Appendixes

Appendix A—Tables

Table A-1: Country Names and Country Codes Used in the MAC Model

Country Name	Country Code
Afghanistan	AFG
Albania	ALB
Algeria	DZA
Andorra	AND
Angola	AGO
Antigua and Barbuda	ATG
Argentina	ARG
Armenia	ARM
Australia	AUS
Austria	AUT
Azerbaijan	AZE
Bahamas	BHS
Bahrain	BHR
Bangladesh	BGD
Barbados	BRB
Belarus	BLR
Belgium	BEL
Belize	BLZ
Benin	BEN
Bhutan	BTN
Bolivia	BOL
Bosnia and Herzegovina	BIH
Botswana	BWA
Brazil	BRA
Brunei Darussalam	BRN
Bulgaria	BGR
Burkina Faso	BFA
Burundi	BDI
Cambodia	KHM
Cameroon	CMR
Canada	CAN
Cape Verde	CPV
Central African Republic	CAF
Chad	TCD
Chile	CHL
China	CHN
Colombia	COL
Comoros	COM
Congo	COG
Cook Islands	COK
Costa Rica	CRI
Cote d'Ivoire	CIV
Croatia	HRV
Cuba	CUB
Cyprus	CYP
Czech Republic	CZE
Democratic Republic of Congo (Kinshasa)	COD
Denmark	DNK
Djibouti	DJI
Dominica	DMA
Dominican Republic	DOM
Ecuador	ECU
Egypt	EGY
El Salvador	SLV
Equatorial Guinea	GNQ
Eritrea	ERI
Estonia	EST
Ethiopia	ETH
Fiji	FJI
Finland	FIN
France	FRA
Gabon	GAB
Gambia	GMB
Georgia	GEO
Germany	DEU
Ghana	GHA
Greece	GRC
Grenada	GRD
Guatemala	GTM
Guinea	GIN
Guinea-Bissau	GNB
Guyana	GUY
Haiti	HTI
Holy See	VAT
Honduras	HND
Hungary	HUN
Iceland	ISL
India	IND
Indonesia	IDN
Iran	IRN
Iraq	IRQ
Ireland	IRL
Israel	ISR
Italy	ITA
Jamaica	JAM
Japan	JPN
Jordan	JOR
Kazakhstan	KAZ
Kenya	KEN
Kiribati	KIR
Kuwait	KWT
Kyrgyzstan	KGZ
Laos	LAO
Latvia	LVA
Lebanon	LBN
Lesotho	LSO
Liberia	LBR
Libyan Arab Jamahiriya	LBY
Liechtenstein	LIE
Lithuania	LTU
Luxembourg	LUX
Macedonia	MKD
Madagascar	MDG
Malawi	MWI
Malaysia	MYS
Maldives	MDV
Mali	MLI
Malta	MLT
Marshall Islands	MHL
Mauritania	MRT
Mauritius	MUS
Mexico	MEX
Micronesia	FSM
Moldova	MDA
Monaco	MCO
Mongolia	MNG
Montenegro	MON
Morocco	MAR
Mozambique	MOZ
Myanmar	MMR
Namibia	NAM
Nauru	NRU
Nepal	NPL
Netherlands	NLD
New Zealand	NZL
Nicaragua	NIC
Niger	NER
Nigeria	NGA
Niue	NIU
North Korea	PRK
Norway	NOR
Oman	OMN
Pakistan	PAK
Palau	PLW
Panama	PAN
Papua New Guinea	PNG
Paraguay	PRY
Peru	PER
Philippines	PHL
Poland	POL
Portugal	PRT
Qatar	QAT
Romania	ROM
Russian Federation	RUS
Rwanda	RWA
Saint Kitts and Nevis	KNA
Saint Lucia	LCA
Saint Vincent & the Grenadines	VCT
Samoa	WSM
San Marino	SMR
Sao Tome and Principe	STP
Saudi Arabia	SAU
Senegal	SEN
Serbia	SER
Seychelles	SYC
Sierra Leone	SLE
Singapore	SGP
Slovak Republic	SVK
Slovenia	SVN
Solomon Islands	SLB
Somalia	SOM
South Africa	ZAF
South Korea	KOR
Spain	ESP
Sri Lanka	LKA
Sudan	SDN
Suriname	SUR
Swaziland	SWZ
Sweden	SWE
Switzerland	CHE
Syrian Arab Republic	SYR
Tajikistan	TJK
Thailand	THA
Timor-Leste	TMP
Togo	TGO
Tonga	TON
Trinidad and Tobago	TTO
Tunisia	TUN
Turkey	TUR
Turkmenistan	TKM
Tuvalu	TUV
Uganda	UGA
Ukraine	UKR
United Arab Emirates	ARE
United Kingdom	GBR
United Republic of Tanzania	TZA
United States	USA
Uruguay	URY
Uzbekistan	UZB
Vanuatu	VUT
Venezuela	VEN
Viet Nam	VNM
Yemen	YEM
Zambia	ZMB
Zimbabwe	ZWE

Table A-2: International Regions Used in the MAC Model

Region	MAC_REGION	Country Count
Africa	AFRC	52
Asia	ASIA	29
Central & South America	CSAM	28
Eurasia	EURA	12
Europe	EURO	38
Middle East	MIEA	8
North America	NAAM	3

Table A-3: Africa Region Country List

Algeria	Cote d'Ivoire	Liberia	Sao Tome and Principe
Angola	Djibouti	Libya	Senegal
Benin	Egypt	Madagascar	Sierra Leone
Botswana	Equatorial Guinea	Malawi	Somalia
Burkina Faso	Eritrea	Mali	South Africa
Burundi	Ethiopia	Mauritania	Sudan
Cameroon	Gabon	Mauritius	Swaziland
Cape Verde	Gambia	Morocco	Tanzania
Central African Republic	Ghana	Mozambique	Togo
Chad	Guinea	Namibia	Tunisia
Comoros	Guinea-Bissau	Niger	Uganda
Congo (Brazzaville)	Kenya	Nigeria	Zambia
Congo (Kinshasa)	Lesotho	Rwanda	Zimbabwe

Table A-4: Asia Region Country List

Afghanistan	Indonesia	Nepal	Singapore
Australia	Japan	New Zealand	Solomon Islands
Bangladesh	Kiribati	Niue	South Korea
Bhutan	Laos	North Korea	Sri Lanka
Brunei	Malaysia	Pakistan	Thailand
Burma	Maldives	Palau	Timor-Leste
Cambodia	Marshall Islands	Papua New Guinea	Tonga
China	Micronesia (Federated States of)	Philippines	Tuvalu
Cook Islands	Mongolia	Samoa	Vanuatu
Fiji	Nauru	Seychelles	Vietnam
India			

Table A-5: Central & South America Region Country List

Antigua and Barbuda	Colombia	Guatemala	Peru
Argentina	Costa Rica	Guyana	Saint Kitts and Nevis
Bahamas	Cuba	Haiti	Saint Lucia
Barbados	Dominica	Honduras	Saint Vincent & the Grenadines
Belize	Dominican Republic	Jamaica	Suriname
Bolivia	Ecuador	Nicaragua	Trinidad and Tobago
Brazil	El Salvador	Panama	Uruguay
Chile	Grenada	Paraguay	Venezuela

Table A-6: Eurasia Region Country List

Armenia	Georgia	Moldova	Turkmenistan
Azerbaijan	Kazakhstan	Russia	Ukraine
Belarus	Kyrgyzstan	Tajikistan	Uzbekistan

Table A-7: Europe Region Country List

Albania	Finland	Lithuania	San Marino
Andorra	France	Luxembourg	Serbia
Austria	Germany	Macedonia	Slovakia
Belgium	Greece	Malta	Slovenia
Bosnia and Herzegovina	Holy See	Monaco	Spain
Bulgaria	Hungary	Montenegro	Sweden
Croatia	Iceland	Netherlands	Switzerland
Cyprus	Ireland	Norway	Turkey
Czech Republic	Italy	Poland	United Kingdom
Denmark	Latvia	Portugal	
Estonia	Liechtenstein	Romania	

Table A-8: Middle East Region Country List

Bahrain	Jordan	Oman	Syria
Iran	Kuwait	Qatar	United Arab Emirates
Iraq	Lebanon	Saudi Arabia	Yemen
Israel			

Table A-9: North America Region Country List

Canada
Mexico
United States

Table A-10: EU-27 Region Country List

Austria	Germany	Netherlands
Belgium	Greece	Poland
Bulgaria	Hungary	Portugal
Cyprus	Ireland	Romania
Czech Republic	Italy	Slovakia
Denmark	Latvia	Slovenia
Estonia	Lithuania	Spain
Finland	Luxembourg	Sweden
France	Malta	United Kingdom

Appendix B: Coal Mining

Drainage and Recovery System Cost Assumptions

The capital costs for a drainage system include the wellhead blower, the satellite compressor station, and the delivery pipelines that connect the compressors to the methane end use. The cost inputs for each of these components are as follows:

Blower cost

- Blower cost ($1,000/hp)
- Blower efficiency (0.035 hp/mcfd)
- Gas flow rate (mine specific value—mcfd)

Satellite compressor cost

- Compressor cost ($1,000/hp)
- Compressor efficiency (0.035 hp/mcfd)
- Gas flow rate (mine specific value—mcfd)

Pipeline cost

- Pipe cost ($40/ft)
- Pipeline length (21,000 ft)

The annual costs to maintain the drainage system include the installation of gob wells in the drainage system and the installation of the gathering system piping that connects the wells to satellite compressors. The costs for each of these components are as follows:

Gob well installation

- Well spacing (1,000 ft/well)
- Mining rate (mine-specific—ft/year)
- Mine depth (1,000 ft)
- Unit drilling cost ($140/ft)

Appendix C: Natural Gas and Oil Systems

Table C-1: Example Break-Even Prices for Natural Gas and Oil System Technology Options in 2010

Abatement Measure	System Component/ Process	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($/$tCO_2e$)	Annual Cost ($/$tCO_2e$)	Annual Revenue ($/$tCO_2e$)	Tax Benefit of Depreciation ($/$tCO_2e$)	Break-Even Price ($/$tCO_2e$)	Incremental Reduction ($MtCO_2e$)
Oil and Gas Production								
Convert gas pneumatic controls to instrument air	Pneumatic device vents	71.0	$335.68	$441.41	$10.01	$82.50	$684.58	15.29
Directed inspection & maintenance at gas production facilities	Chemical injection pumps	15.2	$0.00	$440.34	$10.01	$0.00	$430.33	0.44
Directed inspection & maintenance at gas production facilities	Deepwater gas platforms	6,687.0	$0.00	$7.48	$10.01	$0.00	−$2.53	0.21
Directed inspection & maintenance at gas production facilities	Non-associated gas wells	2.8	$0.00	$289.00	$10.01	$0.00	$279.00	0.97
Directed inspection & maintenance at gas production facilities	Pipeline leaks	5.0	$0.00	$16.44	$10.01	$0.00	$6.43	1.78
Directed inspection & maintenance at gas production facilities	Shallow water gas platforms	1,584.6	$0.00	$21.04	$10.01	$0.00	$11.03	2.57
Flaring instead of venting on offshore oil platforms	Offshore platforms, shallow water oil, fugitive, vented and combusted	7,929.0	$4,584.45	$627.65	$10.01	$929.86	$4,272.24	8.94
Install flash tank separators on dehydrators	Dehydrator vents	18.1	$402.90	$0.00	$10.01	$122.18	$270.71	0.75
Installing catalytic converters on gas fueled engines and turbines	Gas engines - Exhaust vented	36,389.4	$0.06	$0.12	$0.00	$0.01	$0.16	2.55
Installing electronic starters on production field compressors	Compressor starts	2.7	$266.82	$2,172.15	$10.01	$65.58	$2,363.39	0.07
Installing plunger lift systems in gas wells	Non-associated gas wells	2.4	$1,042.59	−$5,818.60	$10.01	$316.18	−$5,102.19	0.82
Installing plunger lift systems in gas wells	Well clean ups (LP Gas Wells)	423.25	$5.87	−$32.73	$10.01	$1.78	−$38.65	29.93
Installing plunger lift systems in gas wells	Gas well workovers	0.8	$2,960.86	−$16,524.21	$10.01	$897.92	−$14,471.28	0.01
Installing surge vessels for capturing blowdown vents	Compressor BD	0.8	$43,398.61	$34,987.60	$10.01	$8,802.49	$69,573.71	0.02
Installing surge vessels for capturing blowdown vents	Vessel BD	0.0	$2,088,733.32	$1,683,919.51	$10.01	$423,655.25	$3,348,987.59	0.01

(continued)

Table C-1: Example Break-Even Prices for Natural Gas and Oil System Technology Options in 2010 (continued)

Abatement Measure	System Component/ Process	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($/$tCO_2e$)	Annual Cost ($/$tCO_2e$)	Annual Revenue ($/$tCO_2e$)	Tax Benefit of Depreciation ($/$tCO_2e$)	Break-Even Price ($/$tCO_2e$)	Incremental Reduction ($MtCO_2e$)
Installing vapor recovery units on storage tanks	Oil tanks	26,252.0	$284.93	$406.41	$9.50	$57.79	$624.05	2.01
Optimize glycol circulation rates in dehydrators	Dehydrator vents	6.9	$0.00	$16.84	$10.01	$0.00	$6.84	0.44
Reduced emission completions for hydraulically fractured natural gas wells	Unconventional gas well completions	2,703.96	$0.00	$11.11	$10.01	$0.00	$1.10	8.82
Reduced emission completions for hydraulically fractured natural gas wells	Unconventional gas well workovers	2,684.4	$0.00	$11.19	$10.01	$0.00	$1.18	10.59
Replace gas-assisted glycol pumps with electric pumps	Kimray pumps	4,792.2	$0.16	$0.41	$10.01	$0.04	−$9.48	0.00
Replacing high−bleed pneumatic devices in the natural gas industry	Pneumatic device vents	9.7	$7.38	$0.00	$10.01	$1.81	−$4.44	2.30
Using pipeline pump-down techniques to lower gas line pressure before maintenance	Pipeline BD	0.12	$0.00	$11,392	$10.01	$0.00	$11,382	0.04
Directed inspection & maintenance on offshore oil Platforms	Offshore platforms, deepwater oil,fugitive, vented and combusted	32,666.4	$0.00	$1.53	$10.01	$0.00	−$8.48	0.36
Gas processing								
Directed inspection & maintenance at processing plants and booster stations	Plants	1,109.0	$0.00	$9.14	$10.01	$0.00	−$0.87	0.50
Directed Inspection & maintenance at processing plants and booster stations - Compressors	Centrifugal compressors (dry seals)	442.9	$0.00	$35.18	$10.01	$0.00	$25.17	0.05
Directed inspection & maintenance at processing plants and booster stations - Compressors	Centrifugal compressors (wet seals)	903.3	$0.00	$6.79	$10.01	$0.00	−$3.22	0.46
Directed inspection & maintenance at processing plants and booster stations - Compressors	Recip. compressors	161.9	$0.00	$37.86	$10.01	$0.00	$27.85	0.62
Early replacement of reciprocating compressor rod packing rings	Recip. compressors	24.7	$138.92	$0.00	$10.01	$42.13	$86.78	0.05

(continued)

Table C-1: Example Break-Even Prices for Natural Gas and Oil System Technology Options in 2010 (continued)

Abatement Measure	System Component/ Process	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($/$tCO_2e$)	Annual Cost ($/$tCO_2e$)	Annual Revenue ($/$tCO_2e$)	Tax Benefit of Depreciation ($/$tCO_2e$)	Break-Even Price ($/$tCO_2e$)	Incremental Reduction ($MtCO_2e$)
Fuel gas retrofit for BD valve - Take recip. compressors offline	Recip. compressors	351.9	$2.96	$0.00	$10.01	$0.90	−$7.95	1.34
Installing catalytic converters on gas fueled engines and turbines	Gas engines - Exhaust vented	523.1	$4.11	$8.36	$0.00	$1.01	$11.46	1.50
Installing surge vessels for capturing blowdown vents	Blowdowns/venting	821.2	$42.41	$34.19	$10.01	$8.60	$57.99	0.37
Reciprocating compressor rod packing (static-pac)	Recip. compressors	0.0	$0.00	$0.00	$0.00	$0.00	$0.00	0.00
Replace gas-assisted glycol pumps with electric pumps	Kimray pumps	5,058.1	$0.15	$0.39	$10.01	$0.04	−$9.51	0.00
Replacing wet seals with dry seals in centrifugal compressors	Centrifugal compressors (wet seals)	5,000.8	$33.48	−$20.56	$10.01	$10.15	−$7.24	2.53
Gas transmission								
Convert gas pneumatic controls to instrument air	Pneumatic Devices	89.9	$2,898.32	$3,811.28	$10.01	$712.36	$5,987.24	2.88
Directed inspection and maintenance at compressor stations	Stations	3,655.9	$0.00	$0.41	$10.01	$0.00	−$9.60	6.61
Directed inspection and maintenance at compressor stations - Compressors	Centrifugal compressors (dry seals)	625.9	$0.00	$24.92	$10.01	$0.00	$14.91	0.04
Directed inspection and maintenance at compressor stations - Compressors	Centrifugal compressors (wet seals)	934.2	$0.00	$16.68	$10.01	$0.00	$6.67	0.55
Directed inspection and maintenance at compressor stations - Compressors	Recip compressor	289.4	$0.00	$54.60	$10.01	$0.00	$44.59	1.73
Directed inspection and maintenance at gas storage wells	Wells (storage)	16.1	$0.00	$40.52	$10.01	$0.00	$30.51	0.23
Directed inspection and maintenance at gate stations and surface facilities	M&R (trans. co. interconnect)	472.4	$0.00	$3.69	$10.01	$0.00	−$6.32	0.89
Directed inspection and maintenance on transmission pipelines	Pipeline leaks	0.1	$0.00	$297.54	$10.01	$0.00	$287.53	0.03
Early replacement of reciprocating compressor rod packing rings	Recip compressor	30.6	$112.24	$0.00	$10.01	$34.04	$68.19	0.09

(continued)

Table C-1: Example Break-Even Prices for Natural Gas and Oil System Technology Options in 2010 (continued)

