Cost estimates of the Kigali Amendment to phase-down hydrofluorocarbons

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ABSTRACT: Hydrofluorocarbons (HFCs) are synthetically produced compounds primarily used for cooling purposes and with strong global warming properties. In this paper, we analyze the global abatement costs for achieving the substantial reductions in HFC consumption agreed in the Kigali Amendment (KA) of the Montreal Protocol from October 2016. We estimate that compliance with the KA is expected to remove 39 Pg CO_2eq or 61 percent of global baseline HFC emissions over the entire period 2018 to 2050. The marginal cost of meeting the KA targets is expected to remain below 60 €/t CO_2eq throughout the period in all world regions except for developed regions where legislation to control HFC emissions has already been in place since a few years. For the latter regions, the required HFC consumption reduction is expected to come at a marginal cost increasing steadily to between 90 and 118 €/t CO_2eq in 2050. Depending on the expected rate of technological development and the extent to which envisaged electricity savings can be realized, compliance with KA is estimated attainable at a global cost ranging from a net cost-saving of 240 billion € to a net cost of 350 billion € over the entire period 2018 to 2050 and with future global electricity-savings estimated at between 0.2% and 0.7% of expected future electricity consumption.

Introduction

Hydrofluorocarbons (HFCs) are synthetically produced compounds primarily used for cooling purposes and with strong global warming properties. Currently, HFCs account for only about 1.5 percent of global human-made greenhouse gas emissions (IPCC, 2014), however, growing demand for cooling services, in particular in developing countries, threatens to increase HFC emissions manifold over the next decades (Velders et al., 2015; USEPA, 2013). In a recently published paper, Purohit and Höglund-Isaksson (2017) present an extension of the Greenhouse Gas - Air Pollution Interactions and Synergies (GAINS) model to cover global fluorinated greenhouse gas (F-gas) emissions, abatement potentials and costs over the period 2005 to 2050. The resolution is at a sector and technology level for 162 country/regions in five-year intervals. In this paper, we use the GAINS model framework to analyze abatement potentials and costs for achieving the deep cuts in HFC consumption by 2050 set out in the Kigali Amendment (KA) to the Montreal Protocol (MP) agreed on in the 28th Meeting of the Parties to the Montreal Protocol, 8-14 October 2016 in Kigali, Rwanda.

The purpose of the Kigali meeting and of the process leading up to the meeting was to amend the MP with control of HFC production and consumption in order to ensure that the phase-out of ozone-depleting substances (ODSs) does not mean substitution with high global warming HFCs, but a switch to alternatives with none or very low global warming potentials (UNEP, 2016a). The KA specifies relative HFC consumption reduction targets from pre-determined baseyear levels for four different Party groups and allows for flexibility of a few years for complying with the targets. In a further amendment of the MP (UNEP, 2016b), the use of the Multilateral Fund to facilitate compliance with the KA by providing financial and technological assistance is specified, however, without providing exact amounts of the additional funding needed and its distribution. This will be agreed upon at the next meeting of the Parties in October 2017 in Montreal, Canada. We hope the findings of this study can provide useful insights for the future distribution of funds across different Party groups.

The KA defines HFC phase-down schedules for four different Party groups. The first group includes 136 primarily developing countries that make up all Article 5 countries as specified under the MP 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 MP are primarily developed countries and under the KA 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. We will hereafter refer to these four Party groups as Article 5 Group I, Article 5 Group II, non-Article 5 Group I, and non-Article 5 Group II.

Method

Estimating baseline HFC emissions

The GAINS baseline scenario for emissions of HFCs has been described in Purohit and Höglund-Isaksson (2017). For major sources, i.e., residential and commercial air-conditioning, mobile air-conditioning and domestic refrigeration, the consumption of HFC in historical years 2005 and 2010 has been derived in a consistent manner across countries, starting from a compilation of data on underlying drivers, e.g., number of vehicles by vehicle types, commercial floor space area, cooling degree days, per capita income, average household sizes, current equipment penetration rates, etc. HFC consumption in commercial and industrial refrigeration, refrigerated transport, foams and other smaller HFC sources, varies greatly between countries e.g., due to differences in industrial structures and consumption patterns, which makes it more challenging to model the HFC consumption consistently across countries from underlying data. For these sectors, historical HFC consumption in years 2005 and 2010 as reported by Annex 1 countries in the Common Reporting Formats (CRFs) to the UNFCCC (2012), has been adopted when available. For non-Annex 1 countries, information on HFC consumption in these sectors has been compiled from various published sources (MoEF, 2009; UNEP, 2011; GIZ, 2014; UNDP, 2014a-b), alternatively, derived in a consistent manner from underlying activity data using default factors from literature. Drivers for future HFC consumption are consistent with the macroeconomic development projected in the Reference scenario of the IEA's Energy Technology Perspectives 2012 (IEA/ETP, 2012) for non-European Union regions and with the Reference scenario of the PRIMES model (Capros et al. 2013) for the European Union. Effects on HFC emissions from uptake of alternative technologies and/or substances are only accounted for to the extent that these technologies have already been adopted or will be required to be adopted in the future to comply with implemented legislation. Such policies include e.g., the EU F-gas regulations from 2006 and 2014, the US SNAP program and air conditioning improvement credits, and Japan's Act on the rational use and proper management of fluorocarbons, see Table 1 of Purohit and Höglund-Isaksson (2017) for a full list of policies assumed adopted in the baseline. Assumptions on cost parameters, e.g., fixed investment costs, operation and maintenance costs, and cost-savings due to improved energy efficiency, are provided in Table S1 of the Supplement. Cost parameters used here are an update of those presented in Purohit and Höglund-Isaksson (2017) and are thought to reflect the very latest knowledge, in particular with respect to possible energy efficiency improvements when using alternative substances and technologies to switch away from HFCs.

The GAINS baseline does not account for future uptake of abatement technology on the sole basis of estimated marginal abatement costs turning out zero or negative. Apart from uncertainty being high in cost estimates in general, there may exist other barriers for technology spread and adoption, e.g., institutional or informational barriers, which are difficult to reflect in a general model setting like GAINS. As basis for informing policy-makers of the need for future policies, we therefore find it constructive to define a baseline which reflects a continuation of the current situation rather than risk making overly optimistic assumptions about technology uptake on the basis of uncertain cost estimates.

Converting consumption targets to emission targets

To analyze expected emission reductions and abatement costs for meeting the KA, we start from the KA targets for phasing down consumption of HFCs and hydrochlorofluorocarbons (HCFCs) (UNEP, 2016a). For each Party group, a baseyear HFC and HCFC consumption level is specified against which consumption reduction targets are defined. The baseyear HFC and HCFC consumption level for Article 5 Group I is defined as the average consumption in years 2020, 2021 and 2022, for Article 5 Group II as the average consumption in years 2024, 2025 and 2026, and for both the non-Article 5 Groups as the average consumption in years 2011, 2012 and 2013. We convert the KA baseyear HFC and HCFC consumption to emissions in CO_2eq terms by adopting estimated GAINS baseline HFC and HCFC emissions in years 2020, 2025, and 2010, respectively, as baseyear emission levels. The relative consumption reduction targets of the KA are applied as relative emission reduction targets. The GAINS model is defined for every five years and baseyear and target compliance years have therefore been set to the nearest year represented in GAINS. Table 1 shows the respective baselines and HFC and HCFC consumption reduction targets as specified in the KA and as converted to emission levels for the analysis in GAINS. Note that HCFC emissions are phased-out (and partly replaced by HFCs) following earlier commitments made by parties to phase-down ODSs under the MP (UNEP, 2007).

Table 1. HFC and HCFC consumption reduction targets agreed in the Kigali Amendment (UNEP, 2016a) and interpreted as emission reduction targets in the GAINS model analysis.

