gases in Taiwan were discussed in the literature [17-23]. Cheng et al. [23] studies SF_6 usage and emission factors reflecting common thin film transistor - liquid crystal display (TFT-LCD) manufacturing practices in Taiwan. Chen and Hu [22] discussed the voluntary F-gases reduction agreement of the semiconductor and LCD industries in Taiwan, showing over 50% reduction rates for the two industries. In the previous studies [17-21], they focused on the environmental risks and policies of HFCs, PFCs and NF_3. In this work, it analyzed the trends of F-gases (i.e., HFCs, PFCs, SF_6 and NF_3) emissions during the period of 2000-2020 by using the updated Taiwan's NIR. Furthermore, the regulatory strategies and measures for reducing the emissions of the four F-gases will be summarized to be in accordance with the international protocols. Finally, the current abatement technologies for controlling the emissions of F-gases were surveyed by the Taiwan's industry alliances like semiconductor association and TFT-LCD association.

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Table 1. Environmental properties of fluorinated greenhouse gases (F-gases) mainly used in Taiwan [1].

F-GHGs	Formula	Atmospheric lifetime (year)	Radiative efficiency (W/(m²·ppb))	GWP [2]	Main applications [3]
HFCs					
HFC-23	CHF_3	228	0.191	14,600	Etching gas
HFC-32	CH_2F_2	5.4	0.111	771	Refrigerant, Etching gas
HFC-41	CH_3F	2.8	0.025	135	Etching gas
HFC-125	CHF_2CF_3	30	0.234	3,740	Refrigerant
HFC-134	CHF_2CHF_2	10	0.194	1.260	Refrigerant
HFC-134a	CH_2FCF_3	14	0.167	1,530	Refrigerant, aerosol propellant
HFC-143	CH_2FCHF_2	3.6	0.128	364	Refrigerant
HFC-143a	CH_3CF_3	51	0.168	5,810	Refrigerant
HFC-152a	CH_3CHF_2	1.6	0.102	164	Blowing agent, aerosol propellant
HFC-227ea	CF_3CHFCF_3	36	0.273	3,600	Extinguishing agent
HFC-236fa	$CF_3CH_2CF_3$	213	0.251	8,690	Extinguishing agent
HFC-245fa	$CHF_2CH_2CF_3$	7.9	0.245	962	Refrigerant
HFC-365mfc	$CH_3CF_2CH_2CF_3$	8.9	0.228	914	Cleaning solvent, Blowing agent
HFC-43-10mee	$CF_3CHFCHFCF_2CF_3$	17	0.357	1,600	Cleaning solvent
PFCs					
PFC-14	CF_4	50,000	0.099	7,380	Etching gas
PFC-116	C_2F_6	10,000	0.261	12,400	Etching gas
PFC-218	C_3F_8	2,600	0.27	9,290	Etching gas
PFC-c-318	cyc (-$CF_2CF_2CF_2CF_2$-)	3,200	0.314	10,200	Etching gas
PFC-31-10	n-C_4F_{10}	2,600	0.369	10,000	Etching gas
Sulfur hexafluoride	SF_6	1,000	0.567	24,300	Insulating gas, Etching gas
Nitrogen trifluoride	NF_3	569	0.204	17,400	Etching gas

[1] Source [3]. [2] Global warming potential (GWP) for 100-year time horizon. [3] Based on the imported statistics in recent years [13].

2. Data Mining Methods

In this study, an analytical description about the trends of F-gases (i.e., HFCs, PFCs, SF_6 and NF_3) emissions during the period of 2000-2020 was addressed by using the updated Taiwan's NIR [12], which was announced by the central competent agency (i.e., EPA) in August 2022. It should be noted that the data on Taiwan' NIR was obtained on the basis of the proposed method by the IPCC in 2006 [24]. The database can be freely accessed on the official website without permission. The regulatory strategies and measures for reducing the emissions of the four F-gases were extracted from the relevant regulations. They included the Air Pollution Control Act, the Climate Change Response Act, and the Waste management, which were accessed on the official website [25]. Concerning the current abatement technologies for controlling the emissions of F-gases, they were surveyed by the Taiwan's industry alliances [26, 27] and the corporate social responsibility (CSR) report of the Taiwan's index enterprise [28].