Abatement Measure	System Component/ Process	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($/$tCO_2e$)	Annual Cost ($/$tCO_2e$)	Annual Revenue ($/$tCO_2e$)	Tax Benefit of Depreciation ($/$tCO_2e$)	Break-Even Price ($/$tCO_2e$)	Incremental Reduction ($MtCO_2e$)
Early replacement of reciprocating compressor rod packing rings and rods	Recip compressor	38.0	$482.06	$0.00	$10.01	$146.19	$325.87	0.11
Fuel gas retrofit for bd valve - take recip. compressors offline	Recip compressor	1,014.8	$1.07	$0.00	$10.01	$0.32	−$9.26	5.65
Install flash tank separators on dehydrators	Dehydrator Vents	279.4	$14.95	$0.00	$10.01	$4.54	$0.41	0.05
Installing catalytic converters on gas fueled engines and turbines	Engine/turbine exhaust vented	227.8	$12.89	$36.68	$0.00	$3.17	$46.40	2.20
Installing surge vessels for capturing blowdown vents	Station venting	695.1	$62.41	$24.68	$10.01	$12.66	$64.42	1.52
Optimize glycol circulation rates in dehydrators	Dehydrator vents	152.6	$0.00	$0.15	$10.01	$0.00	−$9.85	0.02
Reciprocating compressor rod packing (static-pac)	Recip compressor	190.5	$13.16	$0.00	$10.01	$3.99	−$0.84	1.26
Replacing high-bleed pneumatic devices in the natural gas industry	Pneumatic Devices	12.3	$63.72	$0.00	$10.01	$15.66	$38.05	0.43
Replacing wet seals with dry seals in centrifugal compressors	Centrifugal compressors (wet seals)	5,221.4	$32.07	−$19.69	$10.01	$9.72	−$7.35	3.08
Using pipeline pump-down techniques to lower gas line pressure before maintenance	Pipeline venting	11.5	$0.00	$117.37	$10.01	$0.00	$107.36	2.72
Distribution								
Directed inspection and maintenance at gate stations and surface facilities	M&R <100	4.6	$0.00	$305.19	$10.01	$0.00	$295.18	0.03
Directed inspection and maintenance at gate stations and surface facilities	M&R >300	511.6	$0.00	$3.40	$10.01	$0.00	−$6.60	1.58
Directed inspection and maintenance at gate stations and surface facilities	M&R 100-300	220.2	$0.00	$7.90	$10.01	$0.00	−$2.10	2.48
Directed inspection and maintenance at gate stations and surface facilities	Reg <40	0.1	$0.00	$10,118.17	$10.01	$0.00	$10,108.16	0.00
Directed inspection and maintenance at gate stations and surface facilities	Reg >300	460.7	$0.00	$3.78	$10.01	$0.00	−$6.23	1.55

(continued)

Table C-1: Example Break-Even Prices for Natural Gas and Oil System Technology Options in 2010 (continued)

Abatement Measure	System Component/ Process	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($\$/tCO_2e$)	Annual Cost ($\$/tCO_2e$)	Annual Revenue ($\$/tCO_2e$)	Tax Benefit of Depreciation ($\$/tCO_2e$)	Break-Even Price ($\$/tCO_2e$)	Incremental Reduction ($MtCO_2e$)
Directed inspection and maintenance at gate stations and surface facilities	Reg 100-300	93.3	$0.00	$18.66	$10.01	$0.00	$8.65	0.95
Directed inspection and maintenance at gate stations and surface facilities	Reg 40-100	1.1	$0.00	$1,264.77	$10.01	$0.00	$1,254.76	0.03
Directed inspection and maintenance at gate stations and surface facilities	R-vault >300	2.6	$0.00	$662.91	$10.01	$0.00	$652.90	0.01
Directed inspection and maintenance at gate stations and surface facilities	R-Vault 100-300	0.3	$0.00	$5,457.93	$10.01	$0.00	$5,447.93	0.00
Directed inspection and maintenance at gate stations and surface facilities	R-vault 40-100	0.1	$0.00	$14,615.13	$10.01	$0.00	$14,605.12	0.00
Replace cast iron pipeline	Mains—Cast iron	91.7	$1,790.73	$1.99	$10.01	$543.06	$1,239.65	2.54
Replace unprotected steel pipeline	Mains—Unprotected steel	42.3	$3,879.33	$4.30	$10.01	$1,176.46	$2,697.17	2.23
Replace unprotected steel service lines	Services—Unprotected steel	0.7	$281,312.64	$475.95	$10.01	$85,311.70	$196,466.89	2.67

Appendix D: Refrigeration and Air Conditioning

Detailed technical information on each abatement option is provided below. All costs were developed through ICF analysis in consultation with industry experts, as detailed in USEPA (2006) and USEPA (2009), except where otherwise noted.

Enhanced HFC-134a in New MVACs

For modeling purposes, the system type is defined as a new MVAC system in passenger vehicles with a charge size of 0.77 kg of HFC-134a, an annual service/leak rate of 18%, and a lifetime of 12 years. At disposal, it is assumed that 43% of the original refrigerant charge remains and is released.

In the United States and other non-EU developed countries, this option is assumed to penetrate the market starting in 2011 and increase linearly to reach 33% of all new light-duty MVACs by 2015. This option then gradually declines to 0% by 2017, as a competing option, HFO-1234yf, takes over the entire new MVAC market. In the EU, there is no market penetration assumed for this option, because it is assumed to penetrate in the baseline (e.g., in response to Directive 2006/40/EC, which requires replacing HFC-134a with low-GWP alternatives in new model vehicles sold in the EU beginning in 2011 and in all new vehicles sold in the EU by 2017). Market penetrations in developing countries are assumed to be delayed by 10 years, relative to non-EU developed countries.

- **Capital Costs:** The additional capital cost of this option is assumed to be $73 per system—$18 for leakage reduction controls and $55 for efficiency improvements (USEPA and NHTSA, 2011; Centro Ricerche Fiat, 2008). These costs are assumed to be 10% greater in developing countries.
- **Annual O&M Costs:** No annual costs are associated with this option.
- **Annual Revenue:** Enhanced HFC-134a systems are assumed to reduce fuel consumption associated with the operation of the air conditioner by an estimated 42% (USEPA and NHTSA, 2011). This gain in efficiency is estimated to translate into a savings of 12 gallons of gasoline per vehicle per year (Rugh and Hovland, 2003). Assuming an average gasoline price of about $3 per gallon in developed countries (USEIA, 2008), this results in an annual cost savings of approximately $37 per year.[1] Gasoline prices in developing countries are assumed to be 30% greater.

  In addition, cost savings are associated with saved HFC-134a refrigerant, assumed to cost $8 per kg in both developed and developing countries (TEAP, 2012). On an annual basis, these savings are estimated to total roughly $0.55 per MVAC, based on the assumption that 50% of annual emissions could be avoided through this option (i.e., 0.07 kg of refrigerant is saved each year). Although this analysis includes the savings from lower refrigerant leakage, it does not include the costs or savings from service events. Additional savings may be realized if fewer service events are required as a result of the lower leak rate.

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[1] Average gasoline price is based on the reported national average retail price of regular gasoline in 2007 in the United States, inflated to 2010 dollars (BLS, 2011). To the extent that gasoline prices, which are highly volatile, change, so too will the cost savings of this option.

- **Project Lifetime:** It is assumed that a motor vehicle air conditioner would operate for an average of 12 years (i.e., the investment in such a project would yield results for 12 years). Therefore, the project lifetime is assumed to be 12 years and the costs and HFC consumption and emission reductions are calculated over that time period.
- **Reduction Efficiency:** The annual HFC emission reduction efficiency is assumed to be 50%, achieved by reducing the annual leak rate.
- **Annual Reductions:** Annual HFC emissions are reduced by half, because the leakage rate is 50% lower than conventional HFC-134a MVAC systems, equivalent to annual HFC reductions of 0.1 tCO_2e per MVAC.
- **End of Life:** No emission reductions are realized at end of life, because the original charge size is assumed to be the same as that of conventional HFC-134a systems.

HFO-1234yf in New MVACs

For modeling purposes, the system type is defined as a new MVAC system in passenger vehicles with a charge size of 0.77 kg of HFC-134a, an annual service/leak rate of 18%, and a lifetime of 12 years. At disposal, it is assumed that 43% of the original refrigerant charge remains and is released.

In the United States and other non-EU developed countries, this option is assumed to penetrate the market in 2011 and increase linearly to reach 100% in 2017 and remain at that level through 2021. In 2022, after 10 years of market penetration, this option is assumed to be replaced by an enhanced version of this option that is assumed to become available and take over the market. No market penetration is assumed in the EU, because the option is assumed to penetrate in the baseline (e.g., in response to the MAC Directive). In developing countries, market penetrations are assumed to be delayed by 10 years, relative to non-EU developed countries.

- **Capital Costs:** The capital cost of this option is assumed to be approximately $59. This cost assumes that hardware changes will cost $15 (USEPA and NHTSA, 2011; Centro Ricerche Fiat, 2008), and the incremental refrigerant cost will be approximately $44 per system.[2] The hardware costs are assumed to be 10% greater in developing countries.
- **Annual O&M Costs*:*** Because the cost of HFO-1234yf is greater than the cost of HFC-134a, additional costs are associated with replacing leaked HFO-1234yf. Specifically, it is assumed that HFO-1234yf will cost nearly $57 per kg more than HFC-134a (TEAP, 2012), and that 0.14 kg of HFO-1234yf will leak (and require replacement) each year at an estimated cost of nearly $9 per year compared with an annual leakage of 0.14 kg of HFC-134a at a cost of roughly $1 per year. Therefore, the incremental cost is roughly $8 per year.
- **Annual Revenue:** No cost savings are associated with this option.
- **Project Lifetime:** It is assumed that a motor vehicle air conditioner would operate for an average of 12 years (i.e., the investment in such a project would yield results for 12 years). Therefore, the

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[2] The charge size for an HFO-1234yf system is estimated to be 0.77 kg, while the cost of the HFO refrigerant is estimated at $65 per kg and the cost of HFC-134a is approximately $8 per kg (TEAP, 2012).

project lifetime is assumed to be 12 years, and the costs and HFC consumption and emission reductions are calculated over that time period.

- **Reduction Efficiency:** The annual emission reduction efficiency is calculated to be 99.7%, based on the difference in GWP of HFO-1234yf (4) compared with HFC-134a (1,300).
- **Annual Reductions:** Annual emissions are reduced by replacing HFC-134a with HFO-1234yf with a GWP of only four, equivalent to annual HFC reductions of 0.2 tCO_2e per MVAC.
- **End of Life:** Emission reductions are realized at end of life, because HFC-134a is replaced by a new chemical with a GWP of only four. It is assumed that 43% of the original MVAC charge is released at the time of disposal.

Enhanced HFO-1234yf in New MVACs

For modeling purposes, the system type is defined as a new MVAC system in passenger vehicles with an average charge size of 0.77 kg of HFC-134a and a lifetime of 12 years.

In developed countries, this option is assumed to penetrate 100% of the market overnight in 2022, 10 years after the first HFO-1234yf models are introduced in the market. Market penetration in developing countries is assumed to be delayed by 10 years, relative to developed countries.

- **Capital Costs:** The capital cost of this option is assumed to be $102. Similar to the Enhanced HFC-134a options, this option assumes a cost of $18 for leakage reduction controls and $55 for efficiency improvements (USEPA and NHTSA, 2011; Centro Ricerche Fiat, 2008). These costs are assumed to be 10% greater in developing countries. In addition, incremental refrigerant costs will be almost $30 per system (AEI, 2008; TEAP, 2012). The refrigerant costs for this option are lower than the other HFO-1234yf option as a result of the assumption that, over time, with mass production of the chemical and systems to use it, price will drop. As such, the price of HFO-1234yf is assumed to be approximately $45 per kg (TEAP, 2012).
- **Annual O&M Costs:** Because the cost of HFO-1234yf is greater than the cost of HFC-134a, additional costs are associated with the replacement of leaked HFO-1234yf. Specifically, it is assumed that HFO-1234yf will cost nearly $37 per kg more than HFC-134a in 2022, when the option takes effect, and that 0.07 kg of HFO-1234yf will leak (and require replacement) each year—at an estimated incremental cost of $2 per MVAC system.
- **Annual Revenue:** Enhanced HFO-1234yf systems are assumed to reduce fuel consumption by an estimated 42% (USEPA and NHTSA, 2011). This gain in efficiency is estimated to translate into a savings of 12 gallons of gasoline per vehicle per year (Rugh and Hovland, 2003). Assuming an average gasoline price of about $3 per gallon in developed countries (USEIA, 2008), this results in an annual cost savings of approximately $37 per year.[3] Gasoline prices in developing countries are assumed to be 30% greater.

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[3] Average gasoline price is based on the reported national average retail price of regular gasoline in 2007 in the United States, inflated to 2010 dollars (BLS, 2011). To the extent that gasoline prices, which are highly volatile, change, so too will the cost savings of this option.

- **Project Lifetime:** It is assumed that a MVAC system would operate for an average of 12 years (i.e., the investment in such a project would yield results for 12 years). Therefore, the project lifetime is assumed to be 12 years and the costs and HFC consumption and emission reductions are calculated over that time period.
- **Reduction Efficiency:** The annual emission reduction efficiency is calculated to be 99.8%, based on the difference in GWP of HFO-1234yf (four) compared with HFC-134a (1,300) as well as a 50% reduction in annual leak rate.
- **Annual Reductions:** Annual emissions are reduced by replacing HFC-134a with HFO-1234yf with a GWP of only four. The annual emission reductions are 0.2 tCO_2e per MVAC.
- **End of Life:** Emission reductions are realized at end of life, because HFC-134a is replaced by a new chemical with a GWP of only four. It is assumed that 43% of the original MVAC charge is released at the time of disposal.

Distributed Systems in New Large Retail Food

For modeling purposes, the system type is defined as a new large retail food system used in a supermarket that is 60,000 sq. ft. with a refrigerant charge size of 1,633 kg of R-404A, an annual leak rate of 15%, energy consumption of 1.2 million kWh/year, and a lifetime of 15 years. At disposal, it is assumed that 10% of the original refrigerant charge is released.

This technology is already being implemented today in developed countries; such existing units are considered part of the baseline. Wider use of this option is assumed to begin penetrating the new installation market in the United States and other non-EU developed countries in 2011 and increase linearly to reach 40% by 2015, and then decline to 10% by 2030, as other alternatives penetrate the market. In the EU, market penetrations for this option are lower than for other developed countries, reaching only 29% by 2015 and declining to 0% by 2030; this lower market penetration accounts for lower consumption of HFCs (i.e., higher penetration of climate friendly alternatives) in this end use in the baseline. Market penetration in developing countries is assumed to be delayed by 10 years, relative to non-EU developed countries.

- **Capital Costs:** Despite the cost savings associated with using less refrigerant, distributed systems are assumed to cost 5% more than conventional HFC centralized DX systems in developed countries (IPCC, 2005)—i.e., roughly $182,000 for a large (60,000 sq. ft.) supermarket.[4] The incremental cost is, therefore, estimated to translate to roughly an additional $9,100 in developed countries. Capital costs in developing countries are assumed to be 10% greater.
- **Annual O&M Costs:** It is assumed that this option consumes 5% more energy than conventional DX systems (IPCC, 2005), where it is assumed that conventional DX systems consume 1,200,000 kilowatt hours each year (ADL, 2002) at an average electricity price of approximately $0.0614 per kilowatt hour (USEIA, 2011). Thus, for a large supermarket, this option is associated with an

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[4] This cost assumption is based on the following data points: 3,600 pounds of refrigerant are needed to charge a DX system for a 60,000 sq. ft. supermarket (ADL, 2002); five pounds of refrigerant are needed per ton of cooling capacity; and DX systems typically cost approximately $230 per ton of cooling capacity installed; thus 3,600 / 5 = 720 × $230 = $165,000 capital cost for DX (USEPA, 2001); in 2010 dollars, this is equivalent to approximately $182,000.

annual cost of approximately $3,700 in developed countries (1,200,000 × 0.0614× 0.05 = $3,684). In developing countries, electricity costs are assumed to cost 67% more; therefore, annual energy costs are estimated at about $6,140.

- **Annual Revenue:** This system is estimated to prevent 80% of direct annual emissions, as a result of a 50% reduction in charge size and a reduction in annual leakage rate to just 6% (IPCC, 2005). Therefore, for a large supermarket system, 49 kg of refrigerant (R-404A) will be emitted instead of 245 kg that would have otherwise been emitted from a conventional DX system. Assuming a price of R-404A of $9 per kg (TEAP, 2012), the annual refrigerant cost savings is nearly $1,800 per supermarket.
- **Project Lifetime:** It is assumed that a distributed system would be used for an average of 15 years before being replaced or undergoing a major change (i.e., the investment in such a project would yield results for 15 years). Therefore, the project lifetime is assumed to be 15 years, and the costs and HFC consumption and emission reductions are calculated over that time period.
- **Reduction Efficiency:** The annual emission reduction efficiency is calculated to be 80% (i.e., leaks are equal to the following: new charge size of 50% x new leak rate of 6% / original leak rate of 15% = 20%). The reduced charge size and leak rate of distributed systems result in the annual leakage of 49 kg for a large supermarket system compared with 245 kg that would have otherwise leaked from a conventional DX system.
- **Annual Reductions:** Annual reductions are associated with avoided emissions of HFCs that would have been released during regular equipment leakage. The resulting emissions avoided are equivalent to 657 tCO_2e per year per large supermarket retail food system.
- **End of Life:** Because distributed systems have lower charge sizes than conventional DX systems, HFC emissions that would have been released at the end of the equipment's life are avoided. It is assumed that 10% of the original charge size would have been released at disposal.

HFC Secondary Loop and/or Cascade Systems in New Large Retail Food

For modeling purposes, the system type is defined as a new large retail food system used in a supermarket that is 60,000 sq. ft. with a refrigerant charge size of 1,633 kg of R-404A, an annual leak rate of 15%, energy consumption of 1.2 million kWh/year, and a lifetime of 15 years. At disposal, it is assumed that 10% of the original refrigerant charge is released.

This option is assumed to begin penetrating the market in the United States and other non-EU developed countries in 2011 and increase linearly to reach 30% in 2015 and 50% in 2030. In the EU, market penetrations for this option are lower than for other developed countries, reaching only 29% by 2020 and declining to 0% by 2030; this lower market penetration accounts for baseline consumption of HFCs (i.e., higher penetration of climate friendly alternatives) in this end use. Market penetration in developing countries is assumed to be delayed by 10 years, relative to non-EU developed countries.

- **Capital Costs:** Despite the cost savings associated with less refrigerant, this option is assumed to cost between 10% and 25% more than conventional centralized HFC DX systems (IPCC, 2005), where it is assumed that conventional DX systems cost roughly $182,000 for a large (60,000 sq. ft.) supermarket. For calculation purposes, an increase of 17.5% is assumed. The incremental cost is, therefore, estimated to translate to approximately an additional $32,000 ($182,000 × 0.175 = $31,910). Capital costs in developing countries are assumed to be 10% greater.
- **Annual O&M Costs:** No annual costs are associated with this option.

