

Electricity savings and greenhouse gas emission reductions from global phase-down of hydrofluorocarbons

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S1: Current legislation on HFC control considered in the Baselines

To estimate hydrofluorocarbon (HFC) emissions in the baseline scenarios, we take into account the effects on emissions from implementation of existing legislations to control HFC emissions at the regional or national level. The European Union (EU) first legislated to control emissions of HFCs in 2006 (Höglund-Isaksson et al., 2012; Höglund-Isaksson et al., 2013), adopting a regulation on emissions and a directive on mobile air-conditioning (EU, 2006). Regulation 842/2006 on certain fluorinated greenhouse gases (GHGs) aimed only at containment, through measures such as control of leaks, proper servicing of equipment and recovery of the gases at the end of the equipment's life. In May 2014, this was replaced by the much more ambitious Regulation 517/2014 on fluorinated GHGs (the F-Gas Regulation¹), which entered into force on 1st January 2015. It is aimed at achieving a reduction in sales of HFCs on the EU market by 79 percent (GWP-weighted) from 2009–12 levels by 2030 (EU, 2014), with interim reduction steps starting in 2015 and applying roughly every three years. In addition, HFCs are banned outright in some categories of new equipment where alternatives are readily available.

Apart from the EU, Japan, the USA, Australia, Norway, and Switzerland have also implemented national regulations to limit the use of high-GWP HFCs. The USA has already implemented incentive credits for use of low-GWP refrigerants in support of greenhouse gas emission standards for light duty vehicles and removed certain high-GWP HFCs from the Significant New Alternatives Policy (SNAP) list of allowable technologies for specific sectors in 2015 (US EPA, 2015). Although recently legally challenged (Reilly, 2017), the changes to the SNAP list ban the use of many high-GWP HFCs in, for example, commercial refrigeration applications, such as supermarket systems and vending machines, beginning during the period 2016–2020 and in mobile air-conditioning from model year 2021. The implementation of the new SNAP list is estimated to reduce baseline USA HFC emissions by 0.18–0.24 Pg CO₂eq per year (about 43%) by 2050 (Velders et al., 2015). In Japan, the Fluorocarbons Recovery and Destruction Law was amended and became effective on 1st April 2015 as the *Act on Rational Use and Proper Management of Fluorocarbons* (Fluorocarbon Emission Control Law) (METI, 2015). Among other requirements, the Act requires entities manufacturing and importing air-conditioning and refrigeration units to transition to either fluorocarbon-free refrigerants or to low global warming fluorocarbons by certain target years.

For developing countries, several studies discuss the impact of the Clean Development Mechanism (CDM) projects on HFC-23 emissions from HCFC-22 production for emissive and feedstock applications (Wara, 2007; Miller et al., 2010; Montzka et al., 2010; Miller and Kuijpers, 2011; Schneider, 2011). HFC-23 emissions from HCFC-22 production are assumed to be controlled in most developing countries due to CDM (Fenhann, 2014), except China where 36% of HCFC-22 production is controlled (Feng et al., 2012). The Chinese production capacity of HCFC-22 accounts for 78% of the global HCFC production (UNEP, 2014). HCFC-22 is a major source of HFC-23 emissions, which is a strong greenhouse gas with GWP₁₀₀ of 14,800 times that of CO₂ (IPCC, 2007).

In its Intended Nationally Determined Contribution (INDC) submitted in June 2015, China reiterated its commitment under the Montreal Protocol to achieve effective control on emissions of HFC-23 by 2020. In 2015, the Chinese National Development and Reform Commission (NDRC) announced that it plans to achieve abatement of all HFC-23 emissions by 2019 (NDRC, 2015). This would imply installing destruction technology in all plants currently not covered by CDM and ensuring that the destruction technology on plants covered under CDM is being operated and maintained. In line with this information, we assume in recent updates of the GAINS model that all HCFC-22 production facilities in China will be fully controlled from 2020 onwards. It is observed that except for China other developing countries do not make HFC specific emission reduction commitments in the INDCs. In the 28th Meeting of the Parties to the Montreal Protocol in October 2016 in Kigali, the Indian government presented a domestic legislation that mandates control of trifluoromethane (HFC-23) emissions. At present, all HCFC-22 production facilities in India are fully controlled under the Clean Development Mechanism (CDM) and we assume the control on all Indian facilities stays operational and will be maintained in the future.

S2: The Kigali Amendment to the Montreal Protocol

The Kigali Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer entered into force on 1st January 2019, following ratification by 65 countries¹. KA sets targets for the phase-down of HFCs consumption for four different Party groups. The first group primarily includes 136 developing countries that make up all Article 5 countries as specified under the Montreal Protocol with the exception of Bahrain, India, Iran, Iraq, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia, and the United Arab Emirates (UAE). These ten countries are characterized by high ambient air temperatures and make up a second and separate group of Article 5 countries. Countries specified as non-Article 5 countries under the Montreal Protocol are primarily developed countries and under the Kigali Amendment divided into two separate groups with 45 countries in a first group and with the five countries Belarus, the Russian Federation, Kazakhstan, Tajikistan and Uzbekistan forming a separate second group. Table 1 presents the baseline years and HFC phase-down schedule of Article 5 and non-Article 5 Parties. We will hereafter refer to these four Party groups as Article 5 Group 1, Article 5 Group 2, non-Article 5 Group 1, and non-Article 5 Group 2.

¹ The Parties to the Montreal Protocol agreed that the Kigali amendment to the Montreal Protocol would *enter into force* on 1 January 2019, provided that at least 20 Parties had ratified it.