3. Results and discussion

3.1. Analysis of fluorinated greenhouse gases emissions in Taiwan

In Taiwan, the majority of F-gases emissions come from the industrial process and product use (IPPU) sector, which include chemical industry (2B:), metal (aluminum) process (2C), electronics (manufacturings of semiconductor and optoelectronics) industry (2E), alternatives to ozone-depleting substances (2F), manufacturing and use of other products (2G). In addition, most of HFCs substances were used as refrigerant and blowing agent in the energy sector, including service, residential and transport industries. As listed in Table 1, the main applications of these F-gases were used as etching gas, refrigerant, cleaning solvent, blowing agent and extinguishing agent. For the emission trends of the four F-gases, Table 2 and Table 3 listed the individual emissions and total emissions from IPPU sector during the period of 2000-2020, respectively [12]. The corresponding percentage variations on F-gases emissions and their total emissions from IPPU sector every four years were depicted in Figure 1 and Figure 2, respectively [12]. For the total emission of F-gases, it showed significant increasing trend from 2,462 kilotons of carbon dioxide equivalents (CO_{2eq}) in 2000 to the peak value (i.e., 12,643 kilotons) of CO_{2eq} in 2004. Subsequently, it decreased from 10,284 kilotons of CO_{2eq} in 2005 (about 3.54% of the total GHG emissions in 2005) to 3,906 kilotons of CO_{2eq} in 2020 (about 1.37% of the total GHG emissions in 2020), down by 69.1% compared to that in 2004. The following subsections were addressed to highlight the emission trends of individual F-gases.

3.1.1. Hydrofluorocarbons (HFCs)

In general, HFCs with containing one carbon atom (i.e., HFC-23, HFC-32, and HFC-41) were mostly used as etching gas in the semiconductor manufacturing and TFT-LCD industries. In contrast, HFCs with containing two carbon atoms (i.e., HFC-125, HFC-134, HFC-134a, HFC-143 and HFC-143a) were often used as refrigerants in the air-conditioning appliances of residences and vehicles. As indicated in Table 1, HFC-32 was also used as a refrigerant because of its low GWP (i.e., 771). For example, the commercial refrigerant R410A is a mixture of HFC-125 (50%) and HFC-32 (50%). Another commercial refrigerant R407C is a mixture of HFC-125 (25%), HFC-134a (52%) and HFC-32 (23%). Obviously, Table 2 showed the two different stages of HCFs emissions in Taiwan. During the period of 2000-2004, the total HFCs emissions approximately ranged from 2,200 to 2,600 kilotons of CO_{2eq}. However, the total HFCs emissions were approximate to 1,000 kilotons of CO_{2eq} since 2005. To be in accordance with the Montreal Protocol, the Taiwan government promulgated the ban on the production of refrigerant HCFC-22 since 2005, which was only produced by a chemical company. During the manufacture of HCFC-22, a by-product HFC-23 will be generated and emitted from the process. Its emission was obtained by multiplying HCFC-22 production amount with its default emission factor (i.e., 1.4%). As seen in Table 3, the emission amounts of F-gases from the 2B source were null since 2005. Since then, the total F-gases (i.e., HFCs) emission amounts maintained a stable trend because the emission source was mainly derived from the 2F industry. The emission amounts of HFCs refrigerants were estimated by leakage rates proposed by the IPCC method [24]. Regarding the emission amounts of HFCs for other uses (i.e., blowing agent, cleaning solvent, extinguishing agent and aerosol propellant), they were estimated by their imported amounts, but only accounted for less amounts. Concerning the data on the percentages of HFCs (Figure 2), they were 94.2% in 2000, 19.4% in 2004, 17.1% in 2008, 21.2% in 2012, 23.6% in 2016, and 27.0% in 2020.