- **Annual Revenue:** Secondary loop systems are assumed to reduce annual direct emissions by reducing charge size by 70% and reducing the annual leak rate from 15% to 5%. This results in the annual release of 25 kg instead of 245 kg. Thus, an estimated 220 kg of refrigerant will be saved each year. Assuming an average cost of $9 per kg for both R-404A and R-407A (TEAP, 2012), the annual cost savings will equal almost $2,000 per supermarket.
- **Project Lifetime:** It is assumed that an HFC secondary loop system would be used for an average of 15 years before being replaced or undergoing a major change (i.e., the investment in such a project would yield results for 15 years). Therefore, the project lifetime is assumed to be 15 years, and the costs and HFC consumption and emissions are calculated over that time period.
- **Reduction Efficiency:** The annual direct emission reduction efficiency is calculated to be 94.6%. This reduction efficiency assumes that the reduced charge size (by 70%) and annual leak rate (from 15% to 5%) of HFC secondary loop systems result in the annual leakage of 25 kg of R-407A (with a GWP of 1,770) for a large supermarket system compared with 245 kg of R-404A (with a GWP of 3,260) that would have otherwise leaked from a conventional DX system.
- **Annual Reductions:** Annual reductions are associated with avoided leakage of HFCs, equivalent to 785 tCO_2e per supermarket per year, due to the reduced charge size and leakage rate as well as the lower GWP of R-407A relative to R-404A.
- **End of Life:** Because of the smaller charge size, HFC emissions are avoided at the end of the equipment's life. It is assumed that 10% of the original charge size would have been released at disposal.

NH_3 or HCs Secondary Loop and/or Cascade Systems in New Large Retail Food

For modeling purposes, the system type is defined as a new large retail food system used in a supermarket that is 60,000 sq. ft. with a charge size of 1,633 kg of R-404A, an annual leak rate of 15%, energy consumption of 1.2 million kWh/yr, and a lifetime of 15 years. At disposal, it is assumed that 10% of the original refrigerant charge is released.

This option is assumed to begin penetrating the market in the United States and other non-EU developed countries in 2011 and increase linearly to reach 20% by 2030. In the EU, to account for a greater market willingness to adopt natural refrigerants, market penetrations for this option are assumed to be higher than for other developed countries, reaching 35% by 2030. Market penetration in developing countries is assumed to be delayed by 10 years, relative to non-EU developed countries.

- **Capital Costs:** Despite the cost savings associated with less refrigerant, ammonia secondary loop systems are assumed to cost 25% more than conventional centralized HFC direct expansion systems in developed countries (IPCC, 2005), which are in turn assumed to cost approximately $182,000 for a large (60,000 sq. ft.) supermarket. The incremental cost is, therefore, estimated at approximately $45,600 in developed countries ($182,000 × 0.25 = $45,587). Capital costs in developing countries are assumed to be 10% greater; therefore, the one-time cost in developing countries is estimated at $50,145.
- **Annual O&M Costs:** No annual costs are associated with this option.
- **Annual Revenue:** It is assumed that this option consumes 5% less energy than conventional DX systems (Wang et al., 2010; SuperValu, 2012), which are assumed to consume 1,200,000 kilowatt hours each year (ADL, 2002) at an average electricity price of approximately $0.0614 per kilowatt hour (USEIA, 2011). Thus, for a large supermarket, this option is associated with an additional

annual savings of approximately $3,700 in developed countries (1,200,000 × 0.0614× 0.05 = $3,684). In developing countries, electricity costs are assumed to cost 67% more; therefore, annual energy savings are estimated at about $6,140.

In addition, given that this system will prevent 100% of direct annual HFC emissions, it is estimated that 245 kg of refrigerant will be saved each year as a result of reduced leakage. Assuming an average refrigerant (R-404A) cost of $9 per kg (TEAP, 2012), this translates into annual cost savings of $2,205 per supermarket.

- **Project Lifetime:** It is assumed that an ammonia secondary loop system would be used for an average of 15 years before being replaced or undergoing a major change (i.e., the investment in such a project would yield results for 15 years). Therefore, the project lifetime is assumed to be 15 years, and the costs and HFC consumption and emissions are calculated over that time period.
- **Reduction Efficiency:** The annual emission reduction efficiency is 100%, because ammonia has a GWP of zero and can fully replace the HFC blends typically used (e.g., R-404A).
- **Annual Reductions:** Annual reductions are associated with avoided emissions of HFCs, equivalent to 834 tCO_2e per supermarket facility that would have been released during regular equipment leakage.
- **End of Life:** Because ammonia fully replaces the HFC, HFC emissions that would have been released at the end of the equipment's life are avoided. It is assumed that 10% of the original HFC charge size would have been released at disposal.

CO_2 Transcritical Systems in New Large Retail Food

For modeling purposes, the system type is defined as a new large retail food system used in a supermarket that is 60,000 sq. ft. with a refrigerant charge size of 1,633 kg of R-404A, an annual leak rate of 15%, energy consumption of 1.2 million kWh/year, and a lifetime of 15 years. At disposal, it is assumed that 10% of the original refrigerant charge is released.

This option is assumed to begin penetrating the new installation market in the United States and other non-EU developed countries in 2011 and increase linearly to reach 20% by 2020. The market penetration is assumed to remain constant through 2030. In the EU, to account for a greater acceptance of natural refrigerants, market penetrations for this option are assumed to be higher than for other developed countries, reaching 60% by 2030. Market penetration in developing countries is assumed to be delayed by 10 years, relative to non-EU developed countries.

- **Capital Costs:** CO_2 transcritical systems are assumed to be 17.5% more expensive than conventional HFC centralized DX systems in developed countries (Australian Green Cooling Council, 2008; r744.com, 2012), which are assumed to cost nearly $182,000 for a large (60,000 sq. ft.) supermarket. The incremental cost is, therefore, estimated to translate to roughly an additional $31,900 in developed countries. Capital costs in developing countries are assumed to be 10% greater.
- **Annual O&M Costs:** No annual costs are associated with this option.
- **Annual Revenue:** It is assumed that this option consumes 5% less energy than conventional DX systems (*Supermarket News*, 2012), where it is assumed that conventional DX systems consume 1,200,000 kilowatt hours each year (ADL, 2002) at an average electricity price of approximately $0.0614 per kilowatt hour (USEIA, 2011). Thus, for a large supermarket, this option is associated with an annual savings of approximately $3,700 in developed countries (1,200,000 × 0.0614× 0.05 =

$3,684). In developing countries, electricity costs are assumed to cost 67% more; therefore, annual energy savings are estimated at about $6,140.

In addition, given that this system will prevent 100% of direct annual HFC emissions, it is estimated that 245 kg of refrigerant will be saved each year as a result of reduced leakage. Assuming an average refrigerant (R-404A) cost of $9 per kg (TEAP, 2012), this translates into annual cost savings of $2,205 per supermarket.

- **Project Lifetime:** It is assumed that a CO_2 transcritical system would be used for an average of 15 years before being replaced or undergoing a major change (i.e., the investment in such a project would yield results for 15 years). Therefore, the project lifetime is assumed to be 15 years, and the costs and HFC consumption and emission reductions are calculated over that time period.
- **Reduction Efficiency:** The annual emission reduction efficiency is 100%, because CO_2 has a negligible GWP and can fully replace the HFC blends typically used (e.g., R-404A).
- **Annual Reductions:** Annual reductions are associated with avoided emissions of HFCs, equivalent to 834 tCO_2e per supermarket facility that would have been released during regular equipment leakage.
- **End of Life:** Because CO_2 fully replaces the HFC, HFC emissions that would have been released at the end of the equipment's life are avoided. It is assumed that 10% of the original HFC charge size would have been released at disposal.

Retrofits of R-404A in Large Retail Food

For modeling purposes, the system type is defined as a new large retail food system used in a supermarket that is 60,000 sq. ft. with a charge size of 1,633 kg of R-404A, an annual leak rate of 15%, energy consumption of 1.2 million kWh/yr, and a lifetime of 15 years. At disposal, it is assumed that 10% of the original refrigerant charge is released. This option is assumed to be applied to existing supermarket systems that are 7 years old (i.e., roughly half-way through their useful lifetimes).

This option is assumed to begin penetrating 25% of the existing market (that is 7 years old) in all developed countries in 2015 and increase linearly to reach 100% by 2025. Market penetration is then assumed to remain constant through 2030, after which the availability of R-404A DX systems to retrofit will be minimal given assumptions about the penetration of other technologies. Market penetration in developing countries is assumed to be delayed by 10 years, relative to developed countries.

- **Capital Costs:** The retrofit procedure is assumed to require an additional 10 hours of a service technician's time (5 hours for the medium temperature system and 5 hours for the low temperature system). Assuming a technician labor rate of $50 per hour in developed countries, total capital costs are roughly $500. In developing countries, labor is assumed to be one-fifth cost of labor in developed countries; therefore, capital costs in developing countries are estimated to be $100.
- **Annual O&M Costs:** No annual costs are associated with this option.
- **Annual Revenue:** No annual revenue is associated with this option.
- **Project Lifetime:** Given that retrofits are performed on large retail food systems (with an average equipment lifetime of 15 years) at about half-way through their useful lifetime (i.e., 7 years), the project lifetime is assumed to be 8 years, and the costs and HFC consumption and emission reductions are calculated over that time period.

- **Reduction Efficiency:** The annual emission reduction efficiency is calculated to be 46%, based on the difference in GWP of R-407A (1,770) compared with R-404A (3,260).
- **Annual Reductions:** Annual emissions are reduced by replacing R-404A with R-407A, equivalent to annual HFC reductions of 417 tCO_2e per supermarket.
- **End of Life:** Emission reductions are realized at end of life, because R-404A is replaced by R-407A, which has a lower GWP. It is assumed that 10% of the original charge is released at the time of disposal.

HCs in New Small Retail Food Refrigeration Systems

This abatement option is assumed to be applicable to small retail food systems with an average charge size of 0.51 kg of either HFC-134a (90%) or R-404A, an annual loss rate of 8%, and a lifetime of 20 years. At disposal, it is assumed that 35% of the original refrigerant charge is released.

Market penetration of this option is assumed to begin in all developed countries in 2011 and increase linearly to reach 100% of the HFC systems by 2020 (note that 4% of the market is already assumed to transition to HCs in the baseline). Market penetration in developing countries is assumed to be delayed by 10 years, relative to non-EU developed countries.

- **Capital Costs:** According to Unilever (2008), the capital cost for HC cabinets was virtually cost neutral; therefore, no one-time costs are assumed to be associated with this option. It should be noted that additional R&D costs and/or safety-related costs may be associated with manufacturing equipment with HCs (Earthcare, 2008), but these costs may be offset by savings realized through reduced need for refrigerant at first fill as a result of decreased charge size[5] and the lower price of HCs compared with HFCs. Based on Unilever's experience, their investments, spread over the large numbers of cabinets being produced, had little impact on production costs (Unilever, 2008).
- **Annual O&M Costs:** No annual costs are associated with this option.
- **Annual Revenue:** This technology is assumed to prevent the annual release of 0.04 kg of R-134a or R-404A refrigerant; this analysis assumes an average annual leak rate of 8% and an original charge size of 0.51 kg for a conventional small retail food refrigeration unit (0.51 × 0.08 = 0.04). Assuming an average refrigerant price of $8.10 per kg for R-134a and R-404A,[6] an average HC price of $3.50 per kg (TEAP, 2012), and a 50% charge size reduction for HC refrigerant (Unilever, 2008), the net annual savings associated with this option is approximately $0.26.

  Although not quantified in this analysis, further savings may be realized through increased energy efficiency; HC use reportedly results in increased efficiency of 9% (Unilever, 2008). Additional information on the average energy consumption of HFC in small retail food systems would be needed to quantitatively address this savings in the analysis.

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[5] Charge sizes for hydrocarbon refrigerants used in refrigerated (ice cream) cabinets are approximately 50% smaller than charge sizes for HFCs (Unilever, 2008). This ratio is assumed here for small retail food equipment.

[6] Price is a weighted average, assuming 90% R-134a at $8 per kg and 10% R-404A at $9 per kg (TEAP, 2012).

- **Project Lifetime:** It is assumed that a small retail refrigeration unit would be used for an average of 20 years before being replaced (i.e., the investment in such a project would yield results for 20 years). Therefore, the project lifetime is assumed to be 20 years, and the costs and HFC consumption and emission reductions are calculated over that time period.
- **Reduction Efficiency:** The annual emission reduction efficiency is assumed to be 100% because HCs have a negligible GWP and can fully replace the HFCs typically used (i.e., HFC-134a and R-404A).
- **Annual Reductions:** Annual emissions of approximately 0.1 tCO_2e are reduced per unit by replacing HFC-134a/R-404A with HC, which have a negligible GWP.
- **End of Life:** Emission reductions are realized at end of life, because HFC-134a/R-404A is replaced by new chemicals with a negligible GWP. It is assumed that 35% of the original charge is released at the time of disposal.

HCs in New Window AC and Dehumidifiers

For modeling purposes, the system type is defined as an average window AC unit with a charge size of 0.4 kg of R-410A, an annual loss rate of 0.6%, and a lifetime of 11.5 years. At disposal, it is assumed that 50% of the original refrigerant charge is released.

This option is assumed to start penetrating window ACs and dehumidifiers in the United States and other non-EU developed countries in 2015, increasing linearly to reach roughly 34% of the market by 2030 and 50% of the market by 2035. In the EU, where there is a lower consumption of HFCs in this end-use in the baseline, the market penetration for this option is assumed to reach 50% by 2030. The market penetration in developing countries is assumed to be consistent with the market penetration in the EU, as R-290 systems have already been introduced in China for developing country and EU markets (GTZ-Proklima, 2009).

- **Capital Costs**: No one-time costs are assumed for this option even though there is indication that R-290 AC units can be produced more cheaply than R-410A units as a result of the better heat transfer properties and lower pressure drop of R-290, which allows for the use of narrower tubes in the condenser and evaporator (GTZ-Proklima, 2009).
- **Annual O&M Costs**: There are no annual costs associated with this option.
- **Annual Revenue:** Annual savings of $0.33 are associated with the avoided replacement costs of leaked R-410A, which is valued at $9 per kg, compared to HC which is valued at only $3.50 per kg (TEAP, 2012).
- **Project Lifetime:** It is assumed that a window unit or dehumidifier would be used for an average of 11.5 years before being replaced (i.e., the investment in such a project would yield results for 11.5 years). Therefore, the project lifetime is assumed to be 11.5 years and the costs and HFC consumption and emission reductions are calculated over that time period.
- **Reduction Efficiency:** The annual emission reduction efficiency is 100% because propane has a negligible GWP and can fully replace R-410A.
- **Annual Reductions:** On an annual basis, minor emission reductions are associated with avoided leakage of R-410A, equivalent to roughly 0.1 tCO_2e.
- **End of Life:** Emission reductions are realized at end of life, because R-410A is replaced by HCs which have a negligible GWP. It is assumed that 50% of the original charge is released at the time of disposal.

R-32 in New Unitary AC Equipment and PTAC/PTHP

For modeling purposes, the system type is defined as an average unitary AC system (i.e., residential, small commercial, and large commercial unitary AC), with a charge size of 8 kg of R-410A, an annual loss rate of 8.6%, and a lifetime of 15 years. At disposal, it is assumed that 40% of the original refrigerant charge is released.

This option is assumed to begin penetrating residential and small commercial unitary AC systems in developed countries in 2016 and reach 100% by 2025. This option is similarly assumed to penetrate 100% of large commercial unitary AC systems by 2025, but not begin penetrating this market until 2020 (due to technical challenges associated with the use of this option in larger systems). The market penetration is assumed to drop to 0% in 2026, when it is replaced by R-32 with MCHX systems across all AC equipment types. In developing countries, market penetration is assumed to be delayed by 10 years.

- **Capital Costs:** It is assumed that this option results in a one-time cost savings of approximately $30 per system, due to the reduced quantity of refrigerant required as well as the cost differential between R-32 and R-410A. Specifically, it is assumed that R-410A costs $9 per kg compared with $8 per kg for R-32 (TEAP, 2012). In addition, R-32 systems are assumed to perform with a reduced charge volume ratio of 66% compared to R-410A (Xu et al., 2012).
- **Annual O&M Costs:** No annual costs are associated with this option.
- **Annual Revenue:** It is assumed that annual savings are realized because the amount of refrigerant leaked that requires replacement is reduced, and the cost of R-32 is lower than the cost of R-410A. Specifically, it is assumed that 0.45 kg of R-32 must be replaced each year at a cost of $8 per kg rather that 0.69 kg of R-410A being replaced each year at a cost of $9 per kg. Therefore, the annual savings associated with this option is approximately $2.55 per system. No quantitative assumptions are made regarding the improved energy efficiency of R-32, although slight annual savings are expected.
- **Project Lifetime:** It is assumed that a unitary AC unit would be used for an average of 15 years before being replaced or undergoing a major change (i.e., the investment in such a project would yield results for 15 years). Therefore, the project lifetime is assumed to be 15 years, and the costs and HFC consumption and emission reductions are calculated over that time period.
- **Reduction Efficiency:** The annual emission reduction efficiency is calculated to be 75%, based on the difference in GWPs of the new versus old refrigerant (R-410A with GWP of 1,725 to R-32 with GWP of 650) and the reduction in charge size.
- **Annual Reductions:** This option results in annual emission reductions of 1.2 tCO_2e associated with refrigerant leakage, as a result of the smaller charge size and the use of a lower GWP refrigerant.
- **End of Life:** End-of-life emission reductions are realized at the end of the equipment's life, as a result of the lower GWP of the new refrigerant. It is assumed that 40% of the original charge is released at the time of disposal.

MCHX in New Unitary AC Equipment

For modeling purposes, the system type is defined as an average unitary AC system (i.e., residential, small commercial, and large commercial unitary AC), with a charge size of 8 kg of R-410A, an annual loss rate of 8.6%, and a lifetime of 15 years. At disposal, it is assumed that 40% of the original refrigerant charge is released.

Market penetration of this option is applicable to both large and small unitary AC equipment. In developed countries, this option is assumed to begin penetrating the new large unitary AC market in 2011 and increase linearly to reach 100% by 2020. In 2021, the market penetration of this option drops to 0%, as the market adopts other alternatives. For small unitary equipment, this option also begins to penetrate the market in 2011, reaching 50% by 2015, remaining constant until 2020, and then declining linearly to 0% by 2025 as the market transitions to other alternatives. In developing countries, market penetration is assumed to be delayed by 10 years.