Table S1: Baseline and HFC phase-down schedule of Article-5 and non- Article-5 Parties

	Article 5* (A5) Parties: Group 1**		Article 5 (A5) Parties: Group 2⁺	
Baseline Years	2020, 2021 & 2022		2024, 2025 & 2026	
Baseline calculation	Average production /consumption of HFCs in 2020, 2021, and 2022 <i>plus 65%</i> of HCFC baseline production/consumption		Average production /consumption of HFCs in 2024, 2025, and 2026 <i>plus 65%</i> of HCFC baseline production/consumption	
Reduction steps Freeze	2024		2028	
Step 1	2029	10%	2032	10%
Step 2	2035	30%	2037	20%
Step 3	2040	50%	2042	30%
Step 4	2045	80%	2047	85%
	Non-Article 5 (non-A5): Group 1		Non-Article 5 (non-A5): Group 2⁺⁺	
Baseline Years	2011, 2012 & 2013		2011, 2012 & 2013	
Baseline Calculation	Average production /consumption of HFCs in 2011, 2012 & 2013 <i>plus 15%</i> of HCFC baseline production/consumption		Average production /consumption of HFCs in 2011, 2012 & 2013 <i>plus 25%</i> of HCFC baseline production/consumption	
Reduction steps				
Step 1	2019	10%	2020	5%
Step 2	2024	40%	2025	35%
Step 3	2029	70%	2029	70%
Step 4	2034	80%	2034	80%
Step 5	2036	85%	2036	85%

* Article 5 and non-Article 5 parties are defined within the Montreal Protocol based on their annual calculated level of consumption of any controlled substance per capita. Those that exceed this level of annual calculated consumption are classified as non-Article 5 and those that do not exceed it as Article 5 parties.

**Group 1: Article 5 parties not part of Group 2

⁺ Group 2: Bahrain, India, the Islamic Republic of Iran, Iraq, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia and the United Arab Emirates

⁺⁺ For Belarus, Russian Federation, Kazakhstan, Tajikistan, Uzbekistan, 25% HCFC component of baseline and different initial two steps (1) 5% reduction in 2020 and (2) 35% reduction in 2025

Source: UNEP (2016)

Table S2: Technical and economic energy efficiency (EE) potential of cooling technologies in baseline and with low-GWP alternatives

Countries	Year	EE due to systems improvements and low-GWP refrigerant (%)					
		HCFC-22/HFC-410A		HC-290		HFC-32/ HFOs	
		Economic	Technical	Economic	Technical	Economic	Technical
1. Mini-split air-conditioners (1.5 ton base-unit size)							
Brazil	2014	30%	70%	36%	73%	35%	72%
Chile	2014	30%	70%	36%	73%	35%	72%
China	2014	30%	70%	36%	73%	35%	72%
Colombia	2014	30%	70%	36%	73%	35%	72%
Egypt	2014	30%	70%	36%	73%	35%	72%
India	2014	30%	70%	36%	73%	35%	72%
Indonesia	2014	30%	70%	36%	73%	35%	72%
Mexico	2014	30%	70%	36%	73%	35%	72%
Pakistan	2014	30%	70%	36%	73%	35%	72%
Saudi Arabia	2014	30%	70%	36%	73%	35%	72%
Thailand	2014	30%	70%	36%	73%	35%	72%
UAE	2014	30%	70%	36%	73%	35%	72%
Vietnam	2014	30%	70%	36%	73%	35%	72%
2. Packaged air-conditioners (Rooftop units 10 ton AC)							
Asia	2015	31%	49%			37%	53%
North America	2015	31%	49%			37%	53%
Europe	2015	31%	49%			37%	53%
Rest of World	2015	31%	49%			37%	53%
3. VRF/ Ducted air-conditioners (10 ton HP)							
Asia	2015	15%	37%			21%	41%
North America	2015	15%	37%			21%	41%
Europe	2015	15%	37%			21%	41%
Rest of World	2015	15%	37%			21%	41%
4. Chillers, air cooled (Small, <300 tons - 500kW, 143 tons) ⁺							
Asia	~2012-2017	29%	38%			32%	41%
North America	~2012-2017	22%	32%			25%	35%
Europe	~2012-2017	33%	42%			36%	44%
Rest of World	~2012-2017	12%	23%			15%	26%
5. Chillers, air cooled (Large, >= 300 tons - 1500kW, 429 ton) ⁺							
Asia	~2012-2017	30%	38%			33%	41%
North America	~2012-2017	23%	32%			26%	35%
Europe	~2012-2017	35%	42%			37%	44%
Rest of World	~2012-2017	13%	23%			17%	26%

Countries	Year	EE due to systems improvements and low-GWP refrigerant (%)					
		HCFC-22/HFC-410A		HC-290/HC-600a		HFC-32/ HFOs	
		Economic	Technical	Economic	Technical	Economic	Technical
6. Chillers, water cooled (Small, <300 tons - 500kW, 143 tons) ⁺							
Asia	~2012-2017	31%	51%			34%	53%
North America	~2012-2017	18%	41%			21%	44%
Europe	~2012-2017	50%	64%			52%	66%
Rest of World	~2012-2017	25%	46%			28%	49%
7. Chillers, water cooled (Large, >= 300 tons - 1500kW, 429 ton) ⁺							
Asia	~2012-2017	36%	57%			39%	59%
North America	~2012-2017	13%	41%			17%	44%
Europe	~2012-2017	45%	63%			48%	65%
Rest of World	~2012-2017	26%	50%			29%	52%
8. Remote display cabinet - Chilled, multi-deck (RVC2) ⁺⁺							
Asia	2014	69%	75%	68%	74%		
North America	2014	53%	63%	51%	61%		
Europe	2014	13%	30%	8%	26%		
Rest of World	2014	35%	48%	32%	45%		
9. Remote display cabinet - Frozen, open, island (RHF4) ⁺⁺							
Asia	2014	23%	23%	19%	19%		
North America	2014	31%	31%	27%	27%		
Europe	2014	17%	17%	13%	13%		
Rest of World	2014	42%	42%	39%	39%		
10. Integral display cabinet - Chilled, multi-deck (IVC2) ⁺⁺							
Asia	2014	66%	77%	64%	76%		
North America	2014	48%	65%	45%	64%		
Europe	2014	30%	53%	26%	51%		
Rest of World	2014	30%	54%	27%	51%		
11. Integral display cabinet - Chilled, glass door (IVC4) ⁺⁺							
Asia	2014	15%	30%	11%	26%		
North America	2014	15%	30%	11%	26%		
Europe	2014	15%	30%	11%	26%		
Rest of World	2014	15%	30%	11%	26%		
12. Integral display cabinet - Frozen, open, island (IHF4) ⁺⁺							
Asia	2014	41%	41%	37%	38%		
North America	2014	47%	47%	44%	45%		
Europe	2014	24%	25%	20%	21%		
Rest of World	2014	56%	56%	53%	54%		
13. Integral display cabinet - Frozen, glass lid, island (IHF6) ⁺⁺							
Asia	2014	32%	34%	29%	31%		
North America	2014	39%	41%	36%	38%		
Europe	2014	13%	16%	9%	12%		
Rest of World	2014	41%	43%	38%	40%		