3.1.2. Perfluorocarbons (PFCs)

PFCs are known for their rather stable properties because of the strength of the carbon-fluorine bond, leading to their industrial applications in the cleaning of dry etch and chemical vapor deposition (CVD) processes. Therefore, the main emission sources of PFCs are from the semiconductor manufacturing and TFT-LCD industries in Taiwan. As listed in Table 1, these PFCs substances, including PFC-14 (CF_4), PFC-116 (C_2F_6), PFC-218 (C_3F_8) and PFC-c-318 (C_4F_8, octafluorocyclobutane), are potent GHGs due to their long atmospheric lifetimes and high GWP values. The total emissions of PFCs in Taiwan indicated a decreasing trend over the past two decades. Table 2 showed a decline rate of about 75% (i.e., 4,341 kilotons of CO_{2eq} in 2004 vs. 1,447 kilotons of CO_{2eq} in 2020). It can be also seen that the total emissions of PFCs increased significantly from 13 kilotons of CO_{2eq} in 2000 to 4,198 kilotons of CO_{2eq} in 2003. These variations were attributed to the mass production of the Taiwan's electronic industries during the early 2000s and subsequently take actions on the voluntary PFCs reduction technologies like de-PFCs/local scrubber and

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alternatives with low GWP. Also shown in Figure 1, the proportions of PFCs emission accounted for about one-third of the total F-gases emissions since 2004.

3.1.3. Sulfur hexafluoride (SF_6)

In general, the main emission sources of SF_6 include the electrical power, semiconductor manufacturing, TFT-LCD and magnesium production industries. Due to its high inertness and unique dielectric properties, it has been used as a dielectric medium in electric power systems, a silicon etchant for wafer manufacturing, and an inert gas for the casting of magnesium. Based on the data in Table 2 and Figure 1, the trends of total SF_6 emissions were very similar to those of total PFCs emissions because the voluntary SF_6 emission reduction actions have been also taken by the industrial sector. It showed a decline rate of over 80% since 2004 (i.e., 5,193 kilotons of CO_{2eq} in 2004 vs. 842 kilotons of CO_{2eq} in 2020). It should be noted that the emission source of SF_6 from magnesium production in Taiwan can be negligible due to the limited domestic production since the mid-2000s. As seen in Table 3, the emission amounts of the F-gases from the chemical industry (2C) indicated a gradual decline since 2006 because of magnesium production moved out and SF_6 reduction by process change. In addition, the total SF_6 emission amounts also showed a decreasing trend due to the recovery/recycling technologies widely adopted by the electrical power industry (2G). Using the data on the total F-gases emissions, the proportions of SF_6 emission (Figure 2) also showed a significant increase from 4.9% in 2000 to 46.4% in 2008, but they were decreased subsequently to 21.5% in 2020.

3.1.4. Nitrogen trifluoride (NF_3)

It is well known that nitrogen trifluoride (NF_3) is primarily used to remove silicon particles and silicon-containing compounds during the manufacturing of semiconductor devices like flat-panel displays, photovoltaics, light-emitting diodes (LEDs). Although its atmospheric lifetime (i.e., 569 years) is much smaller than other PFCs (2,600-50,000 years) and SF_6 (1,000 years), it is a potent GHG with high GWP (i.e., 17,400) and the mass consumption in the semiconductor manufacturing and TFT-LCD industries since the early 2000s, thus grouping with effect from 2013 and the commencement of the second commitment period of the Kyoto Protocol [5, 29]. Just like the increasing trends of PFCs and SF_6 emissions, the total emissions of NF_3 increased significantly from 10 kilotons of CO_{2eq} in 2000 to 798 kilotons of CO_{2eq} in 2007. Thereafter, the total emissions of NF_3 indicated a jagged pattern, ranging from 200 to 800 kilotons of CO_{2eq} during the period of 2007-2020. Herein, the sharp decline of the total NF_3 emission (i.e., 204 kilotons of CO_{2eq}) in 2008 should be attributed to the 2008 economic recession around the world. On the other hand, the percentages of the total SF_6 emission amounts compared to the total F-gases emission amounts (Figure 2) indicated a rising trend; that is, 0.4% in 2000, 3.2% in 2004, 3.2% in 2008, 9.0% in 2012, 10.8% in 2016, and 14.4% in 2020.

Table 2. Total emissions of fluorinated greenhouse gases since 2000 in Taiwan. [1.]