- **Capital Costs:** One-time costs for this option are based on the reduction in charge size from 8 kg to roughly 5 kg. Assuming a refrigerant cost of $9 per kg (TEAP, 2012), one-time cost savings are assumed to equal approximately $27 per system.
- **Annual O&M Costs:** No annual costs are associated with this option.
- **Annual Revenue:** This technology is assumed to prevent the annual release of 0.26 kg of R-410A refrigerant, as a result of a 37.5% reduction in charge size; this analysis assumes an average annual leak rate of 8.6% for both the original and MCHX equipment and an original charge size of 8.0 kg for conventional unitary AC equipment ($8.0 \times 0.086 \times 0.375 = 0.258$). Assuming a price for R-410A of $9 per kg (TEAP, 2012), the annual savings associated with this option is roughly $2.30. Further savings may be realized through increased energy efficiency; MCHXs can reportedly result in increased efficiency of 5% to 10% in positive displacement chillers (Carrier, 2008). However, the corresponding efficiency increase in unitary AC equipment is unknown and is, therefore, not considered quantitatively in this analysis.
- **Project Lifetime:** It is assumed that a unitary AC unit would be used for an average of 15 years before being replaced or undergoing a major change (i.e., the investment in such a project would yield results for 15 years). Therefore, the project lifetime is assumed to be 15 years with the costs, HFC consumption, and HFC emissions calculated over that time period.
- **Reduction Efficiency:** The annual emission reduction efficiency is calculated to be 37.5%, based on the assumed reduction in refrigerant charge size.
- **Annual Reductions:** Annual reductions of 0.8 tCO_2e per unit are associated with avoided emissions of HFCs that would have been released during regular equipment leakage from the original, higher-charge equipment.
- **End of Life:** Because unitary AC units with MCHX have lower charge sizes than conventional unitary AC units, HFC emissions that would have been released at the end of the equipment's life are avoided. It is assumed that 40% of the original charge is released at the time of disposal.

R-32 with MCHX in New Unitary AC Equipment

For modeling purposes, the system type is defined as an average unitary AC system (i.e., residential, small commercial, and large commercial unitary AC), with a charge size of 8 kg of R-410A, an annual loss rate of 8.6%, and a lifetime of 15 years. At disposal, it is assumed that 40% of the original refrigerant charge is released.

Market penetration of this option is applicable to both large and small unitary AC equipment. In developed countries, this option is assumed to take over 100% of the market in 2026, displacing the market share previously covered by the R-32 and MCHX options (separately). In developing countries, market penetration is assumed to be delayed by 10 years.

- **Capital Costs:** It is assumed that this option results in a one-time cost savings of approximately $46 per system, due to the reduced quantity of refrigerant required as well as the cost differential between R-32 and R-410A. Specifically, it is assumed that R-410A costs $9 per kg compared with $8 per kg for R-32 (TEAP, 2012). In addition, MCHX reduce the charge size by 37.5% while R-32 systems are assumed to perform with a reduced charge volume ratio of 66% compared to R-410A (Xu et al., 2012).

- **Annual O&M Costs:** No annual costs are associated with this option.
- **Annual Revenue:** It is assumed that annual savings are realized because the amount of refrigerant leaked that requires replacement is reduced, and the cost of R-32 is lower than the cost of R-410A. Specifically, it is assumed that 0.28 kg of R-32 must be replaced each year at a cost of $8 per kg rather that 0.69 kg of R-410A being replaced each year at a cost of $9 per kg. Therefore, the annual savings associated with this option is approximately $3.91 per system. Further savings may be realized through increased energy efficiency; MCHXs can reportedly result in increased efficiency of 5% to 10% in positive displacement chillers (Carrier, 2008) and R-32 is also expected to be more energy efficient than R-410A. However, energy efficiency savings are not considered quantitatively in this analysis.
- **Project Lifetime:** It is assumed that a unitary AC unit would be used for an average of 15 years before being replaced or undergoing a major change (i.e., the investment in such a project would yield results for 15 years). Therefore, the project lifetime is assumed to be 15 years with the costs, HFC consumption, and HFC emissions calculated over that time period.
- **Reduction Efficiency:** The annual emission reduction efficiency is calculated to be 84.5%, based on the difference in GWPs of the new versus old refrigerant (R-32 versus R-410A) and the reduction in charge size.
- **Annual Reductions:** Annual reductions of 1.3 tCO_2e per unit are associated with refrigerant leakage, as a result of the smaller charge size and the use of a lower GWP refrigerant.
- **End of Life:** End-of-life emission reductions are realized at the end of the equipment's life, as a result of the lower GWP of the new refrigerant and the lower charge size. It is assumed that 40% of the original charge is released at the time of disposal.

MCHX in New Positive Displacement Chillers

For modeling purposes, the system type is defined as an average screw/scroll chiller using R-410A, R-407C, or HFC-134a refrigerant with a charge size of 270 kg, an annual loss rate of 6%, and a lifetime of 20 years. At disposal, it is assumed that 10% of the original refrigerant charge is released.

Market penetration of this option in developed countries is assumed to begin in 2011 and increase linearly to reach 100% by 2020. In developing countries, market penetration is assumed to be delayed by 10 years.

- **Capital Costs:** One-time costs for this option are based on the reduction in charge size from 270 kg to roughly 169 kg. Assuming a refrigerant cost of $8.67 per kg for R-134a, R-410A, and R-407C (TEAP, 2012), one-time cost savings are assumed to equal approximately $878 per system.
- **Annual O&M Costs:** No annual costs are associated with this option.
- **Annual Revenue:** This technology is assumed to prevent the annual release of 6.1 kg of HFC refrigerant, as a result of a 37.5% reduction in charge size. This analysis assumes an average annual leak rate of 6% and an original charge size of 270 kg for conventional positive displacement chillers (270 × 0.06 × 0.375 = 6.1). Assuming an average refrigerant price of about $8.67 per kg for R-134a, R-410A, and R-407C (TEAP, 2012), the annual savings associated with this option is roughly $53. Further savings may be realized through increased energy efficiency;

MCHXs can reportedly result in increased efficiency of 5% to 10% in positive displacement chillers (Carrier, 2008), but these associated savings are not quantified in this analysis.

- **Project Lifetime:** It is assumed that a positive displacement chiller unit would be used for an average of 20 years before being replaced or undergoing a major change (i.e., the investment in such a project would yield results for 20 years). Therefore, the project lifetime is assumed to be 20 years and the costs and HFC consumption and emission reductions are calculated over that time period.
- **Reduction Efficiency:** The annual emission reduction efficiency is calculated to be 37.5%, based on the assumed reduction in refrigerant charge size.
- **Annual Reductions:** Annual reductions of approximately 11 tCO_2e per chiller are associated with avoided emissions of HFCs that would have been released during regular equipment leakage from the original, higher-charge equipment. This assumes an average GWP of 1,517 for R-134a, R-407C and R-410A.
- **End of Life:** Because positive displacement chillers with MCHXs have lower charge sizes than conventional positive displacement chillers, HFC emissions that would have been released at the end of the equipment's life are avoided. It is assumed that 10% of the original charge is released at the time of disposal.

NH_3 or CO_2 in New IPR and Cold Storage Systems

For modeling purposes, the system type is defined as an average system using R-410A, R-507A, R-404A, or HFC-134a refrigerant with a charge size of 2,000 kg, an annual loss rate of 5%, and a lifetime of 25 years. At disposal, it is assumed that 10% of the original refrigerant charge is released.

A market penetration for new IPR and cold storage equipment in developed countries is assumed to begin in 2016 and increase linearly to reach 40% of the HFC market by 2025. It is assumed that the portion of the market already using ammonia or other low-GWP refrigerants continues to do so. Because of potential safety concerns (toxicity, pressure, flammability) with ammonia and CO_2 and building code restrictions, it is assumed that the majority of the baseline HFC market continues to use HFCs. Market penetration in developing countries is assumed to be delayed by 10 years relative to developed countries.

- **Capital Costs:** In developed countries, there is an assumed incremental one-time cost associated with this option of roughly $210,700; this assumes that a conventional HFC system with an original charge size of 2,000 kg costs $2.127 million, whereas an equivalent system using ammonia/CO_2 costs $1.916 million (Gooseff and Horton, 2008). In developing countries, capital costs associated with the construction of ammonia chillers are assumed to be 10% greater (i.e., $231,700 per unit).
- **Annual O&M Costs:** No annual costs are associated with this option.
- **Annual Revenue:** This option results in increased energy efficiency ranging from 2% to 20% (Gooseff and Horton, 2008); therefore, an 11% energy efficiency gain is assumed for this option. In developed countries, this calculation results in an annual cost savings of roughly $49,400, assuming conventional HFC systems would cost roughly $448,000 per year to operate. In developing countries, electricity costs are assumed to be 67% greater, resulting in an annual cost savings of about $82,300 per system.

  In addition, cost savings are associated with saved refrigerant. For modeling purposes, the average cost of R-134a, R-404A, R-410A, and R-507A was used, at $8.75 per kg (TEAP, 2012). On an annual basis, these savings are estimated to total approximately $875 per IPR/cold storage system—assuming that conventional HFC systems contain an average charge of 2,000 kg, that they emit 5% of this charge each year (i.e., the replacement of 100 kg of HFCs is avoided each year). The cost of ammonia or CO_2 refrigerant is assumed to be negligible compared with the HFCs and is not considered in the analysis.

- **Project Lifetime:** It is assumed that a cold storage or IPR system would be used for 25 years before being replaced or undergoing a major change (i.e., the investment in such a project would yield results for 25 years).
- **Reduction Efficiency:** The annual emission reduction efficiency is calculated to be 100%, because the HFCs are replaced with zero GWP ammonia and CO_2.[7]
- **Annual Reductions:** This option results in annual emission reductions of nearly 260 tCO_2e per system associated with refrigerant leakage, as a result of using zero GWP refrigerant. This is calculated assuming an average GWP of 2,396 for R-134a, R-404A, R-410A and R-507A.
- **End of Life:** End-of-life emission reductions are realized at the end of the equipment's life, as a result of the zero GWP of the new refrigerant. It is assumed that 10% of the original charge is released at the time of disposal.

Refrigerant Recovery at Disposal for All Existing Refrigeration/AC Equipment Types

This option assumes recovery efforts at disposal are increased beyond those already assumed in the baseline. Although these increased efforts could occur anywhere along the disposal chain, for cost and emission reduction modeling purposes, the system type is defined as an auto dismantling facility (i.e., based on the amount of refrigerant recoverable at disposal from a single MVAC recovery device per year). It is assumed that an MVAC recovery device is used to perform about 425 jobs per year and that an average MVAC has a recoverable charge of 0.13 kg at the time of disposal; this analysis assumes an original MVAC charge of 0.77 kg, of which 20% remains at the time of disposal and 85% of that amount is technically recoverable.

Beyond baseline levels, this option is assumed to further penetrate the market in developed countries in 2011 and increase linearly to reach 100% in 2015. Market penetration is then assumed to remain constant at 100% through 2030. Market penetration in developing countries is assumed to be delayed by 10 years.

- **Capital Costs:** The one-time cost associated with this option is the capital cost of a standard recovery-only device designed for MVACs, which is assumed to be approximately $2,026 in developed countries (ICF, 2008). Capital costs are assumed to be 10% greater in developing countries.
- **Annual O&M Costs:** It is assumed that each recovery-only device will be used to recover refrigerant from nearly 425 MVACs per year, each of which will require 10 minutes of technician

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[7] The GWP of CO_2 is assumed to be negligible in this analysis.

labor time, valued at \$15/hour[8] in developed countries (ICF, 2008). In addition, it is assumed that each year a new filter, valued at \$25, is required to properly maintain the recovery device (ICF, 2008). Therefore, annual costs are estimated at \$1,084 in developed countries. In developing countries, technician labor costs are assumed to be one-fifth the cost of that in developed countries; therefore, annual costs are assumed to be \$237 per recovery-only device.

- **Annual Revenue:** Annual cost savings are associated with saved refrigerant, because HFC-134a is assumed to be recovered for reuse, thereby preventing the need for virgin HFC-134a. Recovery of higher-priced or higher-GWP refrigerants would reduce the break-even price. Cost savings are calculated on a per MVAC recovery device basis. Specifically, it is assumed that a recovery-only device is used to recover refrigerant from roughly 425 MVACs per year at the time of disposal, that each MVAC has a charge size of 0.77 kg and has an average of 20% of its original charge remaining at the time of disposal, that 85% of the charge remaining is recoverable, and that the market value of HFC-134a is \$8 per kg (TEAP, 2012). Therefore, the annual cost savings associated with this option are \$443. It should be noted that recovery from other types of equipment, primarily larger equipment types, may result in significantly greater cost savings, because more refrigerant is recoverable from such systems.
- **Project Lifetime:** It is assumed that a refrigerant recovery-only device would be used for an average of 7 years before being replaced (i.e., the investment in such a project would yield results for 7 years). Therefore, the project lifetime is assumed to be 7 years, and the costs and HFC consumption and emission reductions are calculated over that time period.
- **Reduction Efficiency:** For small end uses, emissions at disposal are assumed to decrease to 3% of the charge size, whereas losses at disposal for large equipment are assumed to decrease to 4%. This is based on the following assumptions about best-case recovery scenarios:
  - Small equipment will be disposed of with an average of 20% remaining and recovery equipment can recover at 85% efficiency (i.e., emissions are reduced to $0.20 \times (1 - 0.85) = 3\%$
  - Large equipment will be disposed of with an average of 80% remaining and recovery equipment can recover at 95% efficiency (i.e., emissions are reduced to $0.80 \times (1 - 0.95) = 4\%$
- **Annual Reductions:** This option is assumed to result in an annual emission reduction of 72 tCO_2e per recovery device from the refrigerant recovery of roughly 425 MVACs at the end of the vehicle's life.
- **End of Life:** No additional emission reductions are realized when the recovery device reaches its useful life and is retired.

Refrigerant Recovery at Servicing for Existing Small Equipment

For modeling purposes, the system type is defined as an auto servicing facility (i.e., based on the amount of refrigerant recoverable at service from a single MVAC recovery/recycling device per year). It is assumed that an MVAC recovery device is used to perform about 150 jobs per year and that an average MVAC has a recoverable charge of 0.29 kg at time of service; this analysis assumes an original MVAC

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[8] 2006 hourly mean wage for North American Industry Classification System (NAICS) code 423900-Miscellaneous Durable Goods Merchant Wholesalers (BLS, 2007), adjusted to 2010\$.

charge of 0.77 kg, of which 40% remains at the time of service and 95% of that amount is technically recoverable.

Beyond baseline levels, this option is assumed to further penetrate the market in developed countries in 2011, increasing linearly to reach 20% over baseline levels in 2015 and 40% by 2020. Market penetration is then assumed to remain constant through 2030. In developing countries, market penetration is assumed to be delayed by 10 years.

- **Capital Costs:** Although this option is applicable to several refrigeration and AC end uses, costs based on recovery from an MVAC are assumed to be representative for this option. The one-time cost associated with this option is the capital cost of a recovery/recycling device, which is assumed to be approximately $4,050 in developed countries (ICF, 2008). This is the cost of recovery equipment certified to SAE Standard J2788, which is designed to recover refrigerant from MVACs at 95% efficiency. In developing countries, capital costs are assumed to be 10% greater, or approximately $4,456 per system.
- **Annual O&M Costs:** Annual costs are calculated on a per recovery device basis. It is assumed that each recovery device will be used to perform approximately 150 jobs per year, each of which will require 20 minutes of technician labor time, valued at $17/hour[9] in developed countries (ICF, 2008). In addition, it is assumed that each year a new filter, valued at $25, is required to properly maintain the recovery device (ICF, 2008). Therefore, annual costs in developed countries are estimated at about $870 ([150 × 20/60 × $16.88] + 25 = $870). In developing countries, technician labor time is assumed to be one-fifth of that in developed nations; therefore, the total assumed annual cost is $194.
- **Annual Revenue:** Annual cost savings are associated with saved refrigerant, because HFC-134a is assumed to be recycled, thereby preventing the need for virgin HFC-134a. Cost savings are calculated on a per MVAC recovery device basis. Specifically, it is assumed that 150 MVACs are serviced by a single recovery device each year, that each MVAC has a charge size of 0.77 kg and has 40% of its original charge remaining at time of service, that 95% of the charge remaining is recoverable, and that the market value of HFC-134a is $8 (TEAP, 2012). Therefore, the annual cost savings associated with this option is roughly $350 (150 × 0.77 × 0.4 × 0.95 × 8 = 351).
- **Project Lifetime:** It is assumed that a refrigerant recovery/recycling device would be used for an average of 7 years before being replaced (i.e., the investment in such a project would yield results for 7 years). Therefore, the project lifetime is assumed to be 7 years, and the costs and HFC consumption and emission reductions are calculated over that time period.
- **Reduction Efficiency:** The annual emission reduction efficiency is calculated to be 95%, based on the assumption that recovery devices can recover 95% of the refrigerant remaining in systems at time of service.
- **Annual Reductions:** Annual emission reductions of 57 tCO_2e are realized per facility (i.e., per recovery/recycling device) as refrigerant is recovered from equipment at time of service.
- **End of Life:** This option does not result in any emission reductions at end of life.

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[9] 2006 hourly mean wage for automotive repair and maintenance employees (BLS, 2007), adjusted to $2010.

Leak Repair for Existing Large Equipment

For modeling purposes, the system type is defined as a large supermarket system with a charge size of 1,633 kg of R-404A that leaks at 25% per year.

Beyond baseline levels, this option is assumed to further penetrate in developed countries in 2011 and increases linearly to reach 50% by 2015 and 100% by 2020, then remain constant (at 100%) through 2030. In developing countries, market penetration is assumed to be delayed by 10 years.

- **Capital Costs:** Although this option is applicable to several refrigeration and AC end-uses, costs based on leak repair of large supermarket systems are assumed to be representative for this option. A one-time cost of about $1,870 is assumed in developed countries for performing more significant small repairs on larger retail food systems, such as maintenance of the purge system or replacement of a gasket or O-ring. This cost is based on an estimate provided by USEPA (1998), which accounts for parts and labor needed to perform the repair. In developing countries, one-time costs are assumed to be 10% greater, roughly $2,060 per system.
- **Annual O&M Costs:** No annual costs are associated with this option.
- **Annual Revenue:** An annual cost savings is associated with reduced refrigerant loss. The cost of refrigerant (assumed to be R-404A) is estimated to be $9 per kg, and over 160 kg of refrigerant is assumed to be saved each year, assuming the leak rate of a large supermarket system is reduced from 25% to 15%,[10] resulting in an annual cost savings of approximately $1,470 per leak repair job.
- **Project Lifetime:** It is assumed that a leak repair job would reduce leakage for five years (i.e., the investment in such a project would yield results for five years). Therefore, the project lifetime is assumed to be five years, and the costs and HFC consumption and emission reductions are calculated over that time period.
- **Reduction Efficiency:** The annual emission reduction efficiency is assumed to be 40% (i.e., annual leakage will be reduced by 40%). For example, a supermarket with a leak rate of 25%/year would reduce its leak rate to 15%/year.
- **Annual Reductions:** Annual emission reductions of 532 tCO_2e are realized per system as equipment leakage is reduced by 40%.
- **End of Life:** This option does not result in any emission reductions at end of life.

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[10] It is assumed that the system is used in a 60,000 sq. ft. supermarket and contains a refrigerant charge of 1,633 kg (ADL, 2002).