Countries	Year	EE due to systems improvements and low-GWP refrigerant (%)					
		HCFC-22/HFC-410A		HC-290/HC-600a		HFC-32/ HFOs	
		Economic	Technical	Economic	Technical	Economic	Technical
14. Domestic refrigerators/freezers (Average size) ⁺⁺⁺							
Asia	2015	16%	60%	22%	63%		
North America	2015	22%	47%	28%	51%		
Europe	2015	13%	53%	19%	56%		
Rest of World	2015	15%	57%	21%	60%		
15. Beverage vending machines (500 bottle/unit capacity) ⁺⁺⁺							
Asia	2015	44%	58%	48%	61%		
North America	2015	34%	55%	39%	58%		
Europe	2015	44%	58%	48%	61%		
Rest of World	2015	19%	59%	25%	62%		

RID: Remote and integral displays

⁺HFO as an alternative low-GWP refrigerant

⁺⁺CO₂ as an alternative low-GWP refrigerant

⁺⁺⁺HC-600a as an alternative low-GWP refrigerant

Source: (DOE, 2011; IEA-4E, 2012a; IEA-4E, 2012b; CLASP, 2013; CLASP, 2014; IEA-4E, 2014; IEA-4E, 2015; Shah et al., 2015; Rosenquist, 2016; UNEP, 2017; DOE, 2018; DOE-FEMP, 2018)

Table S3: Annual technical/economic electricity saving potentials in HFC reduction scenarios relative respective pre-KA baseline scenarios

Year	KA Groups	Technical electricity savings (TWh)				Economic electricity savings (TWh)			
		SSP3 - KA	<i>Cooling for All - KA</i>	SSP3 - MTFR	<i>Cooling for All - MTFR</i>	SSP3 - KA	<i>Cooling for All - KA</i>	(SSP3 - MTFR)	<i>Cooling for All - MTFR</i>
2030	Non-A5 (Group-I)	806	806	767	767	491	491	455	455
	Non-A5 (Group-II)	25	25	25	25	16	16	16	16
	A5 (Group-I)	1452	1464	1708	1717	861	865	993	996
	A5 (Group-II)	449	453	518	521	260	262	290	291
	Global	2732	2748	3018	3030	1628	1634	1754	1759
2050	Non-A5 (Group-I)	1304	1304	1238	1238	795	795	734	734
	Non-A5 (Group-II)	58	59	56	57	37	38	35	35
	A5 (Group-I)	4017	4272	3868	4114	2474	2601	2239	2343
	A5 (Group-II)	2503	2535	2410	2440	1515	1530	1351	1364
	Global	7882	8169	7572	7849	4821	4964	4359	4477
2100	Non-A5 (Group-I)	1772	1772	1683	1683	1109	1109	1032	1032
	Non-A5 (Group-II)	109	117	106	113	70	73	65	68
	A5 (Group-I)	7341	9947	7064	9572	4345	5647	3867	4942
	A5 (Group-II)	3581	3760	3447	3619	2100	2189	1853	1927
	Global	12803	15595	12299	14987	7624	9019	6817	7969

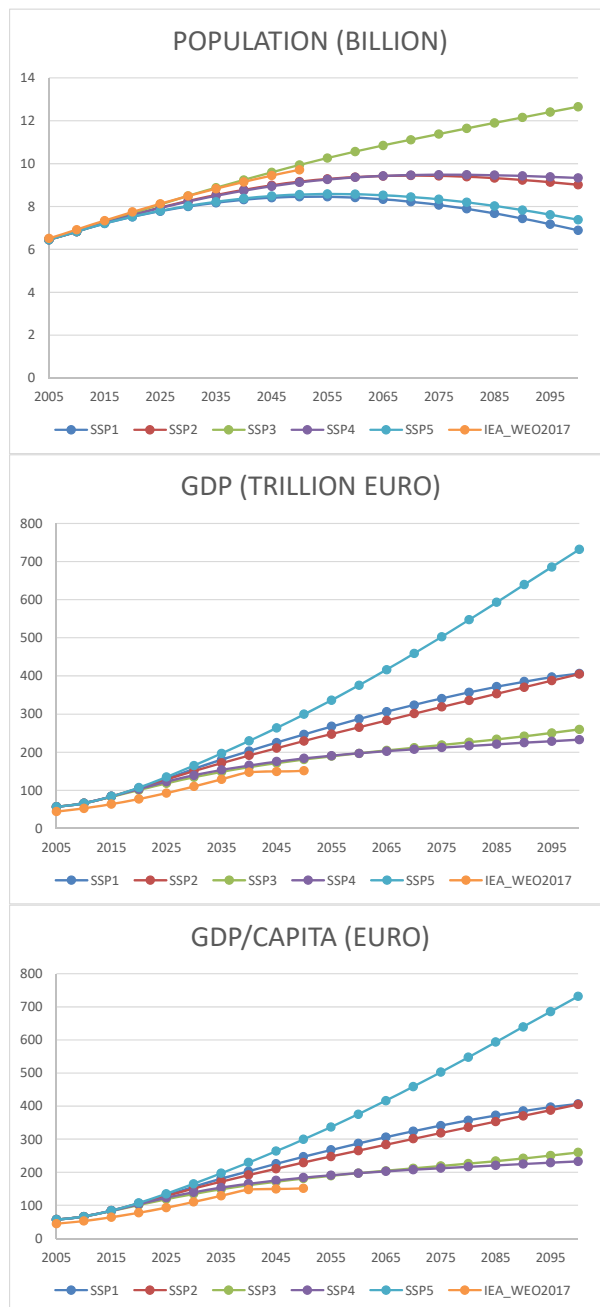


Figure S1: Comparison of future developments in global population and GDP between the IEA-WEO 2017 and the five Shared Socioeconomic Pathways (SSPs) scenarios.