Year	HFCs	PFCs	SF_6	NF_3	Total
2000	2,319	13	120	10	2,462
2001	2,619	2,939	746	235	6,538
2002	2,216	4,143	3,914	398	10,671
2003	2,397	4,198	4,385	540	11,520
2004	2,451	4,341	5,193	659	12,643
2005	1,098	3,470	4,951	765	10,284
2006	1,015	3,664	3,858	688	9,225
2007	1,122	3,372	3,381	798	8,673
2008	1,074	2,082	2,912	204	6,273
2009	1,081	1,560	2,452	577	5,607
2010	971	1,770	2,218	258	5,217

2011	1,053	1,781	1,918	420	5,172
2012	907	1,141	1,852	388	4,288
2013	1,019	1,345	1,997	773	5,134
2014	1,048	1,556	1,730	667	5,001
2015	1,020	1,347	1,523	662	4,552
2016	1,026	1,441	1,418	472	4,356
2017	1,023	1,409	1,416	440	4,298
2018	1,013	1,536	1,302	509	4,360
2019	1,027	1,420	935	473	3,855
2020	1,053	1,447	842	564	3,906

[1] Source [12]; unit: kilotons of CO_{2eq}.

Table 3. Total emissions of fluorinated GHGs (F-gases) from IPPU sector since 2000 in Taiwan. [1.]

Year	Emission source [2]					Total
	2 B	2 C	2 E	2 F	2 G	
2000	2,319	0	143	0	0	2,462
2001	2,567	0	3,971	0	0	6,538
2002	2,157	1,027	5,544	0	1,943	10,671
2003	1,937	1,027	6,212	401	1,943	11,520
2004	1,710	1,357	6,841	682	2,053	12,643
2005	0	1,063	6,722	996	1,503	10,284
2006	0	770	6,789	896	770	9,225
2007	0	440	6,358	922	953	8,673
2008	0	144	4,305	929	895	6,273
2009	0	235	3,857	812	703	5,607
2010	0	57	4,152	770	238	5,217
2011	0	50	3,989	881	252	5,172
2012	0	30	3,280	783	195	4,288
2013	0	38	4,124	812	160	5,134
2014	0	33	3,995	828	146	5,001
2015	0	43	3,530	851	128	4,552
2016	0	41	3,398	835	82	4,356
2017	0	59	3,329	821	79	4,298
2018	0	81	3,319	811	149	4,360
2019	0	43	2,856	846	110	3,855
2020	0	36	2,876	861	133	3,906

[1] Source [12]; unit: kilotons of CO_{2eq}. [2] Emission source notations; 2 B: Chemical industry, 2 C: Metal process, 2 E: Electronics industry, 2 F: Alternatives to ozone-depleting substances, 2 G: Manufacturing and use of other products.

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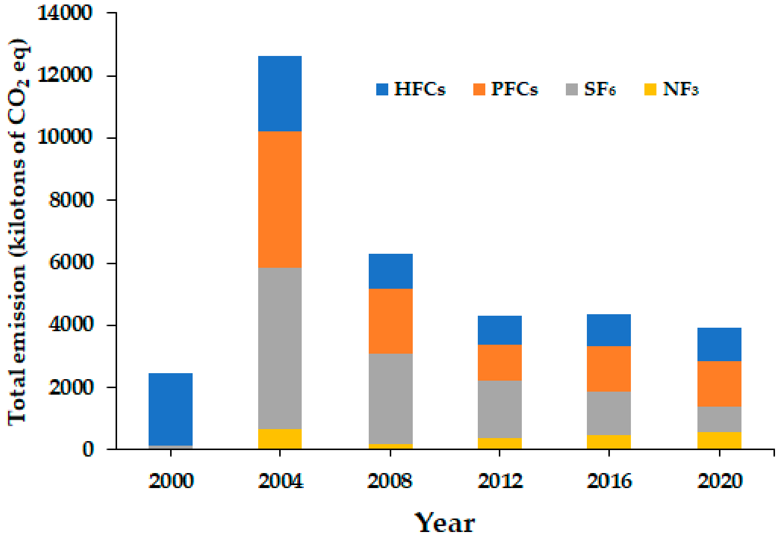

Figure 1. Proportion variations on emissions of fluorinated greenhouse gases (F-gases) in Taiwan since 2000.