Appendix E: Solvent Use

Details on Emission Methodology

HFC solvents include HFC-4310mee, HFC-365mfc, and HFC-245fa. Of these HFCs, HFC-4310mee is the most common solvent cleaner replacement. HFC-365mfc is used as an additive to form solvent blends with HFC-4310mee, helping to reduce the cost of these products. HFC-245fa is used in the aerosol solvent industry. Heptafluorocyclopentane is another HFC that could be used, although it is not yet used in significant amounts. Certain solvent applications, particularly precision cleaning end uses, will continue to use HCFCs, especially HCFC-225ca/cb (until the HCFC phaseout takes place), and to a much lesser extent, PFCs and perfluoropolyethers (PFPEs). Further details on the emission methodology for the solvent sector are described in this appendix to solvent use.

Details on the Four Model Vapor Degreasers

Detailed descriptions of the four facilities are as follows:

- **Precision cleaning applications with retrofitted equipment:** Precision cleaning may apply to electronic components, medical devices, or metal, plastic, or glass surfaces and is characterized by applications that require a high level of cleanliness to ensure the satisfactory performance of the product being cleaned. This facility is defined as a vapor degreaser that is 10 square feet in size, uses HFC-4310mee as a solvent, and emits approximately 250 pounds of solvent annually (3M, 2008). The facility is assumed to have already retrofitted its equipment through engineering control changes and improved containment to minimize emissions to comply with stringent environmental and safety regulations (e.g., the National Emissions Standard for Hazardous Air Pollutants in the United States) that limit emissions from solvent cleaning equipment in the United States and other developed countries.
- **Precision cleaning applications with nonretrofitted equipment:** This facility is characterized to generally distinguish between precision cleaning facilities in developed and developing countries. The degreaser size and type of solvent used is identical to the precision cleaning facility mentioned above; however, this facility is assumed to not have retrofitted equipment to better control emissions because of the lack of regulations requiring such controls. Thus, the amount of HFC solvent lost annually is higher; this analysis assumes a loss of approximately 500 pounds annually for this facility based on the assumption that retrofitted equipment emit 50% less than nonretrofitted equipment (Durkee, 1997).
- **Electronics cleaning applications with retrofitted equipment:** Electronics cleaning, including defluxing and other cleaning operations, is defined as a process that removes contaminants, primarily solder flux residues, from electronics or circuit boards. This facility is defined as a vapor degreaser 10 square feet in size, which uses HFC-4310mee as a solvent, and emits approximately 250 pounds of solvent annually (3M, 2008). Similar to the precision cleaning applications with equipment retrofits, this facility is further assumed to have already retrofitted its equipment through engineering control changes and improved containment to minimize emissions because of regulations in place to control volatile organic compound emissions.
- **Electronics cleaning applications with nonretrofitted equipment:** This facility is characterized to generally distinguish between electronics cleaning facilities in developed and developing countries. The degreaser size and type of solvent used by this facility is identical to the electronics cleaning facility mentioned above; however, this facility is assumed to not have retrofitted

equipment to better control emissions because of the lack of regulations requiring such controls. This analysis assumes emissions of approximately 500 pounds annually from this facility based on the assumption that retrofitted equipment emit 50% less than nonretrofitted equipment (Durkee, 1997).

Details on Mitigation Costs

Cost assumptions for each of the four abatement options are summarized in detail below:

HFC to HFE:

- **Capital Costs:** HFE solvents are very similar to HFC-4310mee in their key chemical properties, such that existing equipment designed with low emission features can still be used with HFE solvents, although the equipment might need minor adjustments, such as resetting of the heat balance. These modifications are not likely to amount to a substantial one-time cost (ICF Consulting, 2003; 3M Performance Materials, 2003); therefore, this analysis assumes no one-time costs for converting to an HFE solvent.
- **Annual O&M Costs:** HFE solvents have pricing structures roughly equal to the pricing structure of HFCs (3M Performance Materials, 2003). Therefore, this analysis assumes no annual costs are incurred when transitioning to an HFE solvent.
- **Annual Revenue:** This analysis does not assume a cost savings. A net cost savings may occasionally be experienced by end users that choose HFE solvents that are lower in density than HFC-4310mee (3M Performance Materials, 2003). For example, because the same volume of solvent is used and solvents are sold on a mass basis, formulations blended with HFE-7200 may be lower in cost relative to formulations containing HFC-4310mee.

Retrofit:

- **Capital Costs:** To retrofit equipment, significant upgrades must be made. One-time costs are based on the assumption that a user chooses to retrofit its equipment through increasing freeboard height, installing a cover, and installing a freeboard refrigeration device. Based on these upgrades, one-time costs are assumed to be $24,500 (Durkee, 1997).
- **Annual O&M Costs:** No annual costs are associated with this abatement option.
- **Annual Revenue:** Annual savings are associated with the avoided consumption of HFC that results from a reduction in emissions. An annual cost savings of almost $4,500 is assumed based on the assumed reduction in emissions of 250 pounds per year of HFCs that would otherwise need to be replaced.

NIK Aqueous:

- **Capital Costs:** Vapor degreasers are not suitable for retrofit to aqueous cleaning processes (Crest Ultrasonic, 2008). Therefore, the cost of replacing an HFC-containing cleaning system with an aqueous system is based on the initial investment in tanks, equipment, and space (Brulin & Company, Inc., 2008). This analysis assumes a one-time cost of $50,000 for the investment in the equipment and the additional space needed for that equipment (3M, 2008).
- **Annual O&M Costs:** The major operating costs for an aqueous system are associated with the cost of energy and the cost of the continuous flow of de-ionized water (Crest Ultrasonic, 2008). An annual cost of $7,400 is used to represent energy and water consumption costs; this cost is based on consumption of 9 kilowatt (kW) per day and $10 worth of de-ionized water per day (3M, 2008).

- **Annual Revenue:** Annual savings are based on the savings associated with not using an HFC-based cleaning system. An annual savings of $6,700 is used to represent energy and HFC solvent cleaner costs associated with using a retrofitted HFC-based cleaning system, while an annual savings of $11,200 is used to represent energy and HFC solvent cleaner costs associated with using a nonretrofitted HFC-based cleaning system; this savings is based on consumption of 4 kW per day and 250 to 500 pounds of HFC lost per year (3M, 2008; Durkee, 1997).

NIK Semi-aqueous:

- **Capital Costs:** Compared with aqueous systems, semi-aqueous systems often require an extra tank or two as well as the need for ventilation. Therefore, semi-aqueous systems are assumed to be slightly higher in cost than aqueous systems (Crest Ultrasonic, 2008). Additionally, vapor degreasers are not suitable for retrofit to semi-aqueous cleaning processes (Crest Ultrasonic, 2008). Therefore, the cost of replacing an HFC-containing cleaning system with a semi-aqueous system is based on the total initial investment in tanks and equipment (Brulin & Company, Inc., 2008). This analysis assumes a one-time cost of $55,000 for the investment in the equipment and the additional space needed for that equipment (3M, 2008).
- **Annual O&M Costs:** The major operating costs for a semi-aqueous system are associated with the cost of energy and the cost of the continuous flow of de-ionized water. When compared with aqueous systems, semi-aqueous add a level of complication and are, therefore, assumed to require more energy. As a result, an annual cost of $9,100 is used to represent energy and water consumption costs; this cost is based on consumption of 12 kW per day and $10 worth of de-ionized water per day (3M, 2008).
- **Annual Revenue:** Annual savings are based on the savings associated with not using an HFC-based cleaning system. An annual savings of $6,700 is used to represent energy and HFC solvent cleaner costs associated with using a retrofitted HFC-based cleaning system, while an annual savings of $11,200 is used to represent energy and HFC solvent cleaner costs associated with using a nonretrofitted HFC-based cleaning system; this savings is based on consumption of 4 kW per day and 250 to 500 pounds of HFC lost per year (3M, 2008; Durkee, 1997).

Appendix F: Foams Manufacturing

Detailed technical information on each abatement option is provided below. All costs were developed through EPA analysis in consultation with industry experts, as detailed in USEPA (2006) and USEPA (2009).

HCs in PU Appliances

This option is applied to a model facility assumed to produces 550,000 domestic refrigerators per year. In the developed countries excluding the European Union, this option is assumed to penetrate the market starting in 2011, increase linearly to reach 25% of all new appliances by 2015, and then reach 100% penetration in 2020. This option is assumed to maintain 100% penetration up to 2030. In the EU, there is no market penetration assumed for this option because there is no HFC consumption assumed in this end-use in the baseline. Similarly, it is assumed that developing countries will transition directly from HCFCs to HCs in this application; thus, this option is not applied to those countries. Details on the costs and emission reductions assumed for this option are provided below.

- **Capital Costs:** The one-time cost for replacing HFCs with HCs is assumed to be $9/kg of blowing agent (UNEP, 2011a). Each unit is assumed to contain 0.98 kg of blowing agent; thus total one-time costs are estimated to be $4.8 million per facility. These costs are associated with safety modifications, installation/retrofit of high-pressure foam dispensers, installation of systems storage tanks, pumps, and premixing stations, as well as training, trials, testing, and certification (TEAP, 2012; UNEP, 2011a).
- **Annual O&M Costs**: Annual costs are associated with the replacement formulations estimated at $3/kg of blowing agent (UNEP, 2011a); this is equivalent to $1.6 million per facility. This does not include the cost of the blowing agent itself; those costs are included in the Annual Revenue calculation.
- **Annual Revenue**: Cost savings are realized as a result of reduced blowing agent costs. Specifically, blowing agent costs for HFC-245fa are estimated at $11/kg, while HCs are estimated at $3/kg (TEAP, 2012). Assuming an agent replacement ratio of about 95%, this results in an annual savings of nearly $4.4 million per facility.
- **Project Lifetime**: It is assumed that capital equipment to convert from using HFCs to HC would be used for an average of 25 years before being replaced (i.e., the investment in such a project would yield results for 25 years). Therefore, the project lifetime per facility is taken to be 25 years, and the costs are calculated over that time period. However, HFC emission reductions are calculated over the lifetime of the foam, including the end-of-life and post-disposal emissions, as described further below.
- **Reduction Efficiency**: The reduction efficiency is 100% because all HFC blowing agent is replaced with HCs which have negligible GWPs.

In terms of emissions, the manufacture of appliances with HCs in place of HFCs will result in reductions during appliance production, use, and disposal. Specifically, emission reductions in this replacement application will occur at the following three stages:

- **Initial Reductions**: HFC emissions are eliminated during the initial stage with this replacement option, being replaced with HC. This analysis assumes that 4% of HFC-245fa emissions occur during manufacturing for polyurethane appliance foams.
- **Annual Reductions:** Replacing HFCs will reduce emissions annually. For this analysis, a 0.25% emission rate per year and a 14-year appliance lifetime are assumed.

- **End-of-Life Reductions**: This analysis estimates that 92.5% of the blowing agent remains in appliance foam at the end of its life and is emitted at disposal; thus, emissions would be avoided with the replacement of HFC-245fa.

HCs in Commercial Refrigeration

This option is assumed to be applied to a facility that produces 50,000 commercial refrigeration units per year. In developed countries, this option is assumed to penetrate the market starting in 2011 and increase linearly to reach 25% by 2015, and 100% by 2020. This option is assumed to maintain 100% penetration through 2030. This option is not applied in developing countries, where it assumed that the market will transition directly from HCFCs to HCs (i.e., no HFC consumption in this application is assumed in the baseline). Details on the costs and emission reductions assumed for this option are provided below.

- **Capital Costs:** The one-time cost for this option is assumed to be $18/kg of blowing agent (UNEP, 2011b). Each unit is assumed to contain 1.4 kg of blowing agent; thus, total one-time costs are estimated to be $1,260,000 per facility. These costs are associated with safety modifications, installation/retrofit of high-pressure foam dispensers, installation of systems storage tanks, pumps, and premixing stations, as well as retrofit of jigs and moulds, training, trials, testing, and certification (TEAP, 2012; UNEP, 2011b).
- **Annual O&M Costs**: Annual costs are associated with replacement formulations, estimated at $1.50/kg of blowing agents (UNEP, 2011b). This translates to a cost of approximately $105,000 per facility.
- **Annual Revenue**: Cost savings are realized due to lower blowing agent costs; specifically, HFC-25fa is estimated at $11/kg while HCs are estimated at $3/kg (TEAP, 2012). Assuming an agent replacement ratio of about 80%, this translates into an annual savings of nearly $602,000 per facility
- **Project Lifetime**: It is assumed that capital equipment to convert from using HFC-245fa to HC would be used for an average of 15 years before being replaced (i.e., the investment in such a project would yield results for 15 years). Therefore, the project lifetime per facility is taken to be 15 years, and the costs are calculated over that time period.
- **Reduction Efficiency**: The reduction efficiency is 100% because HFCs are fully replaced with HCs, which have negligible GWPs.

In terms of emissions, the manufacture of commercial refrigeration equipment with HCs in place of HFCs will result in reductions during equipment production, use, and disposal. Specifically, emission reductions in this replacement application will occur at the following three stages:

- **Initial Reductions**: HFC-245fa emissions are eliminated during the initial stage with this replacement option, being replaced with HC. This analysis assumes that 6% of emissions occur during manufacturing for commercial refrigeration foams.
- **Annual Reductions:** Replacing HFCs reduce emissions annually. For this analysis, a 0.25% emission rate per year and a 15-year equipment lifetime are assumed.
- **End-of-Life Reductions**: This analysis estimates that 90.25% of the blowing agent remains in appliance foam at the end of its life and are emitted upon equipment disposal; thus, emissions would be avoided with the replacement of the HFC.

HC in Polyurethane Spray Foams

This option is applied to a model facility assumed to use 57,500 kg of HFC-245fa/CO_2 PU spray foam annually. In developed countries, this option is assumed to penetrate the market starting in 2011 and increase linearly to reach 30% by 2025, then maintain this 30% penetration rate through 2030. In developing countries, there is no market penetration assumed for this option because there is no HFC consumption assumed in this end-use in the baseline. Details on the costs and emission reductions assumed for this option are provided below, based on USEPA (2009).

- **Capital Costs**: This analysis assumes the one-time cost for replacing HFC-245fa/CO_2 with HCs is $15,700. This one-time cost is associated with costs for new formulations, the number of system houses, and the number of PU spray foam contractors that equally share these costs, as well as a one-time replacement cost for equipment and spray nozzles.
- **Annual O&M Costs**: This analysis assumes operating costs of $45,200 for this abatement option. These costs include the use of fire retardant and worker safety training necessary with the use of HCs, as well as the cost increase from the blowing agent density change. Fire retardant costs are assumed to be $8,400 and are calculated as the amount of foam produced multiplied by the incremental increase in fire retardant used in foam and the fire retardant costs. Worker training costs, which incorporate costs of training per day, the number of workers, and the number of training days, are assumed to be $7,200. The remaining $29,600 is due to the blowing agent density change costs.
- **Annual Revenue**: An annual cost savings of $50,400 is associated with this abatement option because the alternative blowing agents cyclopentane and isopentane are less expensive per year than HFC-245fa/CO_2.
- **Project Lifetime**: It is assumed that capital equipment to convert from using HFC-245fa to HC would be used for an average of 25 years before being replaced (i.e., the investment in such a project would yield results for 25 years). Therefore, the project lifetime per facility is taken to be 25 years, and the costs are calculated over that time period. However, it should be noted that HFC emission reductions are calculated over the lifetime of the foam, as described further below.
- **Reduction Efficiency:** The reduction efficiency is 100% because HFCs are fully replaced with HCs, which have negligible GWPs.

In terms of emissions, the use of HCs in spray foam applications in place of HFCs will result in reductions during foam production, use, and disposal/demolition. Specifically, emission reductions in this replacement application will occur at the following three stages:

- **Initial Reductions**: Emissions are reduced during the initial stage with this replacement option; this analysis assumes that 15% of emissions occur during manufacturing of PU spray foams.
- **Annual Reductions**: Replacing HFC-245fa/CO_2 to HC would reduce emissions annually. For this analysis, a 1.5% emission rate per year and a 56-year lifetime for buildings are assumed.
- **End-of-Life Reductions**: This analysis estimates that approximately 1% of the blowing agent remains in PU spray foam at the end of its life and is emitted upon disposal/demolition; thus, those emissions would be avoided with the replacement of HFC.

CO_2 in Polyurethane Spray Foams

This option is applied to a model facility assumed to use 57,500 kg of HFC-245fa/CO_2 PU spray foam annually. In developed countries, this option is assumed to penetrate the market starting in 2011 and increase linearly to reach 70% by 2025, then maintain this penetration rate through 2030. In developing countries, there is no market penetration assumed for this option because there is no HFC consumption assumed in this end-use in the baseline. Details on the costs and emission reductions assumed for this option are provided below, based on USEPA (2009).

- **Capital Costs**: According to industry experts, contractors that are using HFC-245fa/CO_2 (water) can use the same equipment for CO_2 (water) with only minimal modification (Caleb, 2000). This analysis assumes a one-time cost for replacing HFC-245fa/CO_2 with CO_2 of $4,600. This cost is associated with costs for new formulations, the number of system houses, and the number of PU spray foam contractors who equally share these costs.
- **Annual O&M Costs:** This analysis assumes operating costs of $60,700 for this abatement option. These costs include the use of fire retardant, the alternative foam cost increase, and the cost increase from the blowing agent density change.
- **Annual Revenue**: An annual cost savings of $10,700 is associated with this abatement option because the alternative blowing agent is less expensive than HFC-245fa/CO_2.
- **Project Lifetime**: It is assumed that capital equipment to convert from using HFC-245fa to CO_2 (water) would be used for an average of 25 years before being replaced (i.e., the investment in such a project would yield results for 25 years). Therefore, the project lifetime per facility is taken to be 25 years, and the costs are calculated over that time period. However, HFC emission reductions are calculated over the lifetime of the foam, as described further below.
- **Reduction Efficiency:** The reduction efficiency is 100% because HFCs are fully replaced by CO_2, which has a negligible GWP (of only 1).

In terms of emissions, the use of CO_2 in spray foam applications in place of HFCs will result in reductions during foam production, use, and disposal. Specifically, emission reductions in this replacement application will occur at the following three stages:

- **Initial Reductions**: Emissions are reduced during the initial stage with this replacement option; this analysis assumes that 15% of emissions occur during manufacturing of PU spray foams.
- **Annual Reductions**: Replacing HFC-245fa/CO_2 to CO_2 would reduce emissions annually. For this analysis, a 1.5% emission rate per year and a 25-year lifetime are assumed.
- **End-of-Life Reductions**: This analysis estimates that approximately 1% of the blowing agent remains in PU spray foam at the end of its life and is emitted upon disposal/demolition; thus, those emissions would be avoided with the replacement of the HFC.