Source: IIASA (2017)

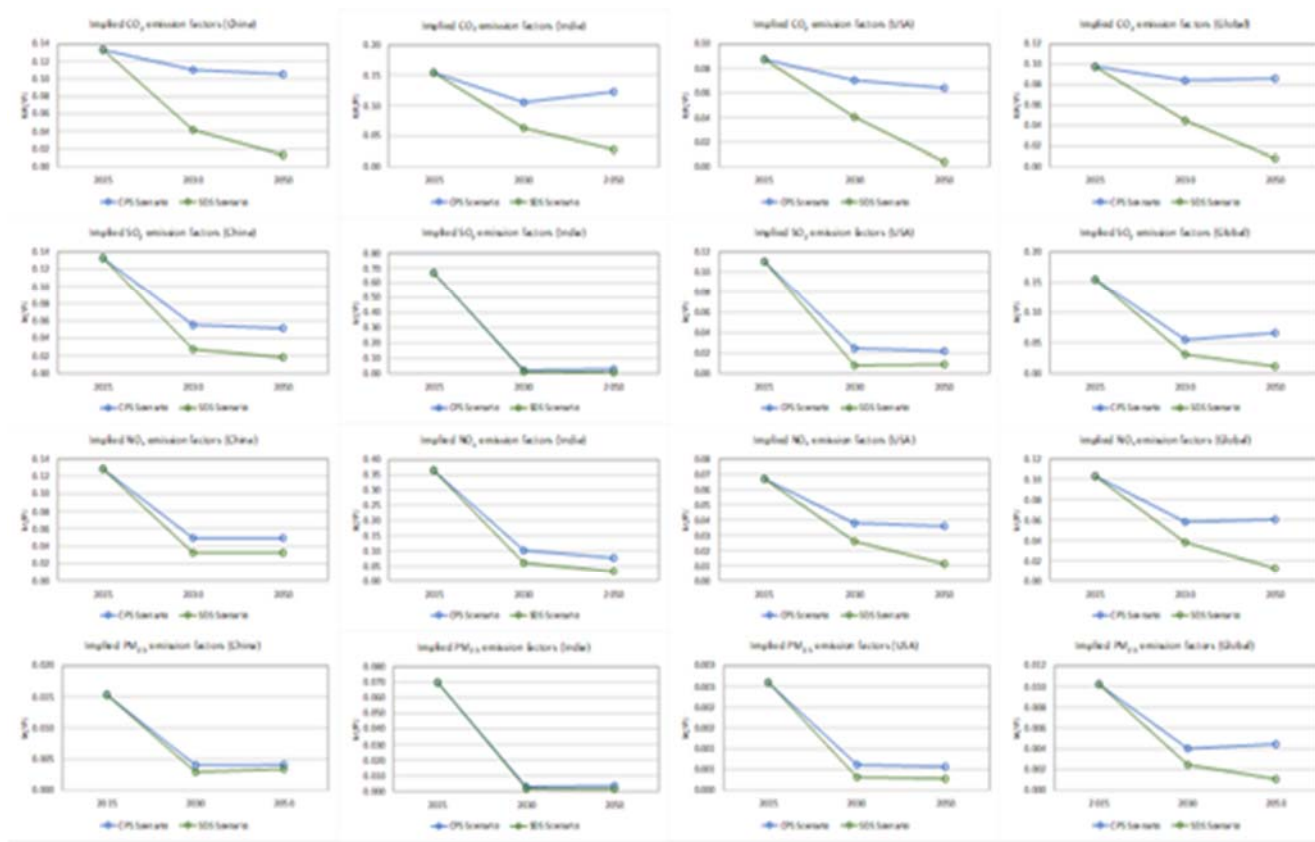


Figure S2: Implied emission factors for electricity production in the power plant sector for CO₂ and the air pollutants (SO₂, NO_x and PM_{2.5}) at global and select country level