	Kigali Amendment		GAINS model interpretation of impact on emissions			
Party group	Compliance period	HFC & HCFC consumption phase-down	Compliance year	HCFC emissions Tg CO_2eq	HFC emissons Tg CO_2eq	HFC & HCFC Tg CO_2eq (% of baseyear emissions)
Article 5 Group I	Baseyear: 100% of average HFC consumption 2020-2022 and 65% of baseline HCFC consumption		2021	155.8	608.9	764.7 (100%)
	2024 to 2028	100%	2025	43.7	721.0	764.7 (100%)
	2029 to 2034	90%	2030	3.3	684.9	688.2 (90%)
	2035 to 2039	70%	2035	3.3	532.0	535.3 (70%)
	2040 to 2044	50%	2040	0	382.4	382.4 (50%)
	2045 onwards	20%	2045 onwards	0	152.9	152.9 (20%)
Article 5 Group II	Baseyear: 100% of average HFC consumption 2024-2026 and 65% of baseline HCFC consumption		2025	13.9	123.3	137.2 (100%)
	2028 to 2031	100%	2030	0.5	136.7	137.2 (100%)
	2032 to 2036	90%	2035	0.5	122.9	123.4 (90%)
	2037 to 2041	80%	2040	0	109.7	109.7 (80%)
	2042 to 2046	70%	2045	0	96.0	96.0 (70%)
	2047 onwards	15%	2050	0	20.6	20.6 (15%)
non-Article 5 Group I	Baseyear: 100% of average HFC consumption 2011-2013 and 15% of baseline HCFC consumption		2012	24.6	378.1	402.7 (100%)
	2019 to 2023	90%	2020	0	362.4	362.4 (90%)
	2024 to 2028	60%	2025	0	241.6	241.6 (60%)
	2029 to 2033	30%	2030	0	120.8	120.8 (30%)
	2034 to 2035	20%	2035	0	80.5	80.5 (20%)
	2036 onwards	15%	2040 onwards	0	60.4	60.4 (15%)
non-Article 5 Group II	Baseyear: 100% of average HFC consumption 2011-2013 and 25% of baseline HCFC consumption		2012	8.0	30.3	38.3 (100%)
	2020 to 2024	95%	2020	0	36.4	36.4 (95%)
	2025 to 2028	65%	2025	0	24.9	24.9 (65%)
	2029 to 2033	30%	2030	0	11.5	11.5 (30%)
	2034 to 2035	20%	2035	0	7.7	7.7 (20%)
	2036 onwards	15%	2040 onwards	0	5.8	5.8 (15%)

Defining HFC abatement costs

GAINS abatement cost estimates follow the principles of cost-benefit analysis theory and praxis (Dreze and Stern, 1987; EC, 2014). According to standard theory of public economics in the presence of market imperfections (e.g., Baumol and Oates, 1988; Dreze and Stern, 1987), society's welfare is made up by all costs and benefits suffered or enjoyed from production and consumption of goods and services no matter whether these have a market value (which allows them to be easily quantified in monetary terms) or not (e.g., the cases of health, environmental quality, and societal stability). In the case of HFC production and consumption, the costs to society constitute the sum of the cost of production and the loss in environmental quality in terms of the global warming effect that consumption and release of HFCs cause in the atmosphere. The benefits of HFC production and consumption are made up by the sum of the profits enjoyed by the HFC producers and the cooling and other services enjoyed by HFC consumers. Because environmental quality is a resource which usually cannot be traded in markets, it risks being over-utilized in a market economy where the relative scarcity of resources are reflected in market prices. In the case of emissions of HFCs and other greenhouse gases, we know from the scientific consensus established by the Intergovernmental Panel on Climate Change (IPCC, 2013) that substantial reductions in all greenhouse gas emissions are necessary to avoid potentially catastrophic levels of global warming. Hence, to enhance society's welfare, it is necessary to weigh the benefits of reduced HFC emissions, and thereby limited risks of climate change, against the costs of replacing HFC consumption with alternative substances and techniques that can ensure the same level of cooling and other services currently enjoyed through HFC consumption. Given that we accept the scientific consensus of IPCC that substantial reductions in greenhouse gas emissions are indeed necessary, we do not need to value the environmental benefits of HFC reductions in monetary terms, but instead focus on optimizing society's welfare by finding the least costly way to achieve the emission reduction targets that are deemed necessary by replacing current HFC consumption with viable alternatives.

According to economic theory (e.g., Baumol and Oates, 1988, p.55), under perfectly competitive market conditions, market prices equal shadow prices of production and as such are reflections of the marginal cost of production. Although markets are never perfect in reality, we assume as an approximation that a part of the cost of replacing HFCs with alternative substances can be measured as the difference in market prices between the two substances. In addition, there may be other costs involved that are not reflected in the unit market price, e.g., some alternatives may require initial investments into new equipment, imply changes in the use of electricity, or be flammable and require extra training of staff handling the substances. In GAINS, we are able to capture most of these costs through information provided in published literature (see Table S1 of the Supplement for further details). A cost that is difficult to estimate, and for which there exists very little information in literature, is that for extra training of staff should such be required to correctly handle flammable or toxic substances. This particular cost may therefore be underestimated here. When the market price of an alternative substance is lower than that for the HFC currently in use or when expected energy efficiency improvements are substantial, the unit cost of switching away from HFCs may turn negative. It should be noted that a negative cost may not automatically lead to technology uptake as there may be other barriers to immediate implementation, e.g., extra training of staff or local market regulations that distort prices in unfavorable ways.

Note also that in consistency with standard economic theory, we do not consider the cost of HFC plant closure to have a lasting negative effect on social welfare. Instead, and despite that plant closures can have dire temporary implications for local employment, the closure of HFC production plants is considered part of normal transitions that continuously take place in a global market economy when an outdated product is replaced by an improved product.

When summarizing cumulative costs over time we add up estimated annual costs made up of variable costs per year and fixed costs annualized over the lifetime of the equipment using an interest rate of four percent. This means, using the distinction by Goulder and Williams (2012) between the financial-equivalent and the social-welfare-equivalent discount rates, that only the financial-equivalent discount rate is considered here. This facilitates the policy implications of the results as it allows for interpreting the resulting marginal cost estimates as the opportunity cost level decisive for abatement uptake to happen in a given year. All cost information presented in this study is expressed in constant 2010 Euros.

Sensitivity analysis

When specifying HFC abatement costs, we identify two factors with particularly high potential to contribute to uncertainty in future abatement costs. These are the impact on costs of the future rate of technological development and of the extent to which envisaged improvements in energy efficiency can be fully realized. To reflect the uncertainty in costs with respect to these two factors, we define three alternative cost scenarios; a “Medium cost” scenario -assuming no effect on costs from technological development but with improvements in energy efficiency in sectors where such can be expected according to recent literature (see Table S1 of the Supplement for details), a “Low cost” scenario –assuming both technological development and improvements in energy efficiency, and a “High cost” scenario –assuming no technological development and improvements in energy efficiency limited only to ammonia use in industrial refrigeration.

From surveying the literature on the current state of technology, we conclude that replacement of HFCs with ammonia or hydrocarbons like propane or isobutane, or switches to CO_2-based technologies, could come with reduced electricity consumption in the sectors listed in Table 2 (USEPA, 2016a; USEPA, 2016b; Tsamos, 2017; Purohit et al., 2017; Schwartz et al., 2011; Wang et al., 2014). Particularly well documented through wide-spread implementation are electricity savings in industrial refrigeration when switching away from HFCs to ammonia (EIA, 2012). Future electricity savings in industrial refrigeration are therefore not put into question here, however, when defining the "High cost" scenario no electricity savings are assumed realized in any of the other sectors listed in Table 2.

Table 2: Specifications of sectors and options assumed to come with electricity savings in the respective cost scenarios ("Medium cost", "Low cost", "High cost").

Sectors and options with assumed electricity savings (in %)	
"Medium cost" and "Low cost" scenarios	"High cost" scenario
Refrigerated transport: CO_2-based (-2%) and propane (-4%) Industrial refrigeration: ammonia (-15%) Residential AC: Propane (-6%) Commercial refrigeration: CO_2-based (-4.5%) and propane (-4.5%) Domestic refrigeration: Isobutane (-1.6%)	Industrial refrigeration: ammonia (-15%)

Technological development may reduce the future cost of HFC abatement as demand for alternative substances and technologies increases in order to comply with the KA. The rate of technological development will be determined by the stringency of national policies implemented and their effectiveness in stimulating continuous technological development (Popp, 2003). A common way to represent technological development in assessment models is to make assumptions about the learning effect on costs from cumulative technology adoption (see e.g., Jamasb and Köhler 2007). As described in more detail in Section S3 of the Supplement, we define for the purpose of a sensitivity analysis a "Low cost" scenario in which the rate of technological development is accounted for through year-specific multiplication factors presented in Table 3 and applied to fixed investment costs and operation and maintenance costs.