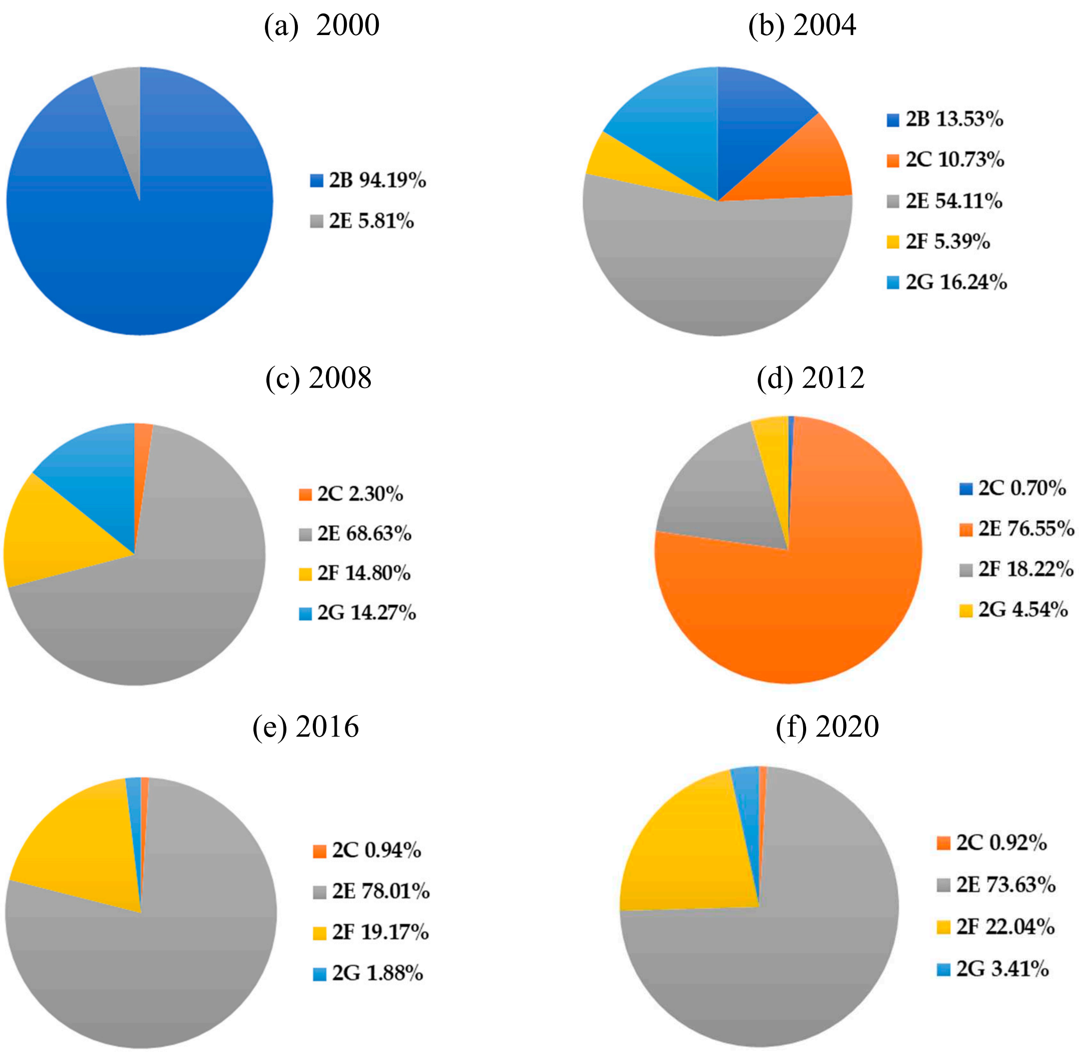

Figure 2. Percentages of fluorinated greenhouse gases (F-gases) emissions from IPPU sector in Taiwan by (a) 2000, (b) 2004, (c) 2008, (d) 2012, (e) 2016, and (f) 2020.

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3.2. Regulatory strategies for controlling the emissions of fluorinated greenhouse gases

In Taiwan, the regulatory strategies for controlling the emissions of fluorinated GHGs (F-gases) are based on the Air Pollution Control Act, the Climate Change Response Act, and the Waste Management Act. The relevant measures will be addressed in the following sub-sections.

3.2.1. Air Pollution Control Act

This Act was recently revised on 1 August, 2018. Under the authorizations of the Act, the Taiwan EPA promulgated the six GHGs as air pollutants on 9 May 2012, including carbon dioxide (CO_2), methane CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). The Article 20 of the Act refers to the countermeasures against air pollution [14], including

- The stationary sources that emit air pollutants shall comply with the emission standards of pipeline (or vent) by installing closed vent/collection system and air pollution control system.
- The EPA in consultation with relevant agencies (i.e., Ministry of Economic Affairs) shall determine the emission standards based on specially designated industry categories, facilities, pollutant items or areas.