Source: IIASA/GAINS Model available at: gains.iiasa.ac.at

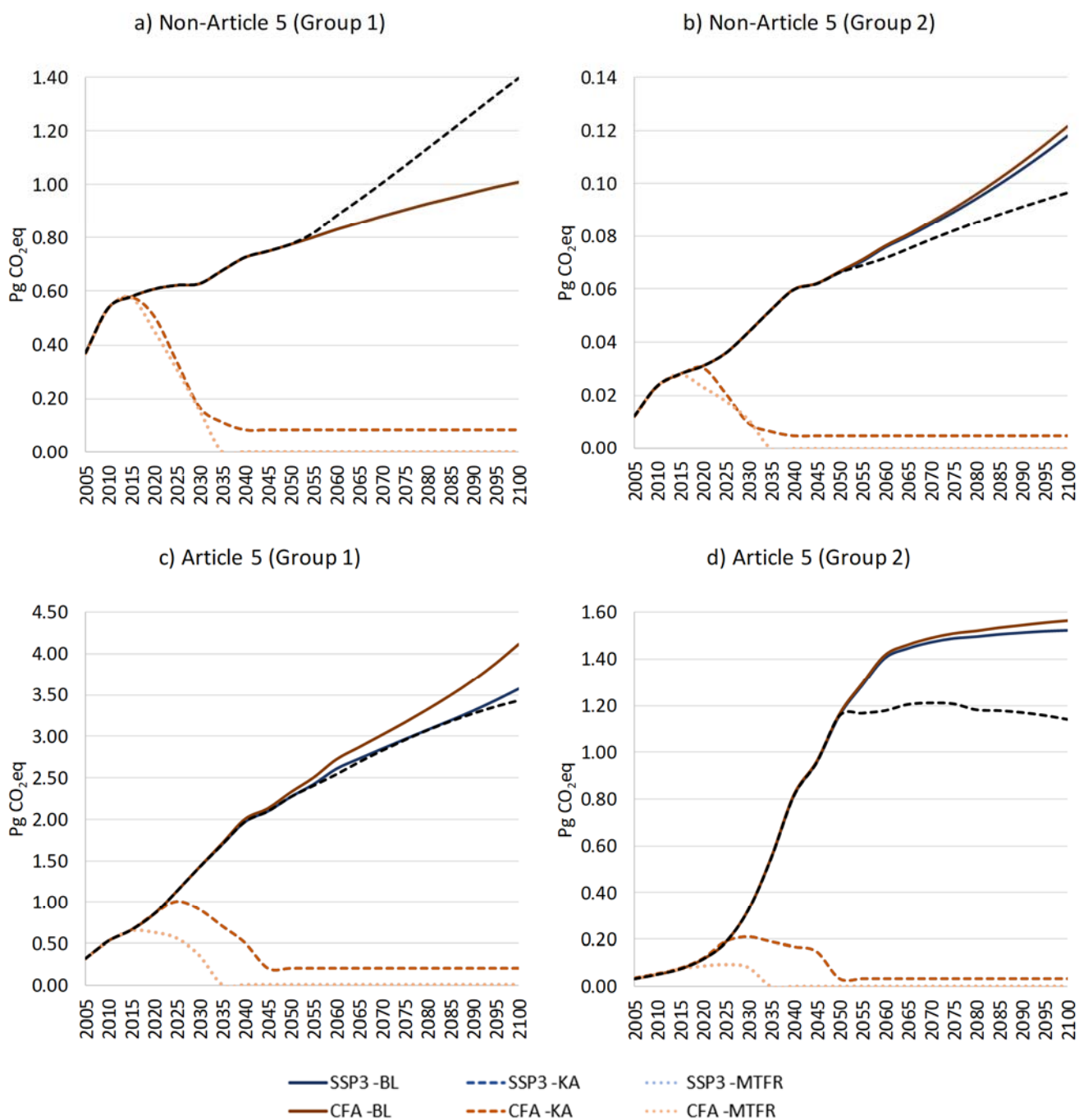


Figure S3: Baseline HFC/HCFC (Pg CO₂eq) by different party groups (SSP3-BL and CFA-BL refer to SSP 3 and *Cooling for All* baselines, respectively)

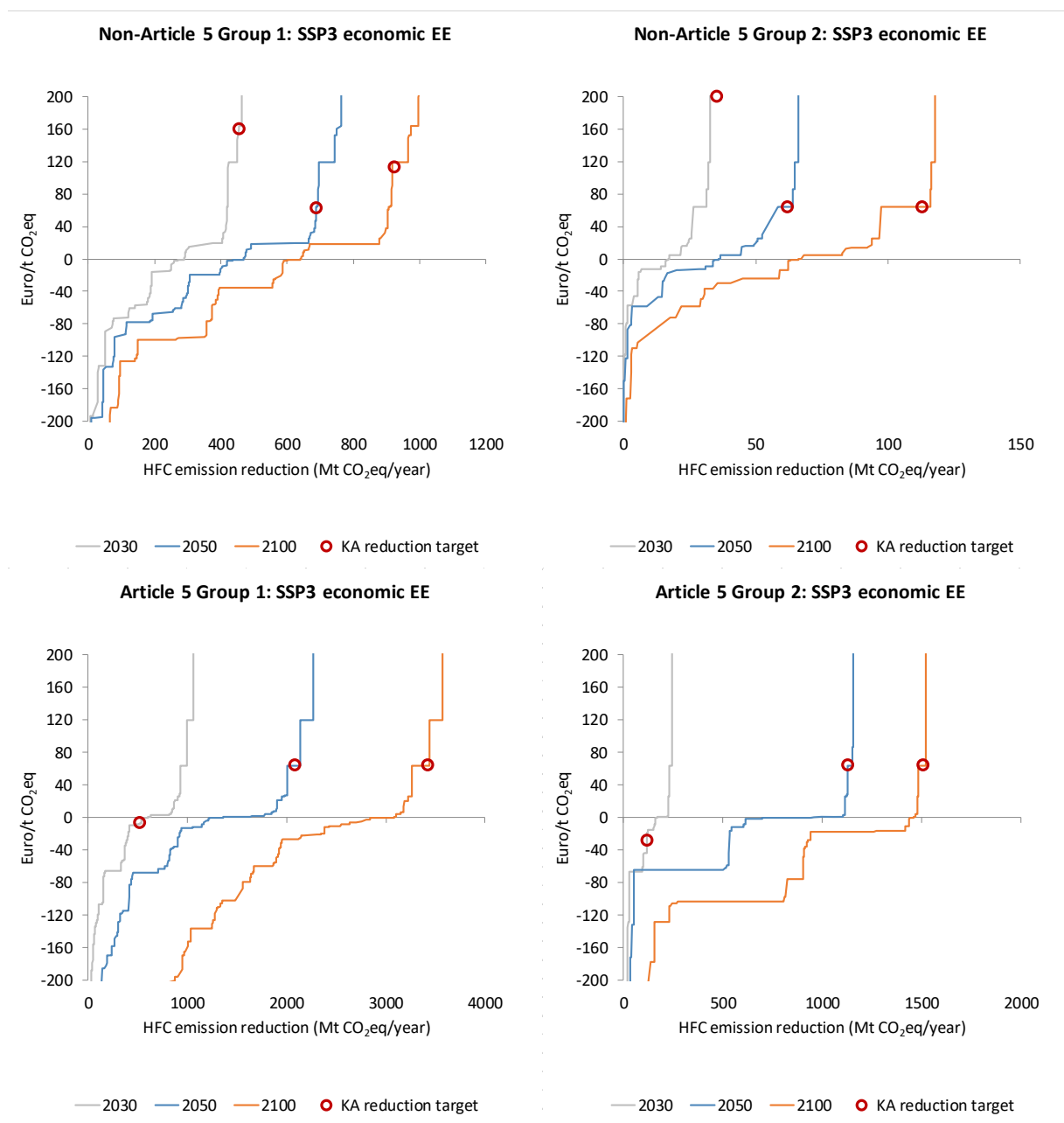


Figure S4: Marginal abatement cost curves (MACCs) starting from a pre-Kigali SSP3 baseline consistent with the IEA-WEO17 New Policies scenario and reducing HFC emissions by Kigali Amendment (KA) party groups under economic energy efficiency improvements and indicating the KA HFC reduction targets in 2030, 2050 and 2100.