Table 3: Specifications of assumed multiplication factors in the analyzed cost scenarios ("Medium cost", "Low cost", "High cost").

Multiplication factors reflecting the rate of technological development		
Year	"Medium cost" and "High cost" scenarios	"Low cost" scenario
2020	1	1
2025	1	0.92
2030	1	0.88
2035	1	0.84
2040	1	0.81
2045	1	0.78
2050	1	0.72

Results

Baseline HFC emission scenario

Figure 1 presents GAINS baseline HFC emissions converted to CO_2eq terms using GWP_{100} with carbon-climate feedback effects from IPCC's Fifth Assessment Report (AR5) (IPCC, 2013). Strong future growth in HFC emissions is expected in the baseline in Article 5 countries primarily driven by an increase in demand for cooling services from mobile and stationary air conditioners. Note that HFC emissions in Article 5 countries in 2005 and 2010 almost exclusively come from mobile air conditioning as cooling demand in other sectors is largely covered through HCFCs. For non-Article 5 countries, major HFC sources are commercial and industrial refrigeration and refrigerated transport. This finding is roughly consistent with the sector distribution of emissions reported by non-Article 5 countries to the UNFCCC (2016) for historical years and shown in the far right graph in Figure 1. Note that the absolute emission level reported by non-Article 5 countries is less than the GAINS estimate, because not all non-Article 5 countries report to UNFCCC and for some countries reporting is incomplete at the sector level. Commercial refrigeration is expected to remain a major sector for HFC emissions in non-Article 5 countries also in the future. By 2050, it is expected that air conditioning sources make up about 30 percent and refrigeration sources about 70 percent of the sum of refrigeration and air conditioning sources in non-Article 5 countries. For Article 5 countries the opposite is true, with roughly 30 percent from refrigeration sources and 70 percent from air conditioning sources. As we will see in the subsequent analysis, this difference in sectoral distribution of HFC emissions between Article 5 and non-Article 5 countries has implications for the cost of achieving substantial emission cuts in the future.

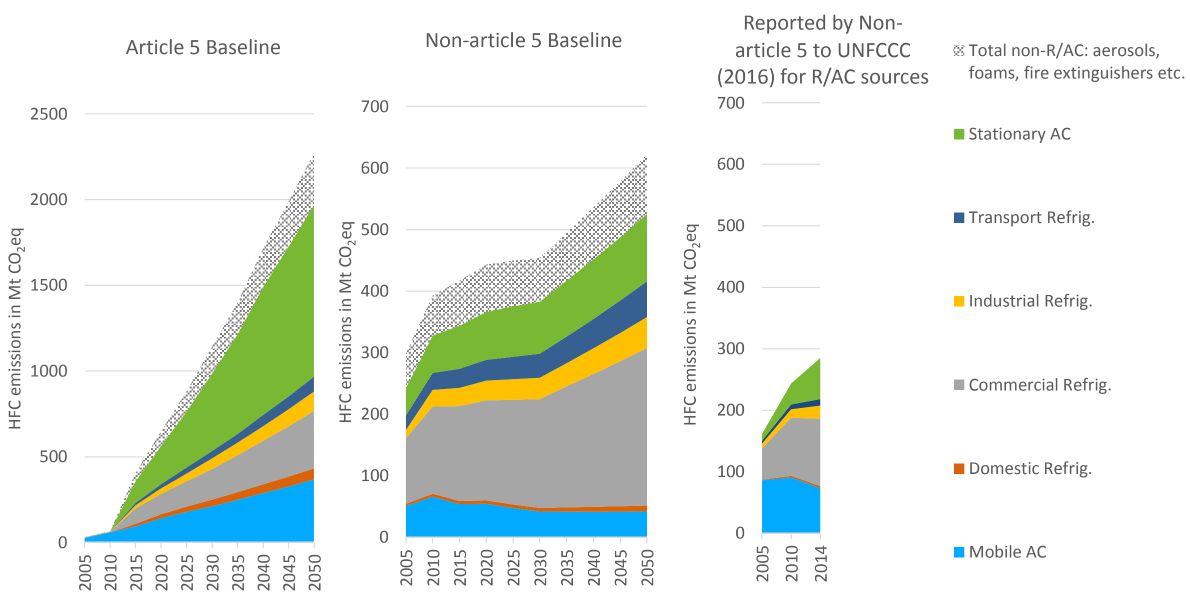

Figure 1. GAINS model Baseline scenarios for HFC emissions by Article 5 and non-Article 5 countries and in comparison to emissions reported to UNFCCC (2016) by Annex-1 countries that are also non-Article 5 countries.

HFC abatement when complying with KA in 2050

As an illustration of the estimated baseline emissions and the emission reductions by different abatement options in specific sectors expected to follow from compliance with the KA, Table 4 provides detailed results for year 2050 with corresponding abatement costs presented in Table 5. The maximum technical abatement potential below baseline emissions in 2050 exceeds 98 percent for all Party groups except the non-Article 5 Group I countries, for which it is limited to 91 percent. In the latter group we find several countries (i.e., EU-28, Canada, USA, Australia, New Zeeland, Norway, Switzerland and Japan) that have already binding legislation in place to control HFC emissions which limits the relative potential for additional abatement. Usually, these measures are good practice measures which limit leakage and require end-of-life recollection. They may, however, also include requirements to switch away from HFCs to alternative substances e.g., CO_2 or unsaturated HFCs (HFOs) or, as in the case of EU's F-gas regulation, allow for switching to HFCs with relatively low global warming potentials (e.g., HFC-152a). Effects on future emissions from existing legislation have been accounted for in the baseline. With some abatement potential achieved already through good practices –investments that become redundant when HFCs are replaced with substances without global warming potential- the additional future abatement potential becomes relatively more limited in these countries. This also means that the marginal abatement cost for achieving additional abatement through replacement with alternative substances is higher because the relative emission reduction achieved is smaller when good practice systems are already in place.

In particular non-Article 5 Group II countries are expected to have a relatively large abatement potential available at zero cost or net profit, estimated at 46% below baseline emissions in 2050. For Article 5 Group II countries the corresponding abatement potential is limited to 25% below baseline emissions in 2050 (see last row of Table 4). This can be explained by the differences in the sector distribution of future emissions. Due to the temperate climate of most non-Article 5 countries, demand for cooling services is to a great extent dominated by industrial and commercial refrigeration, which have relatively extensive opportunities to replace HFCs with low cost alternatives (see Table 5). In contrast, several Article 5 countries are located in high ambient air temperature zones and therefore expected to have strong future growth in demand for cooling services from mobile and stationary air conditioners for which alternative options to HFCs are relatively costly (see Table 5). Estimated total annual abatement costs in 2050 ranges from net cost-savings to net costs for all Party groups except for Article 5 Group II, which is expected to have relatively high costs for switching to HFOs in mobile and commercial air conditioning.

Table 4. Estimated baseline emissions and abatement under Kigali Amendment (KA) in year 2050 by Party group and type of abatement option.