LCD/Alcohol in XPS Boardstock

This analysis assesses the costs for a model facility producing 1,000,000 board feet of 134a/CO_2 XPS boardstock per year. In developed countries, this option is assumed to penetrate the market starting in 2016 and increase linearly to reach 75% by 2020. The option is assumed to maintain a 75% market penetration rate through 2030. This option is not applied in developing countries, as it is assumed that developing countries will transition directly from HCFCs to non-HFC alternatives. Details on the costs and emission reductions assumed for this option are provided below, based on USEPA (2009).

- **Capital Costs**: This analysis assesses the costs for a hypothetical producer to replace an HFC-134a and CO_2-based blend with LCD/alcohol in one of the 10 lines. The capital cost to switch to LCD/alcohol is estimated to be nearly $5.9 million. Blends of CO_2 with alcohol require equipment operating at higher pressure than with HFC-134a. In addition, more highly corrosive by-products formed by using the alternative blowing agent result in safety and incineration considerations that require additional expenditures.

- **Annual O&M Costs**: Using this alternative, the foam manufactured is assumed to compensate for lower insulating performance relative to HFC-blown foams by increasing the thickness of the foam in the application, where possible. Thus, incremental differences in indirect emissions and costs associated with energy penalties are negligible. Annual costs include direct costs such as labor and energy. In addition, loss of profit due to a decrease in capacity is also taken into account; when converting from HFC-134a and CO_2-based blends, there is an estimated loss of 10% capacity, which equates to the loss of production of 10 million bd-ft per year of foam from the one line converted. These costs combined are estimated to be $915,000 per facility.
- **Annual Revenue**: The two types of cost savings associated with this option are those associated with the alternative blowing agent used and those associated with the amount of polystyrene resin used. Together these savings are estimated to be nearly $4.8 million.
- **Project Lifetime**: It is assumed that capital equipment to convert from using HFC-134a/CO_2 to LCD/alcohol would be used for an average of 25 years before being replaced (i.e., the investment in such a project would yield results for 25 years). Therefore, the project lifetime per facility is taken to be 25 years, and the costs are calculated over that time period. However, it should be noted that HFC emission reductions are calculated over the lifetime of the foam, as described further below.
- **Reduction Efficiency**: The reduction efficiency is 100% because HFCs are fully replaced with LCD/alcohol, which has a negligible GWP.

In terms of emissions, the use of LCD/alcohol in XPS foam applications in place of HFC-134a/CO_2 will result in reductions during foam production, use, and disposal/demolition. Specifically, emission reductions in this replacement application will occur at the following three stages:

- **Initial Reductions**: Emissions of HFC-134a are eliminated during the initial stage with this replacement option, being replaced with LCD/alcohol. This analysis assumes that 25% of emissions occur during manufacturing for XPS foams.
- **Annual Reductions**: Replacing HFC-134a/CO_2 based blend with LCD/alcohol-based blend would reduce emissions annually. For this analysis, a 0.75% emission rate per year and a 50-year XPS boardstock foam lifetime are assumed.
- **End-of-Life Reductions:** This analysis estimates that approximately 38% of the blowing agent remains in XPS boardstock foam at the end of its life and is emitted; thus, those emissions would be avoided with the replacement of the HFC.

HFC-134a to HCs in PU One-Component Foam

This option is applied to a model facility assumed to use 130,000 kg of HFC-134a PU one-component foam annually. In developed countries, this option is assumed to penetrate the market starting in 2011, increase linearly to 25% by 2015, and then reach 100% of the HFC-134a market in 2020. Market penetration is then assumed to remain constant through 2030. Market penetration in developing countries is assumed to be delayed by 10 years, relative to developed countries. Details on the costs and emission reductions assumed for this option are provided below based on USEPA (2009).

- **Capital Costs**: The one-time cost for replacing HFC-134a with HCs is $399,000, which includes the cost of installing safety equipment. The capital cost of this option is assumed to be 10% greater (i.e., $438,900) in developing countries.

- **Annual O&M Costs**: This analysis assumes operating costs of $342,000 for this abatement option. These costs include the use of fire retardant and worker safety training necessary with the use of HCs. Fire retardant costs are assumed to be $329,000 and are calculated as the amount of foam produced multiplied by the incremental increase in fire retardant used in foam and the fire retardant costs. Worker training costs, which incorporate costs of training per day, the number of workers, and the number of training days, are assumed to be $13,000.
- **Annual Revenue**: An annual cost savings of approximately $859,000 is associated with this abatement option because propane and butane are less expensive per kilogram than HFC-134a. Per year, HFC-134a blowing agent costs $936,000, whereas the per-year cost of the alternative blowing agent is $77,000.
- **Project Lifetime**: It is assumed that capital equipment to convert from using HFC-134a to HC would be used for an average of 25 years before being replaced (i.e., the investment in such a project would yield results for 25 years).
- **Reduction Efficiency**: The reduction efficiency is 100% because HFCs are assumed to be fully replaced with HCs, which have negligible GWPs.

In terms of emissions, the use of HCs in one-component foam applications in place of HFC-134a will result in reductions during foam production/manufacture. Specifically:

- **Initial Reductions**: During the initial stage, HFC emissions are avoided by using HC blowing agents instead. This analysis assumes that 100% of emissions occur during the manufacturing of PU one-component foams.
- **Annual Reductions**: Not applicable for this option, as all reductions occur during foam manufacture.
- **End-of-Life Reductions:** Not applicable for this option, as all reductions occur during foam manufacture.

HFC-152a to HCs in PU One-Component Foam

This option is applied to a model facility assumed to use 130,000 kg of HFC-152a PU one-component foam annually. In developed countries, this option is assumed to penetrate the market starting in 2011, increase linearly to 25% by 2015, and then reach 100% of the HFC-152a market in 2020. Market penetration is then assumed to remain constant through 2030. This option is not assumed to penetrate markets in developing countries, as no HFC-152a consumption is assumed in the baseline. Details on the costs and emission reductions assumed for this option are provided below based on USEPA (2009).

- **Capital Costs**: HFC-152a is a flammable blowing agent, so safety precautions would already be established in a PU one-component foam facility that uses HFC-152a. However, to accommodate a primary HC blowing agent system, greater precautions must be taken. As a result, the capital cost is conservatively estimated to be the same as the conversion from HFC-134a to HCs, which is $399,000.
- **Annual O&M Costs:** Annual costs associated with the use of fire retardant and worker safety training, which are both necessary with the use of HCs, are assumed to be the same as those estimated for switching from HFC-134a to HC in PU one-component foam, described above and totaling $342,000.
- **Annual Revenue**: An annual cost savings of approximately $409,000 is associated with this abatement option because propane and butane are less expensive per kilogram than HFC-152a.

Per year, HFC-152a blowing agent costs $528,000, whereas per year, the cost of the alternative blowing agent is $119,000.

- **Project Lifetime**: It is assumed that capital equipment to convert from using HFC-152a to HC would be used for an average of 25 years before being replaced (i.e., the investment in such a project would yield results for 25 years).
- **Reduction Efficiency:** The reduction efficiency is 100% because HFCs are fully replaced with HCs, which have negligible GWPs.

In terms of emissions, the use of HCs in one-component foam applications in place of HFC-152a will result in reductions during foam production/manufacture. Specifically:

- **Initial Reductions**: During the initial stage, HFC emissions are avoided by using HC blowing agents instead. This analysis assumes that 100% of emissions occur during the manufacturing of PU one-component foams.
- **Annual Reductions**: Not applicable for this option, as all reductions occur during foam manufacture.
- **End-of-Life Reductions:** Not applicable for this option, as all reductions occur during foam manufacture.

HCs in PU Continuous and Discontinuous Foams

This option is applied to a model facility assumed to use 453,000 kg of HFC-134a annually to produce continuous and discontinuous foam panels. In developed countries, this option is assumed to penetrate the market starting in 2011 and then increase linearly to reach 25% by 2015 and 100% by 2020. Market penetration is then assumed to remain constant through 2030. This option is not assumed to penetrate markets in developing countries, as no HFC consumption is projected in the baseline (i.e., countries are assumed to transition directly from HCFCs to HCs). Details on the costs and emission reductions assumed for this option are provided below based on USEPA (2009).

- **Capital Costs**: According to industry experts, the one-time cost for replacing HFC-134a with HCs is $319,000, which includes the cost of installing safety equipment.
- **Annual O&M Costs:** This analysis assumes operating costs of $2.49 million for this abatement option. These costs include the use of fire retardant, changes in foam density, and worker safety training necessary with the use of HCs. Fire retardant costs are assumed to be approximately $799,000 and are calculated as the amount of foam produced multiplied by the incremental increase in fire retardant used in foam and the fire retardant costs per kilogram. The cost increase in density change is assumed to be $1.68 million and is calculated by multiplying the amount of foam produced by the increase in foam density and the per kilogram cost of the alternative foam. Worker training costs, which incorporate costs of training per day, the number of workers, and the number of training days, are assumed to be $12,000.
- **Annual Revenue:** An annual cost savings of approximately $2.94 million is associated with this abatement option. Per year, HFC-134a blowing agent costs $3.41 million whereas the per-year cost of the alternative blowing agent is $471,000.
- **Project Lifetime:** It is assumed that capital equipment to convert from using HFC-134a to HC would be used for an average of 25 years before being replaced (i.e., the investment in such a project would yield results for 25 years). Therefore, the project lifetime per facility is taken to be 25 years, and the costs are calculated over that time period. However, HFC emission reductions are calculated over the lifetime of the foam, as described below.

- **Reduction Efficiency:** The reduction efficiency is 100% because HFC-134a is fully replaced with HCs, which have negligible GWPs.

In terms of emissions, the use of HCs in foam panels in place of HFC-134a will result in reductions during foam production, use, and disposal/demolition. Specifically, emission reductions in this replacement application will occur at the following three stages:

- **Initial Reductions:** Emissions of HFC-134a are eliminated during the initial stage with this replacement option, being replaced with HCs. This analysis assumes that 5.5% of emissions occur during manufacturing of PU continuous/discontinuous panel foams.
- **Annual Reductions:** Replacing HFC-134a with HC would reduce emissions annually. For this analysis, a 0.5% emission rate per year and a 50-year lifetime are assumed.
- **End-of-Life Reductions**: This analysis estimates that approximately 69.5% of the blowing agent remains in PU continuous/discontinuous panel foam at the end of its life and is emitted; thus, those emissions would be reduced with the replacement of HFC.

Manual Blowing Agent Recovery from Appliances at End of Life

This option is applied to a model facility assumed to dispose 125,000 domestic refrigerators per year. In developed countries excluding the EU, this option is assumed to further penetrate the market starting in 2011 and reach 20% by 2015, and then 50% by 2030. This option is not assumed to penetrate markets in the EU, as foam recovery from appliances is already required and/or widely practiced; further, Europe also has limited to no HFC consumption in appliance foam in the baseline, rendering this option obsolete. Similarly, this option is not applied in developing countries, as it is assumed that such countries will transition directly from HCFCs to HCs in appliance foam. Details on the costs and emission reductions assumed for this option are provided below.

- **Capital Costs**: Capital costs are assumed to be $1.0 million per facility for large band automated saws (CARB, 2011).
- **Annual O&M Costs**: Annual costs to process the units are assumed to be $39 per unit associated with labor, handling/processing and transport; assuming 125,000 units are processed per facility per year, total annual net costs are approximately $4.9 million per facility (CARB, 2011).
- **Annual Revenue:** No annual cost savings are associated with this option beyond the metal recycling savings, which are factored in to the net annual costs.
- **Project Lifetime:** The project lifetime is assumed to be 25 years, based on the lifetime of the appliance recycling equipment.
- **Reduction Efficiency**: It is estimated that 85% of the blowing agent remaining at appliance end of life can be recovered and safely destroyed using manual recovery techniques, with the remaining 15% lost to the atmosphere (CARB, 2011).
- **Initial Reductions**: No initial reductions are associated with this abatement option, because emissions are reduced only on an annual basis from the recovery and destruction of the foam blowing agent at equipment disposal.
- **Annual Reductions**: The manual recovery and subsequent destruction of appliance foam results in the avoided emissions of 99,380 tCO_2e per facility, assuming 125,000 units are processed each year, and each contains 0.98 kg of HFC-245fa (85% of which is destroyed).
- **End-of-Life Reductions**: Although this option reduces end-of-life emission from domestic refrigerators, the reductions are quantified on an annual basis from the perspective of an

appliance recycling facility, not on the basis of a single disposed unit. Therefore, no end-of-life reductions are associated with this abatement option.

Fully Automated Blowing Agent Recovery from Appliances at End of Life

This option is applied to a model facility assumed to dispose 200,000 domestic refrigerators per year. In developed countries except for the EU, this option is assumed to further penetrate the market starting in 2011and then increase linearly to reach 20% in 2030. This option is not assumed to penetrate markets in the EU, as foam recovery from appliances is already required and/or widely practiced; further there is limited to no HFC consumption in appliance foam in the EU's baseline, rendering this option obsolete. Similarly, this option is not applied in developing countries, as it is assumed that such countries will transition directly from HCFCs to HCs in appliance foam. Details on the costs and emission reductions assumed for this option are provided below.

- **Capital Costs:** Capital costs are estimated at $5.0 million associated with the purchase of a fully automated appliance recycling device (CARB, 2011).
- **Annual O&M Costs:** Annual costs to process each appliance are assumed to be $31 per unit; assuming 200,000 units are processed per facility per year, total annual net costs are roughly $6.1 million per facility for labor, handling/processing, transport, and electricity costs. These costs account for annual savings associated with metal recycling (CARB, 2011).
- **Annual Revenue**: No annual cost savings are associated with this option beyond the metal recycling savings included in the net annual costs.
- **Project Lifetime**: The project lifetime is assumed to be 25 years, based on the lifetime of the appliance recycling device.
- **Reduction Efficiency**: it is estimated that 95% of the blowing agent remaining at appliance end of life can be recovered and safely destroyed using fully automated recovery techniques, with the remaining 5% lost to the atmosphere (CARB, 2011).
- **Initial Reductions**: No initial reductions are associated with this abatement option, because emissions are reduced only on an annual basis from the recovery and destruction of the foam blowing agent at equipment disposal.
- **Annual Reductions**: The fully automated recovery and subsequent destruction of appliance foam using automated technology results in the avoided emissions of 155,458 tCO_2e per facility, assuming 200,000 units are processed each year, and each contains 0.98 kg of HFC-245fa (95% of which is destroyed).
- **End-of-Life Reductions**: Although this option reduces end-of-life emissions from domestic refrigerators, the reductions are quantified on an annual basis from the perspective of an appliance recycling facility, not on the basis of a single disposed of unit. Therefore, no end-of-life reductions are associated with this abatement option.

Appendix G: Aerosol Product Use

Detailed Emissions Assumptions

Emissions from aerosols were estimated using assumptions about the market size for aerosol products, use of HFCs per aerosol can, growth rates, loss rates, and transition away from ozone-depleting substances over time, using the Vintaging Model.

Detailed Technical Cost Assumptions

Hydrocarbons

This option replaces HFCs in non-MDI aerosols with an HC-based propellant. HC aerosol propellants are usually mixtures of propane, butane, and isobutane. Their primary advantage lies in their affordability; the price of HC propellants, which range from one-third to one-half that of HFCs. The main disadvantages of HC aerosol propellants are flammability concerns and, because they are VOCs, their contribution to ground-level ozone and smog. Despite these concerns, HC aerosol propellants already hold a sizable share of the market and may be acceptable for additional applications. For this analysis, the GWP of HC is assumed to be 3.48, the average GWP of propane and isobutane. With GWPs of 1,300 and 140 for HFC-134a and HFC-152a, respectively; this option has a reduction efficiency of 99.7% and 97.5%, respectively.

Cost estimates for the conversion of HC propellants are summarized below:

- **Capital Costs**: Costs of converting filling facilities to accept HC propellants can range from $10,000 to potentially as high as $1.2 million; the one-time cost varies based on the need for investments in new equipment and the need to relocate to regions where the use of HCs is considered safe (Nardini, 2002). To accommodate any flammable propellant, a company is required to build a storage tank to house the product. This tank will need to be connected to the main facility through a plumbing system. (Techspray, 2008; MicroCare, 2008) The analysis uses a one-time cost of $325,000 for this option.
- **Annual O&M Costs**: According to discussions with industry, the majority of companies would already have fire insurance and other fire safety precautions intact; therefore, no significant additional costs would be associated with housing a flammable chemical, and the increase in annual costs would be zero (Techspray, 2008; MicroCare, 2008).
- **Annual Revenue**: The lower cost of HCs (estimated at $1/lb) compared with the cost of HFC-134a (estimated at $3/lb) results in an annual savings associated with gas purchases. Filling a can that requires two ounces of propellant with HFC-134a is thus estimated to cost approximately $0.40, which results in a cost savings of $2.8 million for the model facility. Filling a can that requires two ounces of propellant with HFC-152a is also estimated to cost approximately $0.25 (based on the price per pound of HFC-152a of $2/lb). Using HCs results in a cost savings of $1 million for the model facility, assuming a price of $1/lb or $0.125 per two-ounce can.

Not-in-Kind

This option replaces HFCs in non-MDI aerosols with an NIK device. NIK aerosol replacements include finger/trigger pumps, powder formulations, sticks, rollers, brushes, nebulizers, and bag-in-can/piston-can systems. These systems often prove to be a better and more cost-effective option than HFC-propelled aerosols, particularly in areas where a unique HFC property is not specifically needed.

Because all HFCs are replaced with a device that does not use any GHGs, the reduction efficiency of this option is 100%.

Cost estimates for the conversion of HFCs to NIK devices are summarized below:

- **Capital Costs**: This analysis used an incremental capital cost of $250,000 per facility producing an annual total of 10 million cans requiring two ounces of propellant each (USEPA, 2001). Significant variability exists in financial components of projects targeting NIK replacements for HFC-containing aerosol products. This variability is attributable to the wide range of potential aerosol and NIK product types.
- **Annual O&M Costs**: In the case of liquid pumps and solid applicators, capital investments are generally lower, but material costs are higher than for HFCs (UNEP, 1999). To account for higher material costs of the particular sticks, rollers, and pumps being used, the analysis assumes an estimated $500,000 in annual costs for a facility that produces 10 million units annually (e.g., cans, pumps) (USEPA, 2001).
- **Annual Revenue**: Filling a can that requires two ounces of propellant with HFC-134a is estimated to cost approximately $0.40 (based on the price per pound of HFC-134a of $3/lb) compared with no costs for chemicals for an NIK-formulated product, resulting in a savings of $4.1 million for the model facility. Filling a can that requires two ounces of propellant with HFC-152a is estimated to cost approximately $0.25 (based on the price per pound of HFC-152a of $2/lb) compared with no costs for chemicals for an NIK-formulated product, resulting in a savings of $2.3 million for the model facility.