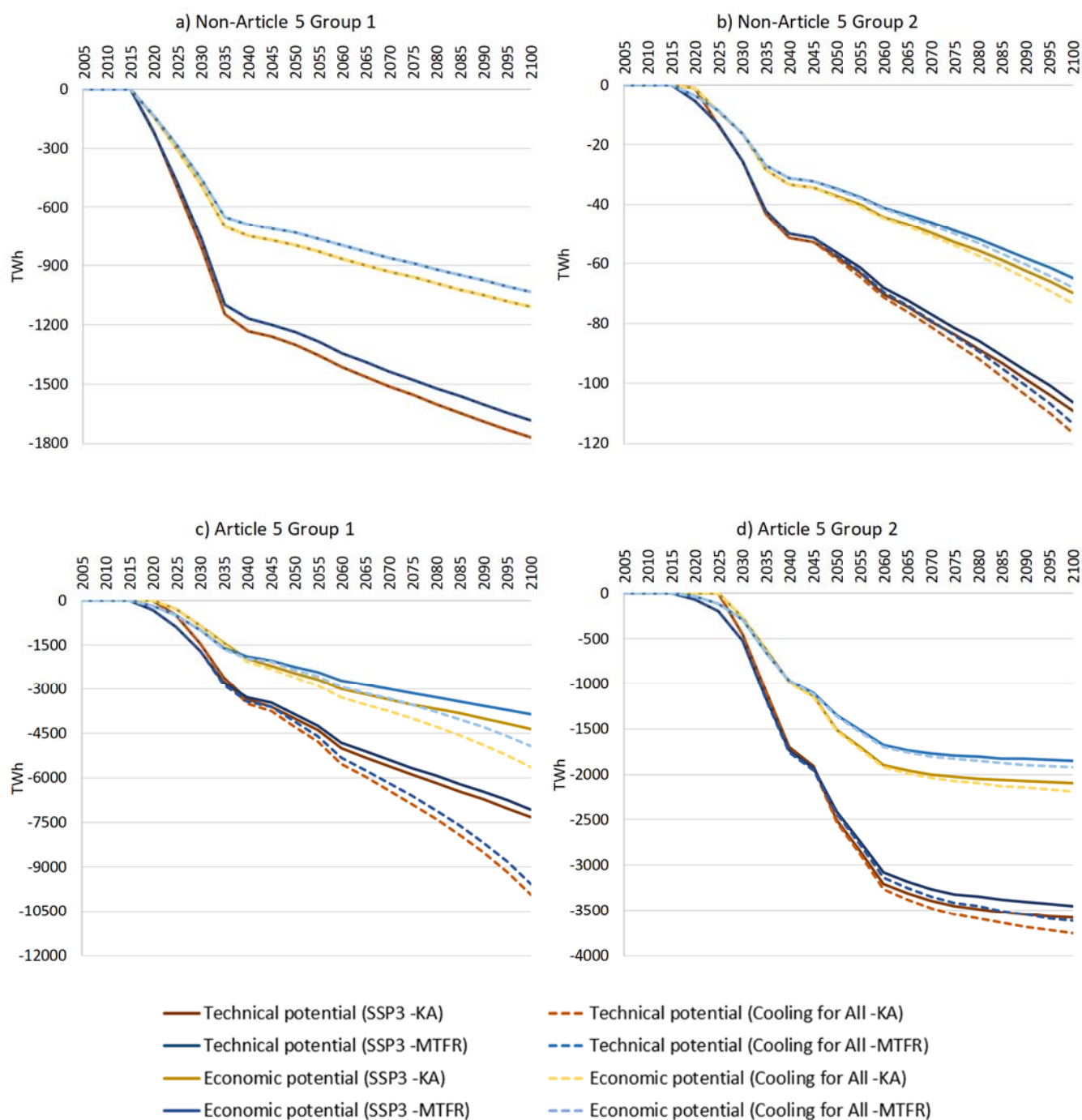


Figure S5: Technical and economic electricity saving (TWh) potential by different party groups