For example, the EPA promulgated the emission standards of volatile organic compounds (VOCs) in the regulations ("Air Pollution Control and Emission Standards for Semiconductor Manufacturing Industry" and "Air Pollution Control and Emission Standards for Optoelectronic Materials and Element Manufacturing Industry"). Herein, the so-called VOCs include HFCs and PFCs, but not include carbon dioxide (CO_2) and methane (CH_4). With the promulgation of the Greenhouse Gas Reduction and Management Act (GGRMA) of 2015, the provisions for controlling GHGs in the Air Pollution Control Act will comply with the CCRA.

3.2.2. Climate Change Response Act

As mentioned above, the Taiwan government passed the Climate Change Response Act (CCRA) on 15 February 2023 for revising the Greenhouse Gas Reduction and Management Act (GGRMA) of 2015 [25]. The Act defines the greenhouse gases (GHGs), which refer to the following substances: carbon dioxide (CO_2), methane CH4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3), and others designated by the central competent authority (i.e., EPA). The most noteworthy point is to set the long-term national GHG net-zero emission goal (carbon neutrality) by 2050. To achieve the goal, all levels of government shall implement GHG reduction and develop negative emission technologies. As mentioned in Sec. 3.1, the major emission sources of the four F-gases were from the industrial (or manufacturing) and waste management sectors in Taiwan. Under the key strategies of the central competent authorities (including the Ministry of Economic Affairs, and EPA), they will focus on the following orientations:

- Process modification: Equipment renew by phase-out, and fluorinated gases (F-gases) reduction by environment-friendly substitutes and recovery/recycling/destruction system installed in the industrial sector.
- Circular economy: Recovery/recycling/storage system installed in the waste (waste electronic appliances like air conditioner and refrigerator, and waste vehicles) management sector.

3.2.3. Waste management Act

As mentioned above, the F-gases (especially in HFCs) have been widely used as refrigerants in the vehicles and air-conditioners. In addition, some HFCs are used as blowing agents in the refrigerators. Therefore, these articles will emit these F-gases while discarding them as waste electrical and electronic equipment (WEEE) and scrap car [11]. In Taiwan, the legal system for the recycling and treatment of waste was based on the Waste Management Act, aiming at defining the categories of waste, and clarifying its obligations and responsibilities. Herein, the so-called waste referred to any movable solid or liquid substance or object due to some discarded reasons like weakened performance and no economic or market value. In response to the extended producer responsibility (EPR) and sustainable material management, the Taiwan government began to implement the zero waste and resource recycling promotion programs since 1997 [30, 31]. Under the authorization of the Act, the regulated recyclable wastes are defined as those that could cause concerns about serious environmental pollution and also possess the value for recycling and reuse. In this regard, the central competent authority (i.e., EPA) has announced the regulated recyclables, including containers, motor vehicles, tires, lead-acid batteries, home electric appliances, information technology (IT) products, dry batteries, lightings, and waste vehicles (car/motorcycle). Concerning the recovery of refrigerant and blowing agent from waste home electric appliances, the Taiwan EPA promulgated the regulations ("Facilities Standards for the Recycling Storage, and Disposal of Electrical and Electronic Waste" and "Facilities Standards for the Recycling Storage, and Disposal of Waste Vehicles"). These regulations required the recycling enterprises to install the recovery (liquefaction or adsorption) equipment and storage tank for HFCs refrigerant in the air conditioning system and blowing agent in the refrigerator foam-insulation system [32, 33].