			Article 5 Group I		Article 5 Group II		non-Article 5 Group I		non-Article 5 Group II		Global	
HFC source	Abatement option	Marginal cost[a] €/t CO_2eq	Baseline emissions Tg CO_2eq	Abatement under KA compliance Tg CO_2eq	Baseline emissions Tg CO_2eq	Abatement under KA compliance Tg CO_2eq	Baseline emissions Tg CO_2eq	Abatement under KA compliance Tg CO_2eq	Baseline emissions Tg CO_2eq	Abatement under KA compliance Tg CO_2eq	Baseline emissions Tg CO_2eq	Abatement under KA compliance Tg CO_2eq
Industrial refrigeration	Ammonia	-71.7 to -45.6	109.7	-109.7	7.3	-7.3	39.5	-37.8	12.1	-12.1	169	-167
Commercial refrigeration	Propane[c]	-49.7 to -11.0	297.7	-59.5	42.4	-8.5	238.3	-46.4	20.3	-4.1	599	-118
Refrigerated transport	CO_2-based	-29.7 to -19.3	90.0	-89.9	18.4	-18.4	66.5	-63.3	5.8	-5.8	181	-177
Foams	CO_2-based	-18.2 to -2.1	144.7	-144.5	21.0	-20.6	45.9	-45.8	8.4	-8.4	220	-219
Residential AC	Propane	-15.9 to -11.1	312.4	-312.0	97.3	-97.1	36.1	-33.3	12.9	-12.9	459	-455
Commercial AC	Propane[c]	-4.8 to 40.5	304.1	-60.7	239.2	-47.8	53.2	-9.8	7.8	-1.6	604	-120
Aerosols	Propane	-1.7	2.1	-1.2	0.3	-0.2	23.6	-9.4	1.1	-0.7	27	-12
Solvents	Ban on use	0.6	52.3	-52.3	0.6	-0.6	3.5	-3.3	0.4	-0.4	57	-57
Domestic refrigeration	Isobutane	0.5 to 3.1	54.1	-54.0	14.3	-14.9	4.6	-3.1	5.6	-5.6	79	-78
Fire extinguishers	Flouroketone	2.5 to 6.2	60.8	-60.8	25.3	-25.3	6.9	-6.0	4.0	-4.0	97	-96
Commercial refrigeration	CO_2-based	11.7 to 178[b]	--[d]	-238.1	--[d]	-33.9	--[d]	-168.1	--[d]	-16.2	--[d]	-456
Mobile AC -heavy duty trucks	CO_2-based	13.8 to 33.7[b]	10.2	-10.2	9.8	-9.8	1.2	-1.2	0.5	-0.5	22	-22
Mobile AC -light duty vans	CO_2-based	13.8 to 33.7[b]	40.6	-40.6	47.2	-47.2	9.0	-8.9	2.9	-2.9	100	-100
Mobile AC -cars	HFO-1234yf	46.6 to 117[b]	190.7	-190.2	76.1	-75.9	18.0	-16.9	11.8	-11.8	297	-295
Mobile AC -buses	HFO-1234yf	60.6 to 140[b]	17.6	0	7.0	0	1.3	-0.5	0.9	0	27	0
Commercial AC	HFO-1234yf	32.8 to 160[b]	--[d]	-111.8	--[d]	-179.0	--[d]	-39.3	--[d]	-2.3	--[d]	-332
Ground-source heat pumps	Propane	80.8 to 193[b]	1.5	0	0.1	0	6.1	-0.1	0.3	0	8	0
Options at very high marginal cost		> 200	--[d]	0	--[d]	0	--[d]	0	--[d]	0	--[d]	0
Sum in 2050			1689	-1536	606	-586	554	-493	95	-89	2943	-2704
Relative reduction required to meet KA in 2050				-91%		-97%		-89%		-94%		-92%

[a] Marginal abatement cost range in 2050 in the Reference scenario

[b] High-end marginal cost applicable to non-Article 5 Group I countries that have a relatively lower abatement potential due to measures already adopted in response to existing F-gas regulations.

[c] Use of propane in commercial refrigeration and air conditioning is assumed limited to max 20% of installed capacity due to technical limitations for using propane in stand-alone hermetic units with large charge sizes.

[d] Baseline emissions by sector are displayed with the first mitigation option appearing in the table.

Table 5: Estimated annual costs by sector for meeting the Kigali Amendment in 2050 in the three specified cost scenarios ("Medium cost", "Low cost", "High cost").

HFC source	Abatement option	Article 5 Group I			Article 5 Group II			non-Article5 Group I			non-Article5 Group II			Global		
		"Low cost"	"Medium cost"	"High cost"	"Low cost"	"Medium cost"	"High cost"	"Low cost"	"Medium cost"	"High cost"	"Low cost"	"Medium cost"	"High cost"	"Low cost"	"Medium cost"	"High cost"
			million €			million €			million €			million €			million €	
Industrial refrigeration	Ammonia	-8575	-6746	-6746	-572	-451	-451	-2787	-2076	-2076	-1014	-787	-787	-12948	-10060	-10060
Commercial refrigeration	Propane	-1355	-941	95	-196	-137	14	-1801	-1347	-202	-103	-71	7.4	-3455	-2495	-86
Refrigerated transport	CO_2-based	-3033	-2203	-530	-620	-451	-108	-2112	-1444	-427	-220	-159	-39	-5985	-4257	-1105
Foams	CO_2-based	-428	-305	-305	-62	-45	-45	-181	-129	-129	-25	-18	-18	-697	-497	-497
Residential AC	Propane	-4642	-4642	-464	-1509	-1509	-145	-422	-422	-50	-186	-186	-19	-6760	-6760	-678
Commercial AC	Propane	1846	2462	2462	948	1265	1265	106	150	150	48	63	63	2948	3941	3941
Aerosols	Propane	-2.1	-2.1	-2.1	-0.3	-0.3	-0.3	-16.3	-16.3	-16.3	-1.1	-1.1	-1.1	-20	-20	-20
Solvents	Ban on use	24	32	32	0.3	0.4	0.4	1.5	2.0	2.0	0.2	0.3	0.3	26	34	34
Domestic refrigeration	Isobutane	-37	33	137	-12	7.4	37.7	-1.3	5.6	23	-3.6	3.6	14	-54	49	212
Fire extinguishers	Flouroketone	114	151	151	48	63	63	23	30	30	7.6	10	10	193	254	254
Commercial refrigeration	CO_2-based	-176	3134	7277	-37	435	1037	-294	3241	7263	-5.7	252	566	-513	7062	16143
Mobile AC -heavy duty trucks	CO_2-based	90	141	141	86	134	134	23	37	37	4.2	6.6	6.6	204	318	318
Mobile AC -light duty vans	CO_2-based	358	559	559	417	649	649	173	277	277	26	40	40	973	1525	1525
Mobile AC -cars	HFO-1234yf	6658	8760	8760	2656	3494	3494	1408	1853	1853	413	544	544	11135	14651	14651
Mobile AC -buses	HFO-1234yf	0	0	0	0	0	0	21.0	27.6	27.6	0	0	0	21	28	28
Commercial AC	HFO-1234yf	5228	6879	6879	5438	7155	7155	1432	1881	1881	106	139	139	12203	16054	16054
Ground-source heat pumps	Propane	0	0	0	0	0	0	7.4	9.9	9.9	0	0	0	7	10	10
Options at very high marginal cost		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sum annual cost in 2050 (million €)		-3930	7310	18443	6584	10612	13101	-4420	2079	8654	-955	-164	527	-2721	19837	40724

Emissions and abatement cost pathways to 2050

In total over the entire period 2018 to 2050, full implementation of the KA is estimated to reduce the global release of HFC emissions by 39 Pg CO_2eq or 61 percent below baseline emissions, as summarized in Table 6. Depending on the expected rate of technological development and the extent to which envisaged electricity savings can be realized in the future, compliance with the KA is estimated possible at a global cost ranging from net cost-savings of 240 billion € to net costs of 350 billion €. Global electricity savings are estimated at between 2300 and 7100 TWh over the entire period 2018 to 2050. This corresponds to between 0.2% and 0.7% of expected future global electricity consumption over the same period as estimated in the New Policies Scenario of the IEA-WEO (2016).

Table 6: Estimated cumulative emissions and abatement costs over the entire period 2018 to 2050.