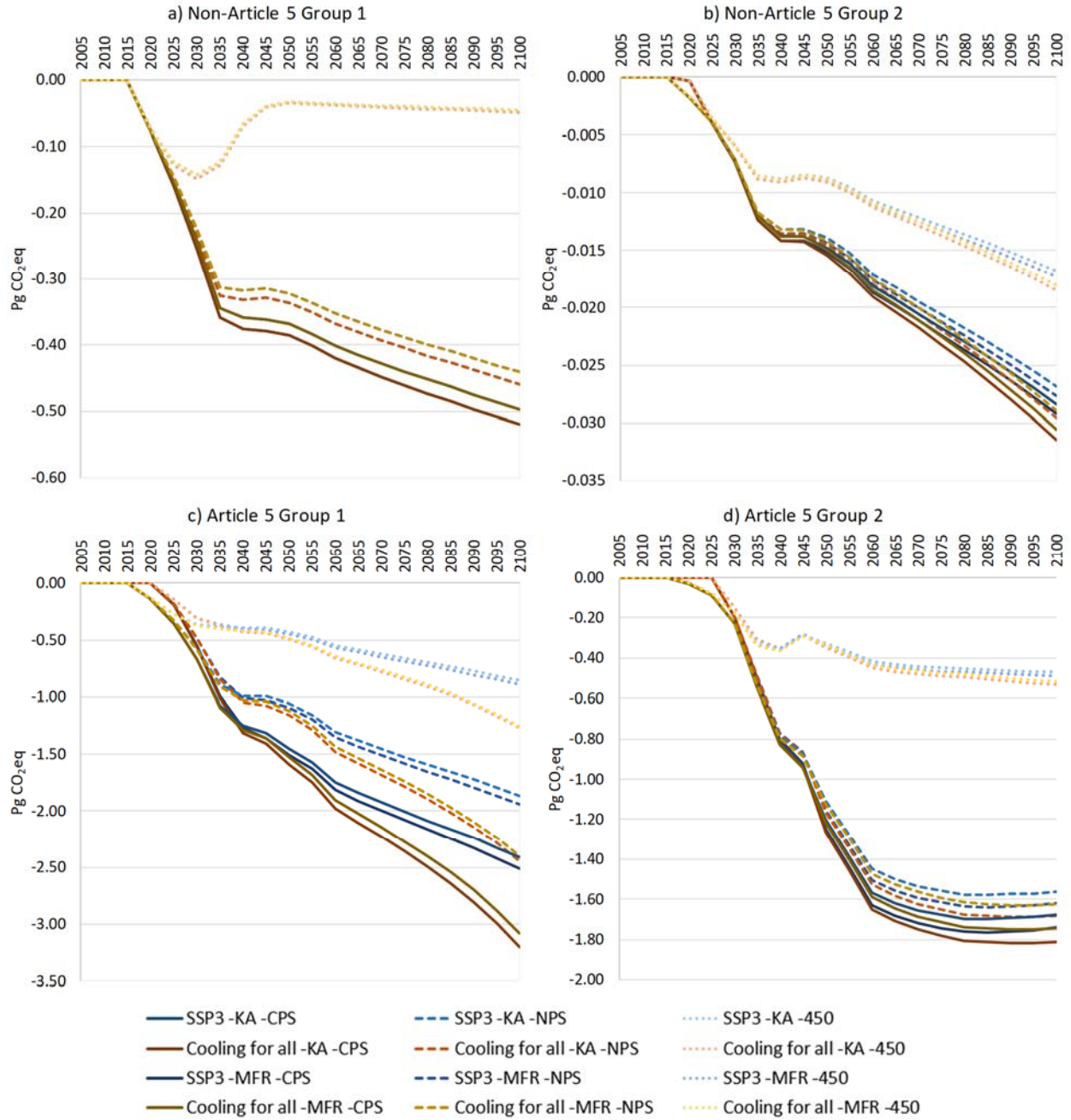


Figure S6: Greenhouse gas emissions reductions in the baseline (SSP3 and *Cooling for All*) and alternative (Kigali Amendment -KA and Maximum Technically Feasible Reductions -MFR) scenarios due to technical electricity savings potential by different party groups.

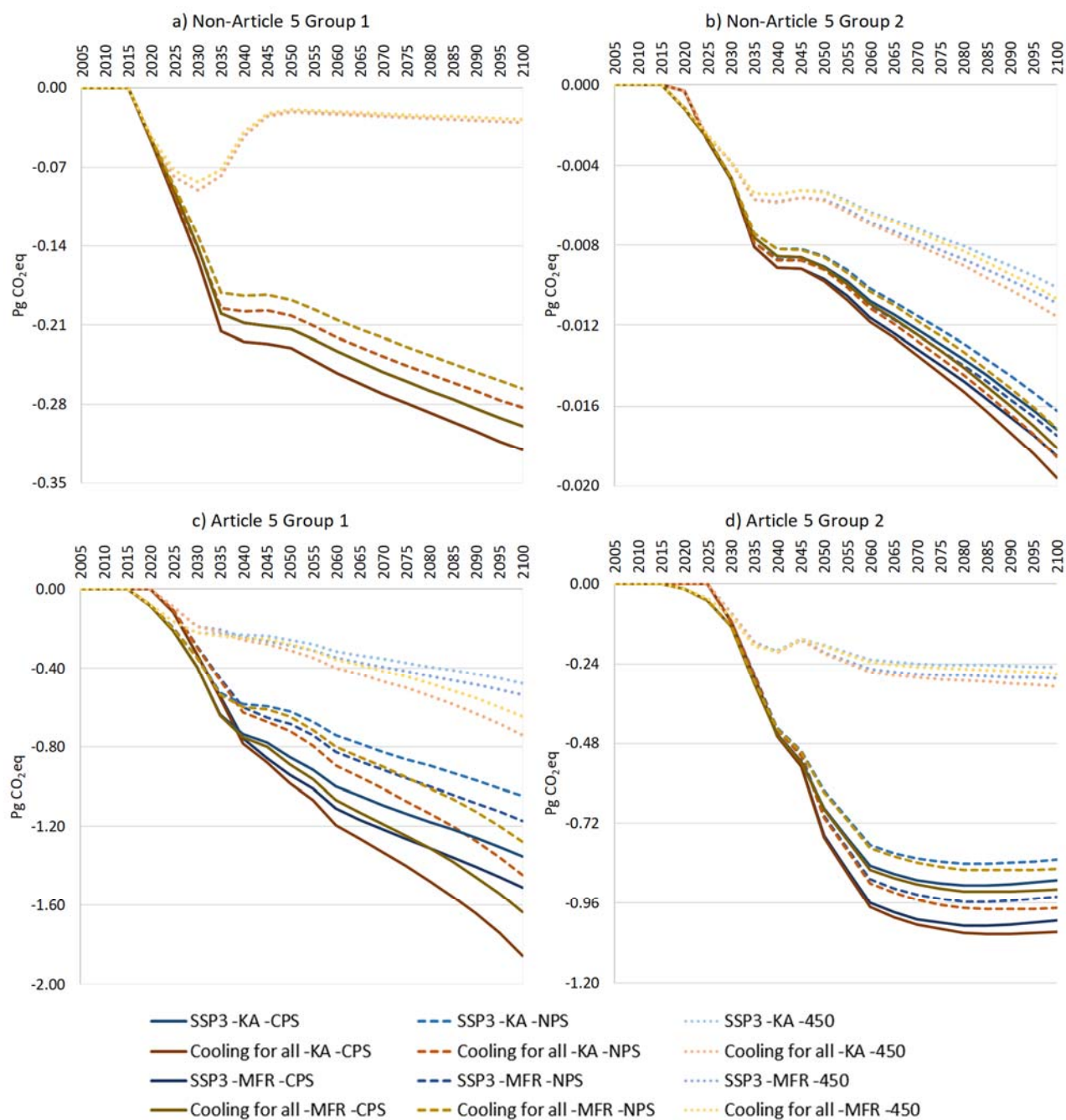
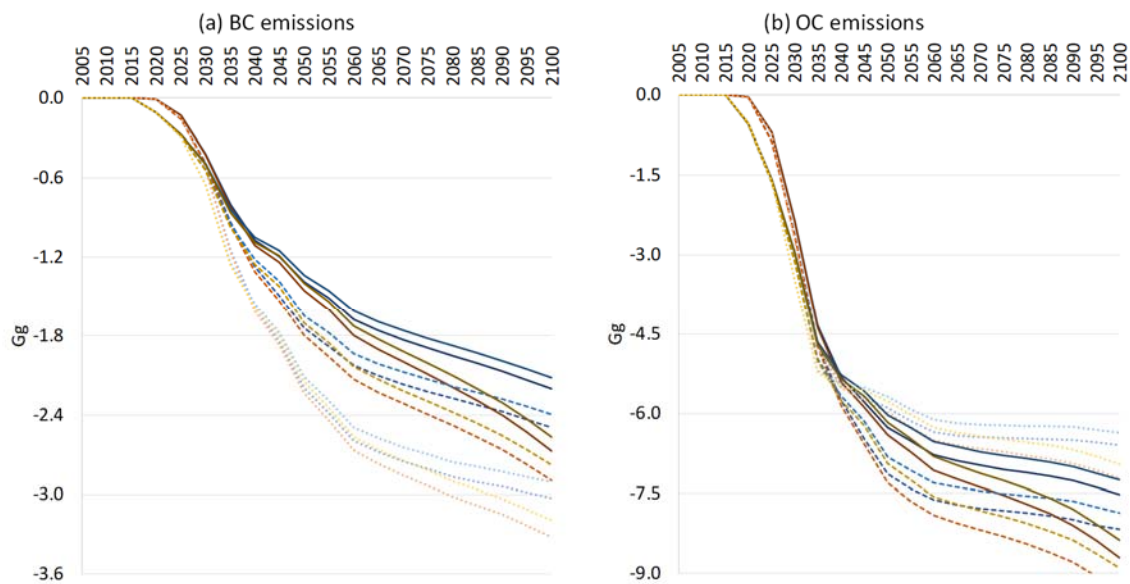