HFO-1234ze

This option examines the transition to HFO-1234ze. HFO-1234ze is nonflammable (at room temperature) and has physical properties that are very similar to both the HFC-134a and HFC-152a. Hence, it may be used as a ‘drop-in’ replacement for HFC propellants (MicroCare, 2011). The manufacturer of this chemical indicates that Europe and Japan have already begun to adopt HFO-1234ze, while interest is also rising in the United States, because of awareness of environmental sustainability (Honeywell, 2011a). A number of dusters using HFO-1234ze are available today (Amazon, 2013; ITW Chemtronics, 2013; Miller Stephenson, 2013; Stanley Supply and Services, 2013). A large scale production facility is being built in the United States with an expected production of HFO-1234ze in late 2013 (Honeywell, 2011b). In the absence of regulations, adoption in Europe and Japan is expected to grow continuously at a moderate rate (reaching a maximum of 15% to 20% of today’s HFC volume); therefore, this option is expected to penetrate up to 15% of the non-MDI HFC-134a market and up to 20% of the non-MDI HFC-152a market, which equates to a total of 17% of the non-MDI aerosol model facility. In the United States, adoption of HFO-1234ze is expected to follow a similar path, but with a later start. In developing countries, no interest in HFO-1234ze is expected in the foreseeable future because of inexpensive options that are the preferred solutions today. The GWP of HFO-1234ze is six (Javadi et al., 2008), the GWP of HFC-134a is 1,300, and the GWP of HFC-152a is 140; thus, this option has reduction efficiencies of 99.5%and 95.7%, respectively.

Cost estimates for the conversion of HFCs to HFO-1234ze are summarized below:

- **Capital Costs**: For this analysis, a one-time cost of roughly $500,000 is assumed to account for the need for bulk storage. According to MicroCare (2011), the transition would be gradual and require inventory space to support the switch in propellant. This is likely a conservative (high) one-time cost estimate, considering it is about the same capital cost considered in the next section for a flammable propellant, whereas HFO-1234ze(E) is not flammable at room temperatures.

- **Annual O&M Costs**: The higher cost of HFO-1234ze (estimated at $4/lb) compared with HFC-134a or HFC-152a (estimated at $3/lb and $2/lb, respectively) results in an annual cost associated with gas purchases.
- **Annual Revenue**: No annual savings are associated with this option. Cost savings may be achieved in certain products where the lower pressure of HFO-1234ze compared to HFC-134a may allow for the use of a lower-pressure and lower-cost aerosol can; however, these savings are not included in the analysis here.

HFC-134a to HFC-152a

This option replaces the HFC-134a, with a GWP of 1,300, with HFC-152a, with a GWP of 140, in non-MDI aerosol products; thus, this option has a reduction efficiency of 89.2%. HFC-134a is the primary nonflammable propellant in certain industrial products. HFC-152a possesses only moderate flammability hazards and might, therefore, be acceptable for some applications where HFC-134a is used, but it may present problems for other applications.

Cost estimates for the conversion of HFC-134a to HFC-152a are summarized below:

- **Capital Costs**: The costs of converting filling facilities to accept HFC-152a are estimated to be about $500,000 (Techspray, 2008; MicroCare, 2008). To accommodate HFC-152a (or any flammable propellant), a company is required to build a storage tank to house the product. This tank will need to be connected to the main facility through a plumbing system (Techspray, 2008).
- **Annual O&M Costs**: Aside from the costs associated with building a storage house, there would be no other significant expenses. According to discussions with industry, the majority of companies would already have fire insurance and other fire safety precautions intact; therefore, no significant additional costs would be associated with housing a flammable chemical, and the increase in annual costs would be zero (Techspray, 2008; MicroCare, 2008).
- **Annual Revenue**: The lower cost of HFC-152a (estimated at $2/lb) compared with HFC-134a (estimated at $3/lb) results in an annual savings associated with gas purchases. Filling a can that requires two ounces of propellant with HFC-134a is estimated to cost approximately $0.40 (based on the price per pound of HFC-134a of $3/lb) compared with the cost associated with HFC-152a of approximately $0.25 per can (based on the price per pound of HFC-152a estimated at $2/lb). Thus, savings are estimated at $1.8 million for the model facility.

Dry Powder Inhalers

This option is applicable to the MDIs. DPIs are a viable option with most anti-asthma drugs, although they are not successful with all patients or all drugs. Micronised dry powder, that contains the drug agent, is contained in the DPI, a non-pressurized delivery system, and is inhaled and deposited in the lungs. They are suitable only in patients who are able to inhale robustly enough to transport the powder to the lungs. DPIs are not suitable for persons with severe asthma or for young children. Unlike MDIs, powdered drug particles contained in DPIs tend to aggregate and may cause problems in areas with hot and humid climates. Other issues that doctors and patients consider when choosing a treatment device include the patient’s manual dexterity, ability to adapt to a new device, and perception of the effectiveness of the medicine and taste of any added ingredients. Ultimately, these and other critical patient care issues must be assessed by the doctor and patient in choosing whether a DPI, MDI or other type of therapy is most appropriate (Price et al., 2004; UNEP, 2010). Where feasible, DPIs—which do not contain GHGs—could be used in lieu of HFC-containing MDIs; hence, the reduction efficiency of this option is 100%.

Cost estimates for the conversion of HFC-134a to DPI devices are summarized below:

- **Capital Costs:** No one-time costs are assumed.
- **Annual O&M Costs:** The annual cost associated with using DPIs was estimated to be approximately $700,000 per metric ton of substance. This cost was based on €533,000 (in 1999 Euros) per metric ton of substance (Enviros, 2000), which translates to an annual cost of $552,544 using the 1999 exchange rate of $0.964629 Euros to 1 U.S. dollar (X-rates.com, 2006).[1] According to the source cited by Ecofys (2000), this annual cost incurred by the industry takes into account the increase in the cost of DPI treatment, the cost to market the new treatment, and the cost to retrain the patients in using the DPI (Enviros, 2000). It is unknown to what extent this value includes capital and annual costs and savings.
- **Annual Revenue:** No cost savings are assumed; a DPI treatment of 200 doses costs, on average, around $10 more than an MDI (Enviros, 2000).

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[1] The 1999 conversion rate is used because the cost cited in Enviros is in 1999 Euros; the annual cost was then converted to 2010 USD.

Appendix H: Fire Protection

Detailed technical information on each abatement option is provided below. All costs were developed through ICF analysis in consultation with industry experts, as detailed in USEPA (2006) and USEPA (2009), except where otherwise noted.

FK-5-1-12 in New Class A Total Flooding Applications

This technology option is assumed to be applicable in new Class A total flooding application end uses, replacing HFCs (primarily HFC-227ea). Class A total flooding application end uses represent an estimated 95% of the total flooding sector based on installed base (i.e., total consumption).[1] The additional adoption of FK-5-1-12 is assumed to only penetrate new systems because replacing installed systems may be cost prohibitive.

This option is assumed to further penetrate the Class A total flooding market in developed countries to reach 20% in 2015 (with a linear increase starting in 2011) and 40% in 2020. Market penetration is then assumed to remain constant at 40% through 2030. Market penetration rates in developing countries are assumed to penetrate to the same percentages but on a 10-year time lag, based on the phaseout schedule under the Montreal Protocol.

- **Capital Costs:** Capital costs of FK-5-1-12 systems in developed countries associated with installation and equipment are estimated to be $9.40 more than conventional HFC systems per cubic meter of protected space. Also, although the floor space requirements for this option are very similar to those of HFC systems, there is a slight increase in the floor space needed to protect each cubic meter of space (approximately 0.0005 square feet) (Wickham, 2003). Assuming an average construction cost of approximately $176 per square foot (R.S. Means, 2007), this translates into an incremental one-time construction cost of $0.09 per cubic meter of protected space. Therefore, the total incremental one-time cost of this option is $9.49 per cubic meter of protected space in developed countries. Capital costs are assumed to be 10% greater in developing countries to account for higher tariffs.
- **Annual O&M Costs:** Because the additional space requirement associated with this option relative to conventional HFC systems is so small (an average of 0.0005 square feet per cubic meter of protected space [Wickham, 2003]), the additional annual costs associated with heating and cooling are also very small—less than one cent annually per cubic meter of protected space. This cost was derived by multiplying the additional space requirement (0.0005 square feet/cubic meter of protected space) by the average electricity cost to heat/cool space—which is assumed to be roughly $7.60 per square foot in developed countries (EIA, 2011; ICF, 2009). In developing countries, annual costs associated with electricity consumption are assumed to be 66% greater. In addition, an annual cost of $0.02 per cubic meter of protected space is assumed to be associated with annual emissions/agent replacement costs. This cost is based on the assumption that approximately 0.74 kilograms of FK-5-1-12 agent is required to protect every cubic meter of protected space, that 2% of this amount is leaked each year, and that FK-5-1-12 has an incremental cost (relative to HFC-227ea) of approximately $2/kg (Werner, 2011).

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[1] See footnote 3.

- **Annual Revenue:** Because the agent cost of FK-5-1-12 is greater than that of HFC-227ea, no annual cost savings are assumed for this option.
- **Project Lifetime:** It is assumed that an FK-5-1-12 total flooding system would be used for an average of 20 years before being replaced or undergoing a major change (i.e., the investment in such a project would yield results for 20 years). Therefore, the project lifetime is assumed to be 20 years, and the costs and HFC consumption and emission reductions are calculated over that time period.
- **Reduction Efficiency:** The annual emission reduction efficiency is calculated to be 99.97%, based on the difference in GWP between FK-5-1-12 and HFC-227ea. Slightly lower reduction efficiency would be achieved when replacing HFC-125.
- **Annual Emission Reductions:** Annual HFC reductions equivalent to 0.04 tCO_2e per model facility (i.e., per cubic meter of protected space) are associated with avoided emissions of HFC-227ea. These reductions are partially offset by the additional energy consumption associated with increased cooling/heating requirements (equivalent to less than 0.0001 tCO_2e per year).
- **End-of-Life Emission Reductions:** No HFC emissions are assumed to be avoided at the end of the equipment's life, because proper disposal or reuse is assumed in the baseline.

Inert Gas Systems in New Class A Total Flooding Applications

This technology option is assumed to be applicable in new Class A application end uses, replacing HFCs (primarily HFC-227ea). Class A total flooding application end uses represent an estimated 95% of the total flooding sector.[2]

This option is assumed to penetrate the Class A total flooding markets in developed countries to reach 10% in 2015 (with a linear increase beginning in 2011), 20% in 2020, and 30% in 2025. Market penetration is assumed to remain constant at 30% through 2030. Market penetration rates in developing countries are assumed to penetrate to the same percentages but on a 10-year time lag, based on the phaseout schedule under the Montreal Protocol.

- **Capital Costs:** Inert gas systems are assumed to cost $7.13 more than conventional HFC-227ea systems in developed countries, which are estimated to cost roughly $33 per cubic meter of protected space (average across all space sizes) (Wickham, 2003). In addition, because inert gas systems require more space to house gas cylinders than conventional HFC systems (an additional 0.023 square feet per cubic meter of protected space [Wickham, 2003]), in some cases there will be additional one-time costs to construct the additional space for storage. Assuming a construction cost of about $176 per square foot (R.S. Means, 2007), this additional space requirement translates into an incremental one-time cost of $4.03 per cubic meter of protected space. Therefore, the total incremental capital cost of this option is $11.16 per cubic meter of protected space. Capital costs are assumed to be 10% greater in developing countries to account for higher tariffs.
- **Annual O&M Costs:** Depending on the application, the space required to house additional gas cylinders (an additional 0.023 square feet per cubic meter of protected space) will need to be heated and cooled. Based on average U.S. electricity costs of about $7.60 per square foot (ICF,

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[2] See footnote **Error! Bookmark not defined.**.

2009; EIA, 2011), the heating and cooling costs associated with this option result in an assumed annual cost of $0.17 per cubic meter of protected space for developed countries. In developing countries, annual costs are assumed to be 81% greater because of higher electricity costs.

- **Annual Revenue:** Because, on average, 0.633 kilogram of HFC-227ea is needed to protect one cubic meter of space (Wickham, 2003) and assuming a release rate of 2% of the installed base, the emission of approximately 13 grams of HFC-227ea is avoided each year per cubic meter of protected space. Based on an average HFC-227ea cost of about $24 per kilogram (Werner, 2011), this translates into an annual savings of $0.28 per cubic meter of protected space. These annual savings are assumed to be the same in all regions.
- **Project Lifetime*:*** It is assumed that an inert gas total flooding system would be used for an average of 20 years before being replaced or undergoing a major change (i.e., the investment in such a project would yield results for 20 years). Therefore, the project lifetime is assumed to be 20 years, and the costs and HFC consumption and emission reductions are calculated over that time period.
- **Reduction Efficiency:** The annual emission reduction efficiency is calculated to be 100%, given that the GWP of inert gas is zero.
- **Annual Emission Reductions:** Annual HFC reductions equivalent to 0.04 tCO_2e per model facility (i.e., per cubic meter of protected space) are associated with avoided emissions of HFC-227ea. These reductions are partially offset by the additional energy consumption associated with increased cooling/heating requirements (equivalent to 0.002 tCO_2e per year).
- **End-of-Life Emission Reductions:** No HFC emissions are assumed to be avoided at the end of the equipment's life, because proper disposal or reuse is assumed in the baseline.

Water Mist Systems in New Class B Total Flooding Applications

This technology option is assumed to be applicable in large ($\geq$3,000 m^3), new Class B total flooding application end uses, replacing HFCs (primarily HFC-227ea, but also HFC-125 and HFC-23). This analysis assumes that systems designed to protect against Class B fire hazards represent an estimated 5% of the total flooding sector;[3] the adoption of water systems is assumed to only penetrate new systems because replacing installed systems may be cost prohibitive.

This option is assumed to penetrate the Class B total flooding markets in developed countries to reach 25% over baseline levels in 2015 (with a linear increase beginning in 2011), 50% in 2020, and 75% in 2025. Market penetration is assumed to remain constant at 75% through 2030. Market penetration rates in developing countries are assumed to penetrate to the same percentages but on a 10-year time lag, based on the phaseout schedule under the Montreal Protocol.

- **Capital Costs:** Capital costs of water mist systems used in marine systems to protect spaces of 3,000 m^3 and larger in developed countries are estimated to be $4.82 more per cubic meter of protected space than conventional HFC-227ea systems in large spaces (which are estimated to cost an average of about $30 per cubic meter of protected space in these sized spaces) (Wickham,

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[3] See footnote 3.

2003).[4] In addition, because water mist systems require more space than conventional HFC systems (an additional 0.0472 square feet per cubic meter of protected space [Wickham, 2003]), one-time costs associated with constructing additional space are also considered. Assuming a construction cost of roughly $176 per square foot (R.S. Means, 2007), this additional space requirement translates into an incremental one-time cost of $8.32 per cubic meter of protected space. Therefore, the total incremental capital cost of this option is assumed to be $13.14 per cubic meter of protected space in developed countries. Capital costs are assumed to be 10% greater in developing countries to account for higher tariffs.

- **Annual O&M Costs:** Depending on the application, the space required to house additional gas cylinders (an additional 0.0472 square feet per cubic meter of protected space) will need to be heated and cooled. Based on average U.S. electricity costs of roughly $7.60 per square foot (ICF, 2009; EIA, 2011), the heating and cooling costs associated with this option result in an annual cost of $0.36 per cubic meter of protected space in developed countries. In developing countries, annual costs are assumed to be 81% greater because of higher electricity costs.
- **Annual Revenue:** Because an average of 0.63 kilogram of HFC-227ea is needed to protect one cubic meter of space (for 3,000 m^3 to 5,000 m^3 spaces) (Wickham, 2003), and assuming a release rate of 2% of the installed base, it is assumed that the emission of approximately 13 grams of HFC-227ea is avoided each year (i.e., 0.63 kilogram × 2%). Based on an average HFC-227ea cost of roughly $24 per kilogram, this translates into an annual savings of $0.28 per cubic meter of protected space (Werner, 2011). These annual savings are assumed to be the same in all regions.
- **Project Lifetime:** It is assumed that a water mist Class B total flooding system would be used for an average of 20 years before being replaced or undergoing a major change (i.e., the investment in such a project would yield results for 20 years). Therefore, the project lifetime is assumed to be 20 years, and the costs and HFC consumption and emission reductions are calculated over that time period.
- **Reduction Efficiency:** The annual emission reduction efficiency is calculated to be 100%, given that water has a GWP of zero (i.e., use of water is not expected to increase atmospheric levels of water vapor).
- **Annual Emission Reductions:** Annual HFC reductions equivalent to 0.04 tCO_2e per model facility (i.e., per cubic meter of protected space) are associated with avoided emissions of HFC-227ea that would have been released during regular equipment leakage. These reductions are partially offset by the additional energy consumption associated with increased cooling/heating requirements (equivalent to about 0.004 tCO_2e per year).
- **End-of-Life Emission Reductions:** No HFC emissions are assumed to be avoided at the end of the equipment's life, because proper disposal or reuse is assumed in the baseline.

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[4] The cost of conventional HFC-227ea systems is less per cubic meter of protected space in large spaces than in small ones.

Appendix I: Primary Aluminum Production

The reduction efficiencies of the two abatement options can be determined by calculating the difference between the model facility PFC emission factor and the state-of-the-art PFPB PFC emission factor. Reduction efficiencies for a major (i.e., complete) retrofit will likely be in range of 55% to 96%, depending on the reduction cell type being upgraded. Based on communications with industry (Marks, 2006), minor retrofits at VSS and HSS facilities achieve 50%, SWPB 75%, and CWPB 25% of the emission reductions of a complete retrofit. As a result, the reduction efficiencies for a minor retrofit will likely be in the range of about 24% to 41%; with a range of 55% to 96% for a major/complete retrofit, again depending on the reduction cell type being upgraded.

Table I-1 shows the abatement options and corresponding reduction efficiencies by model facility type. It should be noted that state-of-the art PFPB facilities (e.g., Qatalum: Qatar Aluminium Co. in Mesaieed, Qatar and Sohar Aluminium Company in Sohar, Oman) are categorized as residual emission facilities.

Table I-1: Abatement Options and Corresponding Reduction Efficiencies by Facility Type

Facility Type	Abatement Option
Residual (PFPB, state of the art)	N/A (Little to no room for additional abatement)
VSS	Minor retrofit (achieves ≈39% reduction efficiency) Major retrofit (achieves ≈77% reduction efficiency)
HSS	Minor retrofit (achieves ≈39% reduction efficiency) Major retrofit (achieves ≈78% reduction efficiency)
SWPB	Minor retrofit (achieves ≈24% reduction efficiency) Major retrofit (achieves ≈96% reduction efficiency)
CWPB	Minor retrofit only (achieves ≈55% reduction efficiency)[a]
PFPB (other)	Minor retrofit only (achieves ≈55% reduction efficiency)[b]

[a] According to Marks (2011b), there is no opportunity for conventional CWPBs to achieve improved anode effect performance through installation of point feeders because they already have “bar break” feed systems, which have roughly the same anode effect performance as point feeders. Therefore, the reduction efficiency for process computer control systems is assumed to equal the entire emission reduction potential going from conventional CWPB to state-of-the-art PFPB.