Scenario	Cumulative variable 2018-2050	Unit	Article 5 Group I	Article 5 Group II	non-Article 5 Group I	non-Article 5 Group II	Global
All scenarios	Baseline emissions	Tg CO_2eq	37431	9777	15018	2333	64559
	Emissions when meeting KA	Tg CO_2eq	16385	3459	4839	479	25162
	Reduction in emissions	Tg CO_2eq	-21047	-6317	-10179	-1854	-39397
	Relative reduction in cumulative emissions	%	-56%	-65%	-68%	-79%	-61%
"Medium cost" scenario	Total costs for meeting KA	billion €	-65	63	16	-4	11
	Electricity savings	TWh	2999	434	3334	331	7097
"Low cost" scenario	Total costs for meeting KA	billion €	-178	32	-81	-15	-243
	Electricity savings	TWh	2999	434	3334	331	7097
"High cost" scenario	Total costs for meeting KA	billion €	99	97	142	11	348
	Electricity savings	TWh	1085	60	1005	163	2313

The upper Panels 2a, 2b, 3a and 3b in Figures 2 and 3 show HFC emission reduction pathways in the baseline (black line), in the case of maximum technically feasible implementation of emission control (dashed line), and when meeting the HFC consumption targets set out in the KA (red line). The lower Panel 2c in Figure 2 shows how for Article 5 Group I compliance with KA means estimated net annual abatement costs remain below zero until 2040, because there are enough low cost or profitable abatement opportunities e.g., in industrial refrigeration and residential air conditioning (AC), to meet the targets at very low costs. After 2040 annual costs increase as the emission reductions that correspond to the HFC consumption targets require further adoption of abatement capacity also in sectors with relatively more costly abatement. Panel 2d in Figure 2 shows how the Article 5 Group II region has relatively small opportunities to reduce emissions in sectors with low abatement costs. Estimated annual costs for complying with KA therefore increase steadily already from 2030 onwards. Panel 3c in Figure 3 shows how the estimated abatement cost pathways for KA compliance of the non-Article 5 Group I vary considerably between different cost scenarios. The reason is that this Party group has a relatively large abatement potential in commercial refrigeration for which energy efficiency enhancements of 4.5% are envisaged possible when switching to propane or CO_2-based technology and relatively limited abatement potentials in stationary and mobile AC for which energy efficiency savings are not envisaged when switching to HFO-1234yf. Finally, Panel 3d in Figure 3 shows the estimated annual abatement cost pathways of the non-Article 5 Group II region. Due to relatively large low cost abatement potentials in industrial and commercial refrigeration and relatively limited reduction potentials in stationary and mobile AC, this Party group is expected to meet the KA targets at zero costs or net profits, given that envisaged electricity savings can be realized in more sectors than industrial refrigeration.

Figure 4 shows the estimated marginal abatement cost levels required to meet the KA targets by respective Party groups and under different cost scenarios. As shown, despite lower total abatement costs in the “Low cost” scenario compared with the “Medium cost” and “High cost” scenarios, the required marginal abatement cost level is not affected much by different rates of technological development or by differences in electricity savings realized. A reason is that options at higher marginal abatement cost levels, e.g., the use of HFOs in mobile and commercial AC, are not expected to come with substantial electricity savings. For both Article 5 Party groups (Panels 4a and 4b), the marginal abatement cost level required to comply with KA is estimated to remain close to zero until 2030 and then increase to between 43 and 57 Euro/t CO_2eq in 2050. For non-Article 5 Group I, the required marginal abatement cost level starts increasing already after 2020 to a level between 38 and 45 Euro/t CO_2eq, and from 2040 onwards come close to or exceed 100 Euro/t CO_2eq (Panel 4c). For non-Article 5 Group II, the required marginal abatement cost level is estimated to remain between 37 and 57 Euro/t CO_2eq over the entire period 2025 to 2050. The reason for the steeper increase in the required marginal cost level for non-Article5 Group I is that for this Party group the emission reduction targets that correspond to the KA HFC consumption targets are relatively closer to an emission reduction that is deemed maximum technically feasible given that many of these countries have already legislation implemented to control the use of HFCs. It should however be noted that if the cost of HFOs drops at a faster rate than suggested by the rate of technological development adopted here in the “Low cost” scenario, the marginal cost required for KA compliance could become lower in all Party groups.

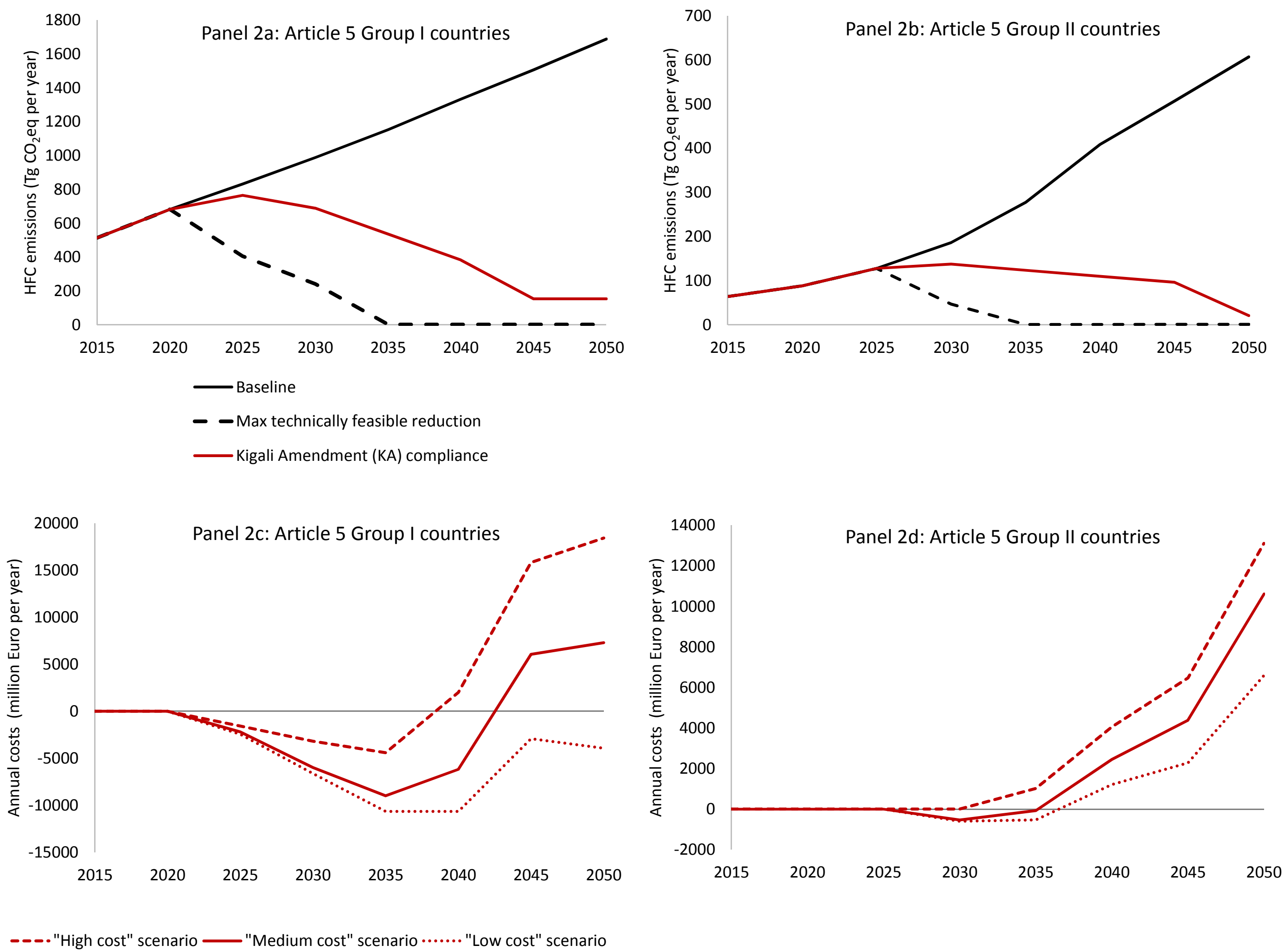

Figure 2. Annual HFC emissions and costs for complying with Kigali amendment targets for Article 5 Group I countries (Panels 2a and 2c) and Article 5 Group II countries (Panels 2b and 2d).