3.3. Survey of current abatement technologies for controlling the emissions of fluorinated GHGs

Concerning the abatement technologies for controlling the emissions of fluorinated GHGs, there are many different options available to control their emissions from process industries, especially in the semiconductor manufacturing and TFT-LCD industries. They are basically grouped into three different approaches [17, 34]: (1) material modification and/or substitution, (2) capture recovery-recycling technology, and (3) thermal destruction-local scrubbing technology. The first method should be prioritized, but it could be limited to use more environment-friendly refrigerants and cleaning solvents. According to the Significant New Alternatives Policy (SNAP) database set by the US environmental Protection Agency [35], the available environment-friendly refrigerants with low GWP and high safety include hydrofluoro-olefins (HFOs), hydrochlorofluoro-olefins (HCFOs) and hydrofluoro-ethers (HFEs). Regarding the environment-friendly cleaning solvents, the fluorinated substances, including HFOs, HCFOs and HFEs, are listed in the SNAP program. These acceptable substitutes have been specified and also used in the industrial processes. The second method was to adopt the capture recovery-recycling technologies, including cryogenic condensation, adsorption, and membrane separation. However, their recovery availabilities were less found in the industrial processes because of the physicochemical properties of target F-gases (i.e., high fugacity, high stability, low polarity, and low solubility in water), the complicated composition in vent gas, and the high purification requirements of recovered F-gases. Therefore, the most commonly used method for controlling the emissions of F-gases from the process was based on the thermal destruction-local scrubbing technology. These de-PFCs/local scrubber systems have been installed in the Taiwan's semiconductor manufacturing process [28]. Currently, the thermal destruction methods included the following types: plasma-based, catalyst-based, or combustion-based. Taking NF_3 destruction as an example [20], the following equations showed its possible stoichiometry reactions with oxygen, hydrogen and moisture (water vapor).

$$2NF_3 + 2O_2 \rightarrow NO + 3F_2$$

$$2NF_3 + 3H_2 \rightarrow N_2 + 6HF$$

$$2NF_3 + 3H_2O \rightarrow 6HF + NO + NO_2$$

These thermal decomposition products or by-products are easily dissolved into water. For this reason, the vent exhausts from the thermal destruction unit were further removed by the wet scrubbing unit. Although the decomposition product NO is only slightly soluble in water, it is apt to form NO_2 under the oxidative environment. Obviously, these decomposition products are acidic compounds, which will react with alkaline solution to produce fluoride like NaF. For example, sodium hydroxide (NaOH), a strong base, will react with HF, F_2 or NO_2 molecules to form the non-toxic substances, which can be illustrated below.

$$HF + NaOH \rightarrow NaF + H_2O$$

$$2F_2 + 4NaOH \rightarrow 4NaF + O_2 + 2H_2O$$

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$$2NO_2 + 2NaOH \rightarrow NaNO_2 + NaNO_3 + H_2O$$

Furthermore, the by-product fluoride or fluoride-containing wastewater in semiconductor or optoelectronic industries may be converted to a valuable product (cryolite, Na_3AlF_6) by a crystallization process [36].

4. Conclusions

Fluorinated greenhouse gases (F-gases) have been widely used as industrial and commercial products, such as refrigerant, blowing agent, cleaning solvent, etching gas and extinguishing agent. In this paper, the trends of F-gases (i.e., HFCs, PFCs, SF_6 and NF_3) emissions and their sources from the industrial process and product use (IPPU) sector during the period of 2000-2020 have been analyzed. The findings showed significant increasing trend from 2,462 kilotons of carbon dioxide equivalents (CO_{2eq}) in 2000 to the peak value (i.e., 12,643 kilotons) of CO_{2eq} in 2004. Subsequently, it decreased from 10,284 kilotons of CO_{2eq} in 2005 (about 3.54% of the total GHG emissions in 2005) to 3,906 kilotons of CO_{2eq} in 2020 (about 1.37% of the total GHG emissions in 2020), down by 69.1% compared to that in 2004. Obviously, these achievements were closely related to the progressive efforts by the regulatory requirements and the industry's voluntary reduction strategies. Although the abatement technologies for controlling the F-gases emissions in the Taiwan's semiconductor manufacturing and TFT-LCD industries can be based on material substitution and capture recovery-recycling technology, the current technology focused on thermal destruction-local scrubbing system. To further reduce the emissions of F-gases, the Kigali Amendment, which entered into force on 1 January 2019, added HFCs to the list of controlled substances under the Montreal Protocol. In this regard, the environment-friendly refrigerants with low GWP and high safety, including hydrofluoro-olefins (HFOs), hydrochlorofluoro-olefins (HCFOs) and hydrofluoro-ethers (HFEs), will be more and more used in the refrigeration and air-conditioning in the near future. Concerning the reduction of PFCs, SF_6 and NF_3 emissions, the thermal destruction-local scrubber approach will be the mainstream technology.

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