Figure S7: Greenhouse gas emissions reductions in the baseline (SSP3 and *Cooling for All*) and alternative (Kigali Amendment -KA and Maximum Technically Feasible Reductions -MFR) scenarios due to economic electricity savings potential by different party groups

Technical energy efficiency potential



Economic energy efficiency potential

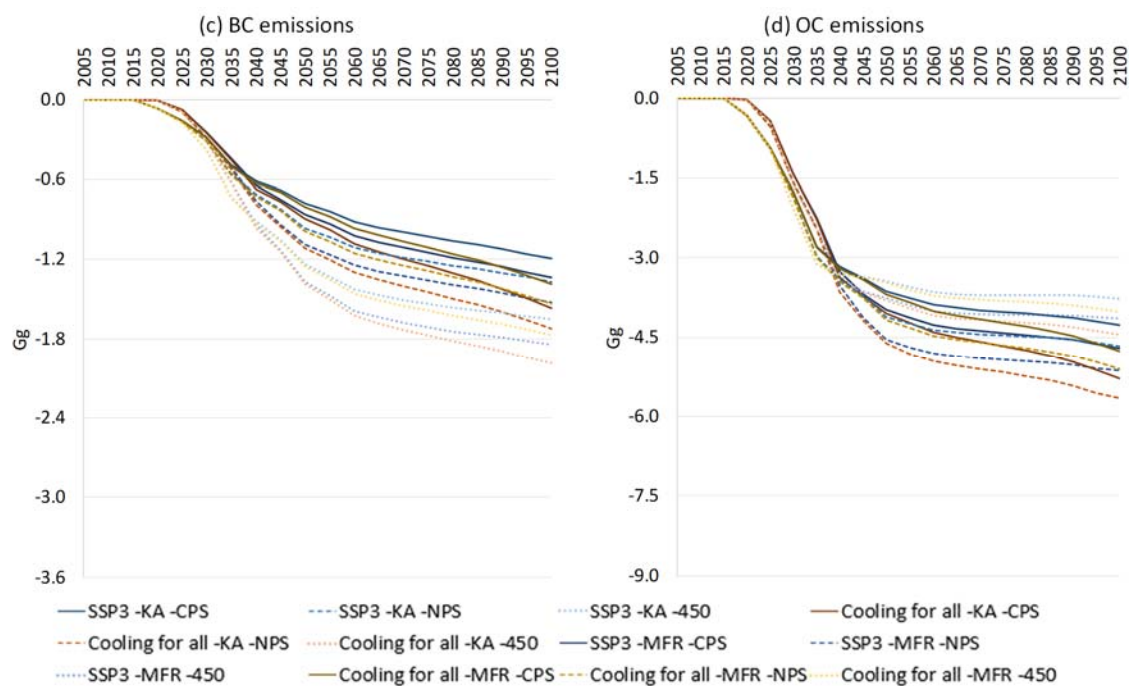


Figure S8: Impacts on BC/OC emissions due to electricity savings associated with alternative HFC phase-down pathways.

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