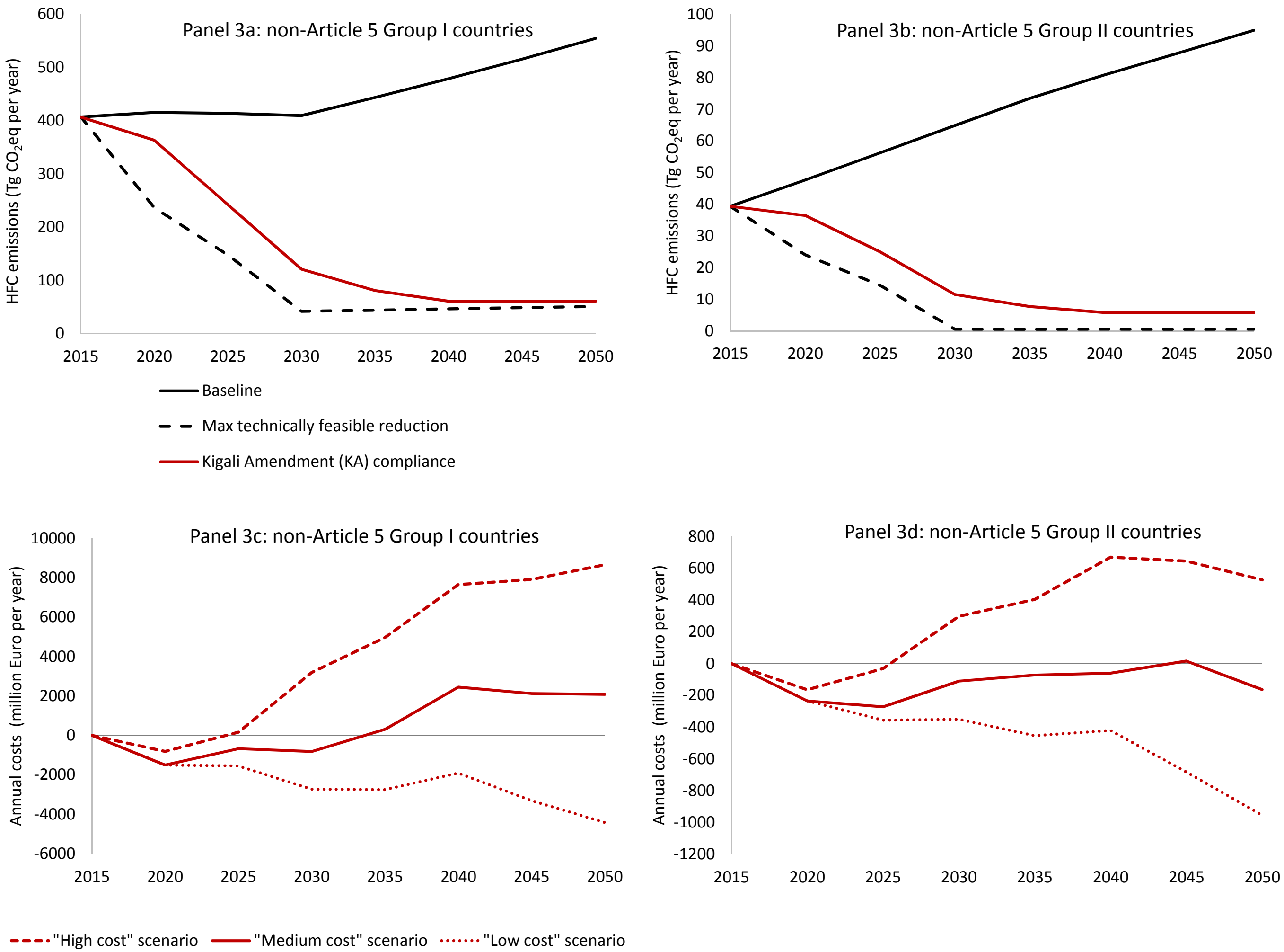

Figure 3. Annual HFC emissions and costs for complying with Kigali amendment targets for non-Article 5 Group I countries (Panels 3a and 3c) and non-Article 5 Group II countries (Panels 3b and 3d).

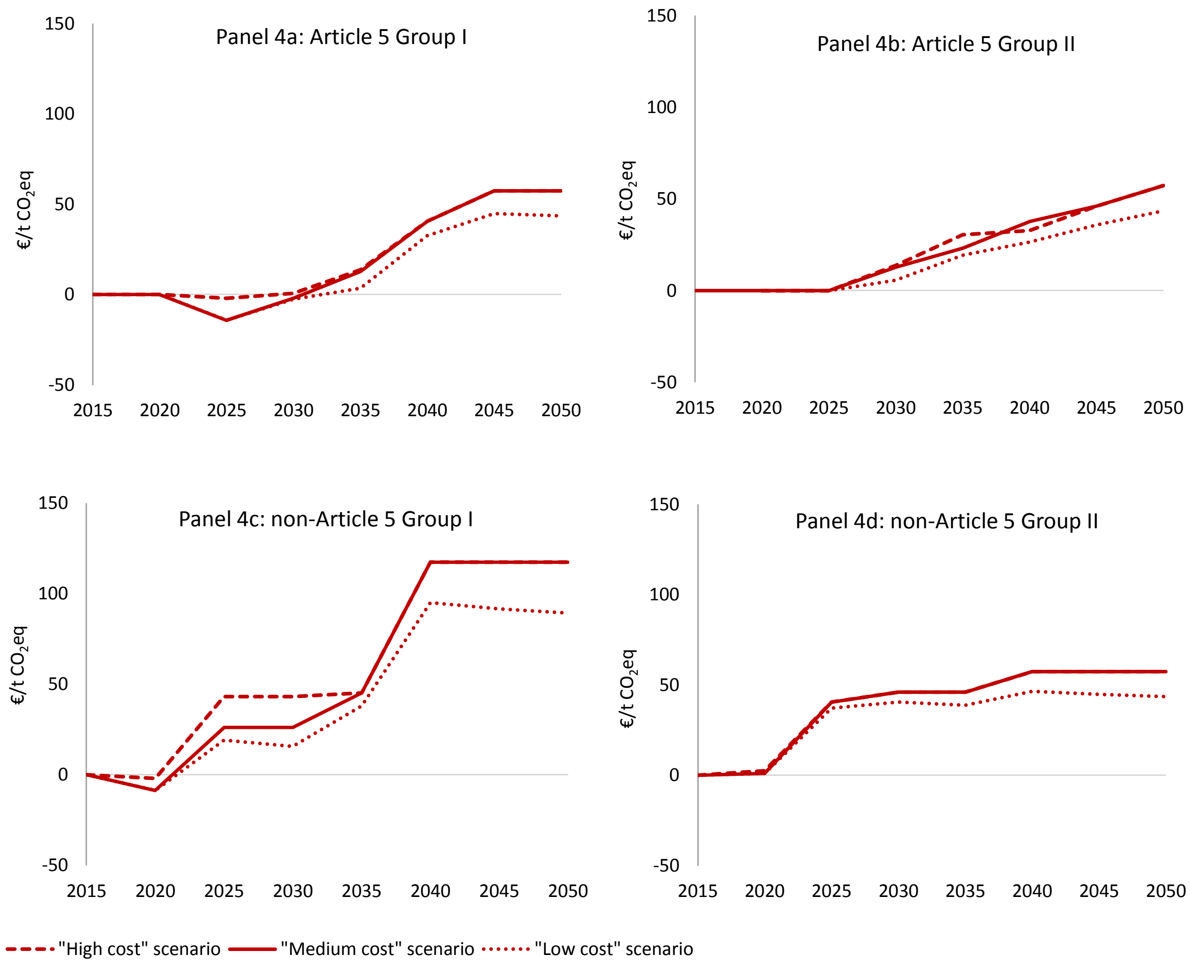

Figure 4: Estimated marginal abatement cost levels required to meet the Kigali Amendment (KA) targets by respective Party group and year.

Conclusions

In this paper, we analyze the abatement costs of achieving the hydrofluorocarbon (HFC) emission reduction targets that correspond to the HFC consumption phase-down pathways specified for four different Party groups under the Kigali Amendment (KA) to the Montreal Protocol adopted at the 28th Meeting of the Parties to the Montreal Protocol on 8-14 Oct 2016 in Kigali, Rwanda.

To estimate the costs of complying with the KA, we first convert the agreed HFC consumption reduction targets into emission reduction targets measured in kt CO_2eq and then use the F-gas module of IIASA's GAINS model to simulate marginal abatement cost curves for each Party group. We identify two factors with particular potential to influence future abatement costs, namely the future rate of technological development and the extent to which currently envisaged energy efficiency improvements can be realized when replacing HFCs with alternative options. Considering the uncertain impact of these two factors, we identify upper and lower boundaries for the future costs of meeting the KA. We find that all Party groups will initially find it relatively easy to meet the KA targets as there are estimated to be large potentials to reduce emissions at very low or even negative costs. This changes, however, in the period after 2040 when particularly Article 5 countries are expected to face increasing costs for compliance as more costly options also have to be considered. All Party groups would however benefit from further technological development and from full realization of envisaged improvements in energy efficiency, even suggesting for three Party groups that net annual abatement costs across sectors could turn out negative in the most optimistic scenario. This is however not the case for Article 5 countries with high ambient air temperatures for which abatement costs are expected to increase significantly after 2040 due to their relatively high demand for cooling services in mobile and commercial air conditioning, which are sectors with relatively high abatement costs and limited opportunities for energy efficiency improvements. Alleviating some of the future cost burden for this Party group in particular seems like an obvious target for the Multilateral Fund to be set up under the KA.

We find in general that the distribution of abatement costs across different Party groups is significantly influenced by differences in the sectoral composition of the future demand for cooling services. We find that opportunities for low cost or even profitable switches to alternative options to HFCs are particularly prevalent in industrial refrigeration (ammonia), refrigerated transport (CO_2-based) and to some extent in commercial refrigeration (propane). In contrast, we find that switching away from HFCs is relatively more costly in mobile air conditioning (CO_2-based and HFO-1234yf) and commercial air conditioning (propane and HFO-1234yf). Accordingly, we find that reducing HFC emissions is relatively more costly for Article 5 countries in regions with high ambient air temperatures and a high demand for air condition cooling services than for non-Article 5 countries in temperate regions and with a relatively high demand for industrial and commercial refrigeration services.

We find the targets set under KA to be relatively well balanced across Party groups with respect to the level of policy stringency needed to meet the targets. For three Party groups compliance is estimated possible at a marginal abatement cost that stays below 60 €/t CO_2eq for the entire period 2018 to 2050. An exception is the non-Article 5 countries that already have HFC regulations in place and therefore have relatively limited possibilities to achieve further emission reductions. For this group of countries successful compliance with the KA is estimated to require implementation of policies that are relatively more stringent than for other Party groups, with marginal abatement cost levels rising steadily to between 90 and 118 €/t CO_2eq in 2050. Hence, the targets specified for this Party group can be seen as relatively more ambitious than for the other Party groups.

Over the entire period 2018 to 2050, we estimate that compliance with the KA is expected to remove 39 Pg CO_2eq or 61 percent of global baseline HFC emissions. Depending on the expected rate of technological development and the extent to which envisaged electricity savings can be realized, the global cost of compliance is estimated to range from a net cost-saving of 240 billion € to a net cost of 350 billion € for the period 2018 to 2050. Estimated global electricity-savings due to adoption of more energy efficient technologies correspond to between 0.2% and 0.7% of the expected global electricity consumption for the same period.

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Supplement to:

Cost estimates of the Kigali Amendment to phase-down hydrofluorocarbons

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Content

S1: Unit abatement cost calculation

F-gas abatement costs per unit of activity (here the activity is kt HFC consumed) are in the GAINS model calculated as the sum of annualized investment costs, non-energy operation and maintenance costs, labor costs and changes in energy costs. The unit cost of technology *m* in country/region *i* and year *t* is defined as:

$$C_{itm} = I_{im}\left[\frac{(1+r)^T \times r}{(1+r)^T - 1}\right] + M_{im} + \left(L_{im} \times w_{it}\right) + \left(E_{im} \times p_{it}^{electr}\right) \qquad (1)$$

where $I_{im}\left[\frac{(1+r)^T \times r}{(1+r)^T - 1}\right]$ represents the annualized investment cost for technology *m* in country *i* and with interest rate *r* and technology lifetime of *T* years. M_{im} are the non-energy and labor related annual operation and maintenance costs for technology *m.* To reflect the change in labor costs, L_{im} is a fraction of annual work hours multiplied by the annual average wage of manufacturing industry workers taken from ILO (2010) and projected with expected growth in GDP from IEA/OECD (2012). Finally, E_{im} is the change in electricity demand and p_{it}^{electr} is the industry sector electricity price in country *i* in year *t*. Input parameters by sector and technology are presented in Table S1.

The price of electricity is assumed linked to the gas price in the following way (Höglund-Isaksson, 2012):

$$p_{it}^{electr} = 3 + 2\, p_{it}^{gas} \;. \qquad (2)$$

The expected trajectory of future gas prices through 2030 follows IEA/OECD (2012) for non-EU countries and Capros et al. (2013) for EU countries.

S2: Marginal abatement cost calculation

The marginal abatement cost curve displays the relationship between the cost of reducing one additional emission unit and the associated emission control potential.

The marginal cost per unit of reduced emissions is defined for each technology available to a sector as the unit cost divided by the difference between the technology emission factor and the no control emission factor reflecting the global warming effect of using HFCs in a particular sector, such that:

$$MC_{itm}^{Tech} = \frac{C_{itm}}{ef_{it}^{No\_control} - ef_{itm}} \quad (3)$$

where $ef_{it}^{No\_control}$ is the no control emission factor and ef_{itm} is the emission factor after abatement control has been implemented.

We refer to this as the "technology marginal cost". Within a sector, the technologies available are first sorted by their respective technology marginal cost. The technology with the lowest technology marginal cost is ranked the first-best technology and assumed adopted to its maximum technically feasible extent in a given sector. The second-best technology is the technology with the second lowest technology marginal cost and is assumed available for adoption provided it can achieve an emission factor that is lower than the first-best technology. The marginal cost of the second-best technology when implemented in the marginal cost curve is defined as:

$$MC_{it2} = \frac{C_{it2} - C_{it1}}{ef_{it1} - ef_{it2}}, \quad (4)$$

and so on for the third, fourth, fifth and sixth best technology.

Table S1: Details on cost parameters used to derive unit abatement costs for options to replace HFCs.

Sector description	Technology description	Unit of activity data	Removal efficiency	Cost parameters per unit of activity data				
				Lifetime of equipment	Investment	Operation & maintenance	Electricity demand	Labour time
				years	million €	million €/year	GWh	fraction of annual work hrs (1800 hrs)
Aerosols	Alternative hydrocarbon propellant (i. e. propane (HC-290), iso-butane (HC-600a), n-propane etc.)	kt HFC	-99.79%	0	0	-2	0	0
	Alternative propellant (e. g. HFO-1234ze)		-99.58%	0	0	14.29	0	0
Commercial air conditioning, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-30%	10	0.00	15.57	0.00	0.000088
	Alternative hydrocarbon refrigerant (i. e. propane, iso-butane, propene (HC-1270), etc.)		-99.85%	10	138.27	-0.71	0.00	0
	Alternative technology: pressurized CO_2		-99.95%	10	112.78	2.97	0.00	0
	Alternative low GWP refrigerant (i. e. HFO-1234yf)		-99.80%	10	169.17	2.25	0.00	0
Commercial air conditioning, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-88%	10	0	15.57	0	0.000088
	Alternative hydrocarbon refrigerant (i. e. propane, iso-butane, propene, etc.)		-99.85%	10	0	0	0	0
	Alternative technology: pressurized CO_2		-99.95%	10	0	0	0	0
	Alternative low GWP refrigerant (i. e. HFO-1234yf)		-99.80%	10	0	0	0	0
Commercial refrigeration, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-33%	10	0.00	6.25	0.00	0.000121
	Alternative hydrocarbon refrigerants (i. e. propane, iso-butane, propene, etc.)		-99.91%	10	243.33	-28.35	-202.50	0
	Alternative technology: pressurized CO_2		-99.97%	10	486.65	-28.35	-202.5	0
Commercial refrigeration, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-80%	10	0.00	6.25	0.00	0.000121
	Alternative hydrocarbon refrigerants (i. e. propane, iso-butane, propene, etc.)		-99.91%	10	0	0	0	0
	Alternative technology: pressurized CO_2		-99.97%	10	0	0	0	0
Domestic small hermetic refrigerators, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-80%	15	0.00	0.83	0.00	0.000121
	Alternative hydrocarbon refrigerant (i. e. iso-butane)		-99.79%	15	92.65	-4.42	-33.33	0
Fire extinguishers, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-20%	20	0	0.61	0	0.000007
	Alternative agent: Fluoro-ketone (FK-5-1-12)		-100%	20	25.88	0.37	0	0
Fire extinguishers, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-90%	20	0	0.61	0	0.000007
	Alternative agent: Fluoro-ketone (FK-5-1-12)		-100%	20	0	0	0	0
Ground source heat pumps, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-30%	15	0	1.39	0	0.000116
	Alternative hydrocarbon refrigerants (i. e. Propane (HC-290), propene (HC-1270), etc.)		-99.86%	15	134.35	-0.44	0	0
	Alternative technology: pressurized CO_2		-99.95%	15	338.18	-0.38	0	0
Ground source heat pumps, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-80%	15	0	1.39	0	0.000116
	Alternative hydrocarbon refrigerants (i. e. Propane (HC-290), propene (HC-1270), etc.)		-99.86%	15	0	0	0	0
	Alternative technology: pressurized CO_2		-99.95%	15	0	0	0	0

Continued Table S1: Details on cost parameters used to derive unit abatement costs for options to replace HFCs.

Sector description	Technology description	Unit of activity data	Removal efficiency	Cost parameters per unit of activity data				
				Lifetime of equipment	Investment	Operation & maintenance	Electricity demand	Labour time
				years	million €	million €/year	GWh	fraction of annual work hrs (1800 hrs)
Industrial refrigeration (including food and agricultural sectors), emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-42%	30	0.00	1.09	0	0.000008
	Alternative refrigerant: Propane (HC-290)		-99.88%	30	272.25	-31.65	0	0
	Alternative refrigerant: ammonia (NH_3)		-100%	30	728.00	-48.05	-337.50	0
	Alternative technology: pressurized CO_2		-99.96%	30	133.64	-5.88	0	0
Industrial refrigeration (including food and agricultural sectors), emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-88%	30	0	1.09	0	0.000008
	Alternative refrigerant: Propane (HC-290)		-99.88%	30	0	0	0	0
	Alternative refrigerant: ammonia (NH_3)		-100%	30	0	0	0	0
	Alternative technology: pressurized CO_2		-99.96%	30	0	0	0	0
Mobile air-conditioner in buses, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-50%	12	0	1	0	4.16667E-06
	Alternative refrigerant: HFO-1234yf		-99.72%	12	68.63	6.73	0	0
	Alternative technology: pressurized CO_2		-99.93%	12	193.41	3.17	0	0
Mobile air-conditioner in buses, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-80%	12	0	1	0	4.16667E-06
	Alternative refrigerant: HFO-1234yf		-99.72%	12	0	0	0	0
	Alternative technology: pressurized CO_2		-99.93%	12	0	0	0	0
Mobile air-conditioner in heavy duty trucks, emissions banked in equipment	Good practice: end-of-life recollection	kt HFC	-50%	12	0	0.5	0	0.0000187
	Alternative refrigerant: HFO-1234yf		-99.72%	12	48.67	5	0	0
	Alternative technology: pressurized CO_2		-99.93%	12	56.78	-2	0	0
Mobile air-conditioner in heavy duty trucks, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-80%	12	0	0.5	0	0.0000187
	Alternative refrigerant: HFO-1234yf		-99.72%	12	0	0	0	0
	Alternative technology: pressurized CO_2		-99.93%	12	0	0	0	0
Mobile air-conditioner in cars, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-50%	12	0	0.5	0	0.0000373
	Alternative refrigerant: HFO-1234yf		-99.72%	12	48.67	6.92	0	0
	Alternative technology: pressurized CO_2		-99.93%	12	170	-0.08	0	0
Mobile air-conditioner in cars, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-80%	12	0	0.5	0	0.0000373
	Alternative refrigerant: HFO-1234yf		-99.72%	12	0	0	0	0
	Alternative technology: pressurized CO_2		-99.93%	12	0	0	0	0
Mobile air-conditioner in light duty trucks, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-50%	12	0	0.5	0	0.0000373
	Alternative refrigerant: HFO-1234yf		-99.72%	12	48.67	5	0	0
	Alternative technology: pressurized CO_2		-99.93%	12	56.78	-2	0	0
Mobile air-conditioner in light duty trucks, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-80%	12	0	0.5	0	0.0000373
	Alternative refrigerant: HFO-1234yf		-99.72%	12	0	0	0	0
	Alternative technology: pressurized CO_2		-99.93%	12	0	0	0	0

Continued Table S1: Details on cost parameters used to derive unit abatement costs for options to replace HFCs.

Sector description	**Technology description**	**Unit of activity data**	**Removal efficiency**	**Cost parameters per unit of activity data**				
				Lifetime of equipment	Investment	Operation & maintenance	Electricity demand	Labour time
				years	million €	million €/year	GWh	fraction of annual work hrs (1800 hrs)
One component foams	Alternative hydrocarbon blowing agents (i. e. Iso-butane (HC-600a), Iso-pentane, n-pentane, etc.)	kt HFC	-99.74%	15	1.74	0	0	0
	Alternative technology: pressurized CO_2		-99.91%	15	6.96	-1	0	0
	Alternative blowing agent: HFO-1234ze		-99.47%	15	3.48	7	0	0
Other foams	Alternative hydrocarbon blowing agents (i. e. Iso-butane (HC-600a), Iso-pentane, n-pentane, etc.)	kt HFC	-99.74%	15	1.74	0	0	0
	Alternative technology: pressurized CO_2		-99.91%	15	6.96	-1	0	0
	Alternative blowing agent: HFO-1234ze		-99.47%	15	3.48	7	0	0
Refrigerated transport, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-20%	10	0	16.17	0	0.0000427
	Alternative hydrocarbon refrigerant: Propane (HC-290), propene (HC-1270)		-93.45%	10	294.49	-41.88	-196.92	0
	Alternative technology: pressurized CO_2		-99.95%	10	389.32	-14.26	-98.46	0
Refrigerated transport, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-80%	10	0	16.17	0	0.0000427
	Alternative hydrocarbon refrigerant: Propane (HC-290), propene (HC-1270)		-99.84%	10	0	0	0	0
	Alternative technology: pressurized CO_2		-99.95%	10	0	0	0	0
Residential air conditioning, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-30%	10	0	3.3	0	0.000088
	Alternative hydrocarbon refrigerant (i. e. propane (HC-290), iso-butane (HC-600a), propene (HC-1270), etc.)		-99.85%	10	0	-0.6	-60.00	0
	Alternative technology: pressurized CO_2		-99.95%	10	116.8	-0.5	0.0	0
	Alternative low GWP refrigerant (i. e. HFO-1234yf)		-99.80%	10	87.6	2.3	0.0	0
Residential air conditioning, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-88%	10	0.0	3.3	0.0	0.000088
	Alternative hydrocarbon refrigerant (i. e. propane (HC-290), iso-butane (HC-600a), propene (HC-1270), etc.)		-99.85%	10	0	0	0	0
	Alternative technology: pressurized CO_2		-99.95%	10	0	0	0	0
	Alternative low GWP refrigerant (i. e. HFO-1234yf)		-99.80%	10	0	0	0	0
Solvents	Ban of use	kt HFC	-100%	0	0	1	0	0

Sources: Schwarz et al., 2011; IPCC/TEAP, 2005; UNEP/TEAP, 2012; USEPA, 2013; Purohit et al., 2016; USEPA, 2016a; USEPA, 2016b; Tsamos, 2017; Purohit et al., 2017; Wang et al., 2014; EIA, 2012.

S3: Deriving the rate of technological development

Technological development may reduce the future cost of HFC abatement as demand for alternative substances and technologies increases in order to comply with the KA. The rate of technological development will be determined by the stringency of national policies implemented and their effectiveness in stimulating continuous technological development (Popp, 2003). A common way to represent technological development in assessment models is to make assumptions about the learning effect on costs from cumulative technology adoption (see e.g., Jamasb and Köhler 2007). In such experience curves, the learning effect is usually measured in terms of a percentage reduction in unit costs C for each doubling of the cumulative capacity installed Cap, i.e.,

$$C = \alpha \times Cap^{-\varepsilon} \quad \text{and} \qquad (5)$$

$$LR = 1 - 2^{-\varepsilon} \quad , \qquad (6)$$

where α is a constant, ε is the learning elasticity and LR is the learning rate. Jamasb and Köhler (2007) survey the literature on experience curves to sample empirical estimates of learning rates for energy efficiency technologies. They conclude that the variability is very large both between technologies and sectors and for different time periods. For the purpose of a sensitivity analysis, we define in the "Low cost" scenario a rate of technological development in which the adopted technology capacity doubles every 20 years, the learning elasticity is 15%, and the learning rate 20%. Resulting year-specific multiplication factors applied to fixed investment costs and operation and maintenance costs are presented in Table 3 of the Manuscript.

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