[b] By definition, a PFPB has point-feeding technology, so the reduction efficiency for process computer control systems is assumed to equal the entire emission reduction potential going from the average PFPB emission factor to the state-of-the-art PFPB (assumed to be the median PFPB emission factor).

The analysis assumes that practically all existing facilities are running potlines using some type of computer controls (Marks, 2011b); therefore the minor retrofit option involves, “[the installation or] upgrade of process computer control systems.” Computer systems provide greater control over alumina feeding, enable control of repositioning the anodes as they are consumed during aluminum production, and enhance the ability to predict and suppress AEs (i.e., control current efficiency). Upgrading the computer controls is assumed to allow a model facility to realize a certain percentage (either 50% or 100% depending on the technology type) of the maximum current efficiency improvement possible from a complete retrofit; the remaining percentage is attributed to the major (i.e., alumina point feeding) retrofit (Marks, 2011a).

In addition, a certain amount of baseline technology adoption has also been assumed for the major retrofit and is reflected in the technical applicability values for each technology type. For example, one company (Rusal) in Russia has installed point feeders in one of their major (VSS) facilities, Krasnoyarsk, that produces about 1 million metric tons annually (Marks, 2011b); out of the 3.653 million metric tons of primary aluminum produced by VSS facilities globally in 2009 (IAI, 2010); as a result, the technical applicability of a major retrofit at a VSS model facility is reduced from 100% to 73% (i.e., by 1/3.653 or 27%). Similar baseline adoption adjustments are made for CWPB and PFPB model facilities.

Capital Cost Detail

Capital costs for installing the major and minor retrofit systems represent the costs associated with installing the process computer control systems and alumina point-feeding technologies at the aluminum production facilities. The capital costs, obtained from IEA (2000) and confirmed by Marks (2011a), are presented in Table I-2.

Table I-2: Capital Costs by Facility Type (2010 USD)

Facility	Minor Retrofit (Process Computer Control Systems only)	Major Retrofit (Process Computer Control Systems plus Alumina Point Feeding)
VSS	$5,980,801	$84,546,778
HSS	$5,980,801	$89,039,533
SWPB	$6,238,348	$11,804,213
CWPB	$7,125,452	N/A
PFPB (other)	$8,026,865	N/A
PFPB (state of the art)	N/A	N/A

Annual Cost and Savings Detail

The annual revenues were assumed to be the additional profits that would result from increased aluminum production (from increased current efficiency). The additional profits were estimated by multiplying an estimated average profit margin per metric ton of aluminum ($255) by the estimated increase in aluminum production for each model facility and retrofit.[1]

The current efficiency changes, annual O&M costs, and annual revenues for each facility type and retrofit are obtained from IEA (2000), as confirmed by Marks (2011a), and are shown in Table I-3 and Table I-4.

Table I-3: Increase in Current Efficiency, Annual O&M Costs, and Annual Revenues for Minor Retrofit

Facility	Increase in Current Efficiency	Annual O&M Costs (2010 USD)	Annual Revenues (2010 USD)
VSS	2%	$119,616	$1,019,402
HSS	1%	$59,808	$509,701
SWPB	1.5%	$93,575	$764,552
CWPB	1%	$71,255	$509,701
PFPB (other)	1%	$80,269	$509,701

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[1] An average profit margin of 12% was calculated using the market price of aluminum (London Metals Exchange, 2011) and a review of production costs associated with aluminum smelting (Harbor Intelligence, 2009).

Table I-4: Increase in Current Efficiency, Annual O&M Costs, and Annual Revenues for Major Retrofit

Model Facility	Increase in Current Efficiency	Annual O&M Costs (2010 USD)	Annual Revenues (2010 USD)
VSS	4%	$3,381,871	$2,038,805
HSS	2%	$1,780,791	$1,019,402
SWPB	3%	$354,126	$1,529,104
CWPB	N/A	N/A	N/A
PFPB (other)	N/A	N/A	N/A

Appendix J: HCFC-22 Production

Countries that produce HCFC-22 are 1) Argentina, 2) China, 3) Germany, 4) India, 5) Japan, 6) Mexico, 7) Netherlands, 8) Russian Federation, 9) South Korea, 10) Spain, 11) United States, and 12) Venezuela. Countries with historical HCFC-22 production only are 1) Australia, 2) Brazil, 3) Canada, 4) France, 5) Greece, 6) Italy, 7) South Africa, and 8) United Kingdom.

To estimate historical emissions of HFC-23, country-specific HCFC production data as reported to the United Nations Environmental Program (UNEP) Ozone Secretariat (UNEP, 2010), country-specific production capacity information from the Chemical and Economics Handbook (CEH) (CEH, 2001; Will et al., 2004; Will et al., 2008), and field data on HFC-23 emissions from HCFC-22 production (Montzka et al., 2010) were used. Dispersive and feedstock HCFC-22 production were estimated as follows:

- **Dispersive HCFC-22 production**. UNEP (2010) reports total dispersive, or nonfeedstock, overall HCFC production totals by country in Ozone Depletion Potential (ODP)-weighted tons. Information on HCFC-22 production capacities (CEH, 2001; Will et al., 2004) were used to apply a percentage to the total HCFC production as reported by UNEP (2010) to determine the portion that is HCFC-22, which is then "unweighted" using HCFC-22's ODP (0.055).
- **Feedstock HCFC-22 production**. A ratio of dispersive production to feedstock production was developed to estimate production of HCFC-22 for feedstock. This ratio was estimated over the time series based on data for 1990 from USEPA (2006) and on data for 1996 and 2007 from Montzka et al. (2010) and by linearly interpolating the intervening years. The ratio of dispersive production to feedstock production was then used to grow dispersive HCFC-22 production to total HCFC-22 production, without exceeding reported production capacities.[1]

Estimated HCFC-22 production levels were subsequently multiplied by a HFC-23/HCFC-22 coproduction ratio (i.e., tons of HFC-23 emitted per ton of HCFC-22 produced). In some cases, the emission estimate assumes baseline market penetration of thermal abatement technologies. Depending on how well the process is optimized, these ratios can range from 1.4% to 4% (Rotherham, 2004; McCulloch and Lindley, 2007). The HFC-23/HCFC-22 coproduction ratio for Annex I countries was assumed to be 2% across the entire time series (Montzka et al., 2010). The HFC-23/HCFC-22 coproduction ratio for non-Annex I countries and Russia was assumed to be 3% from 1990 through 2005 (USEPA, 2006) and 2.4% from 2006 through 2007 (Montzka et al., 2010). The lower emission rate takes into account any HFC-23 emission offsets from CDM projects in these countries and the JI project at Russia's HCFC-22 plant in Perm. Where UNFCCC-reported HFC-23 emission estimates were available through the UNFCCC flexible query system, these estimates were used in place of estimates calculated using production data (UNFCCC, 2012).

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[1] For countries in Western Europe, this methodology was employed for Greece, the Netherlands, and Spain, countries for which HCFC production is only HCFC-22 according to plant capacity information. The total HCFC-22 production estimates for these countries were subtracted off reported production for the Western Europe region (Will et al., (2004) across the time series, and the remaining HCFC-22 production for Western Europe was allocated to France, Germany, Italy, and the United Kingdom based on total HCFC-22 production capacity for each country as reported in CEH (2001, 2008) and Will et al. (2004). For China, apparent production from 2000 through 2007 as reported by Will et al. (2008) was used to represent total HCFC-22 production for these years. Estimates of China's HCFC-22 production for 1990 through 1999 were backcasted by applying a ratio of total HCFC-22 production reported in Will et al. (2008) to UNEP-reported nonfeedstock HCFC production for 2000.

HFC-23 emission projections were developed for Annex I countries: Germany, Japan, the Netherlands, Russia, Spain, and the United States.[2] For the United States, National Communications projections of emissions were used for 2010 to 2020 (UNFCCC, 2009); emissions trends were used to project HFC-23 emissions for the remainder of the time series (2025 through 2030). For all other Annex I countries, the dispersive production and feedstock production portion of emissions were projected separately. It was assumed that emissions from dispersive production would decrease linearly from 2007 so that no emissions resulted from HCFC-22 dispersive production by the 2020 phaseout date under the Montreal Protocol. To project the feedstock production portion of HFC-23 emissions, USEPA applied the 5% global growth rate of feedstock HCFC-22 production as reported in Montzka et al. (2010).

HFC-23 emission projections were developed for non-Annex I countries: China, India, Mexico, South Korea, and Venezuela. HCFC-22 production projections were developed for both dispersive and feedstock production overall for the region and then disaggregated by country using the percentage of each country's contribution to the 2007 HCFC-22 production's total. HCFC-22 projected production was then apportioned into four different model facilities for each developing country—these are discussed in Section IV.8.3. HFC-23 emissions were then projected as follows:

- The HFC-23/HCFC-22 coproduction ratio of 2.9% (representative of the CDM's annual mean ratio for 2009) (Miller et al., 2010) was used to estimate emissions.
- To account for HFC-23 not released to the atmosphere for facilities with abatement, the HFC-23/HCFC-22 coproduction ratio was modified by 55% representing the reduction efficiency associated with the incinerator. Although reduction efficiency is closer to 95% for incineration, a lower reduction efficiency takes into account startups, shutdowns, and malfunctions. This modification results in emission estimates comparable to those published by Miller et al. (2011), which relied on actual CDM abatement reporting to determine nonreleased HFC-23 from facilities with CDM projects.

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[2] For the U.K., France, and Italy; HCFC-22 production was assumed to end; therefore, no emission projections were developed. For Australia and Canada, UNFCCC reported emissions of HFC-23 were zero beginning in 2000 and 1995, respectively. No further data were available on Australia, so USEPA assumed Australia will not produce HCFC-22 in the future. Will et al. (2004) reports that Canada only produces one HCFC, HCFC-123, so USEPA assumed that Canada will not produce HCFC-22 in the future.

Appendix K: Electric Power Systems

The cross-cutting engineering cost inputs used for the assessment of all abatement options are as follows (all costs in 2010 USD):

Table K-1: Engineering Cost Inputs

Option	Uncontrolled System (developing country)	Partially controlled System (United States)	Source
Size of system (SF_6 nameplate capacity)	100,000 pounds	100,000 pounds	N/A
Emission rate	16%	9%	Expert judgment (uncontrolled systems); 2009 average rate from U.S. inventory (partially controlled systems)
Cost of bulk SF_6 (per pound)	$16	$8	Rothlisberger (2011a)[a]
Labor cost of technician (per hour)	$1.38	$34	BLS, 2011
SF_6 Recycling			
Option lifetime (years)	15	15	Rothlisberger (2011a)
Capital cost per gas cart	$96,000	$96,000	Expert judgment (middle of range provided by Rothlisberger [2011a])
Number of gas carts that could be utilized at 100,000 pound system	5	5	Expert judgment (middle of range provided by Rothlisberger [2011b])
Gas carts currently at system	0	4	NCGC (2010) and NEPA (2005) (uncontrolled systems); expert judgment (partially controlled systems)
Annual O&M labor per gas cart (hours)	780	780	Expert judgment (middle of range provided by Rothlisberger [2011b])
Technical applicability to baseline emissions	30%	10%	Expert judgment (uncontrolled systems); Rothlisberger (2011a) (partially controlled systems)
Market penetration	100%	100%	Expert judgment
Reduction efficiency	90%	90%	Rothlisberger (2011a)
SF_6 reduced through application (pounds)	46,833	8,618	N/A
LDAR			
Option lifetime (years)	5	5	Czerepuszko (2011a)
Capital cost per unit	$98,000	$98,000	Czerepuszko (2011a)
Number of cameras that could be utilized at 100,000 pound system	1	1	Czerepuszko (2011a)
Annual O&M labor per camera and associated repairs (hours)	400	200	Expert judgment
Existing penetration in region	3%	7%	Czerepuszko (2011a)

(continued)

Table K-1: Engineering Cost Inputs (continued)

Option	Uncontrolled System (developing country)	Partially controlled System (United States)	Source
LDAR (continued)			
Technical applicability to baseline emissions	10%	10%	Rothlisberger (2011b) (uncontrolled systems); Rothlisberger (2011a) (partially controlled systems)
Market penetration	100%	100%	Expert judgment
Reduction efficiency	50%	50%	Czerepuszko (2011b)
SF_6 reduced through application (pounds)	8,673	4,788	N/A
Equipment Refurbishment			
Option lifetime (years)	20	20	Expert judgment
Capital cost per breaker refurbished	$143,000	$143,000	McCracken et al. (2000)
Percentage of system consisting of leak-prone equipment subject to refurbishment	5%	20%	Expert judgment
Percentage of leak-prone equipment already refurbished	0%	10%	Expert judgment
Nameplate capacity of refurbished breaker (pounds)	1,130	1,130	McCracken et al. (2000)
Technical applicability to baseline emissions	20%	40%	Expert judgment (uncontrolled systems); Rothlisberger (2011a) (partially controlled systems)
Market penetration	20%	20%	Expert judgment
Reduction efficiency	95%	95%	Expert judgment
SF_6 reduced through application (pounds)	6,591	7,278	N/A
Improved SF_6 Handling			
Option lifetime (years)	1	1	Rothlisberger (2011a)
Cost per adapter kit	$1,350	$1,350	Expert judgment (middle of range provided by Rothlisberger [2011a])
Number of adapter kits that could be utilized at 100,000 pound system	20	20	Expert judgment
Percentage of kits already purchased	50%	50%	Rothlisberger (2011a)
Number of technicians per system	23	23	Expert judgment (middle of range provided by Rothlisberger [2011b])
Number of annual training per technician (hours)	16	16	Rothlisberger (2011a)

(continued)

Table K-1: Engineering Cost Inputs (continued)

Option	Uncontrolled System (developing country)	Partially controlled System (United States)	Source
Improved SF_6 Handling (continued)			
Percentage of technicians already trained	50%	80%	Rothlisberger (2011a)
Technical applicability to baseline emissions	40%	40%	Rothlisberger (2011b) (uncontrolled systems); Rothlisberger (2011a) (partially controlled systems)
Market penetration	100%	100%	Expert judgment
Reduction efficiency	90%	90%	Rothlisberger (2011a)
SF_6 reduced through application (pounds)	62,444	34,474	N/A

[a] Rothlisberger (2011a) provided a range of $12 to $20 USD for the estimated cost of bulk SF_6 in developing countries.

Appendix L: Magnesium Manufacturing

This section presents detailed information on how costs were built out for each abatement option available for reducing SF_6 emissions from magnesium production and processing operations.

Replacement with Alternative Cover Gas—Sulfur Dioxide (SO_2)

Historically, SO_2 has been used as a cover gas in magnesium production and processing activities. However, because of toxicity, odor, and corrosivity concerns, SO_2 use was discontinued in most countries. Current SO_2 technology research aims to improve process feed systems and control technology, as well as address the toxicity and odor issues with improved containment and pollution control systems (Environment Canada, 1998). The use of SO_2 has the potential to reduce SF_6 emissions by 100%, because a complete replacement of the cover gas system is involved. It is assumed to be technically applicable to all three model facilities. The maximum market penetration for this option is assumed to be 80% of the emissions of SF_6 for recycle/remelt facilities, and 10% for both die casting and primary production facilities. The lifetime of this option is assumed to be 15 years. Table L-1 summarizes engineering costs for use of SO_2 as an alternative cover gas in each type of facility.

- **Capital Costs:** The assumed capital spending requirements for the implementation of an SO_2 system were based on cost information from a case study published by the USEPA SF_6 Emission Reduction Partnership (USEPA, 20xx), and industry sources (Meridian, 2011). Capital costs associated with implementing a SO_2 alternative cover gas system include costs for new piping, pollution control equipment, and safety equipment for workers, which are applicable across model facility types. Capital costs for the die casting and primary production processes were assumed to be equal to that for the recycle/remelt process (Meridian, 2011). The total capital cost for each of the model facilities was assumed to be $490,781.
- **Annual O&M Costs:** Annual costs represent the costs of purchasing the necessary quantity of the SO_2 for use in the production process in a given model facility. The ratio of SO_2 to SF_6 for usage rate (kg of cover gas/ton of metal processed) as cover gas in the production process is 1:1, resulting in significant annual cost savings. It is assumed that facilities incur annual costs of $16,763 each for the assumed die casting and primary production facilities and $74,883 for the recycle/remelt facility.
- **Annual Revenue:** The price of SO_2 is significantly lower than that of SF_6 (Werner and Milbrath, 2011), leading to a nearly 90% reduction in total gas purchase cost at the facility level. It is assumed that primary producers and die casters use similar amounts of SF_6. However, it is believed that recycle/remelt facilities use significantly more SF_6 due to magnesium melt time representing a greater portion of their production process, requiring more frequent use of cover gases to prevent combustion through oxidation. Cost savings associated with avoided SF_6 purchases were estimated to be $131,633 each for both die casting and primary production model facilities and $588,018 for the recycle/remelt model facility.

Table L-1: Engineering Costs for Alternative Cover Gas—SO_2

Model Facility Type	Option Lifetime (years)	Type of Gas Abated	Technical Effectiveness	Abatement Amount (tCO2e)	Capital Cost (2010 USD)	Annual Revenue (2010 USD)	Annual Costs (2010 USD)
Die casting	15	SF_6	10%	107,144	$490,781	$131,633	$16,763
Recycle/remelt	15	SF_6	80%	478,621	$490,781	$588,018	$74,883
Primary production	15	SF_6	10%	107,144	$490,781	$131,633	$16,763

Replacement with Alternative Cover Gas—HFC-134a

Research has shown that candidate fluorinated compounds such as HFC-134a can be a cover gas substitute for SF_6 (Milbrath, 2002; Ricketts, 2002; Hillis, 2002). Although fluorinated gases have an advantage over SO_2 because they have potentially fewer associated health, safety, odor, and corrosive impacts, some current fluorinated gas alternatives (including HFC-134a) still have GWPs. However, the GWP of HFC-134a is significantly less than that of SF_6; thus, the GWP-weighted cover gas emissions could be reduced by 95%. HFC-134a is assumed to be technically applicable to all model facilities. The maximum market penetration for this option is assumed to be 45% of the emissions of SF_6 for die casting and primary production facilities, and 10% for recycle/remelt facilities. The lifetime of this option is assumed to be 15 years. Table L-2 summarizes engineering costs for use of HFC-134a as an alternative cover gas in each type of facility.

- **Capital Costs:** There are no assumed capital spending requirements for the implementation of HFC-134a as an alternative cover gas as it is a simple drop-in option and does not require additional/new systems or training.
- **Annual O&M Costs:** Annual costs represent the costs of purchasing the necessary quantity of the alternative cover gas for use in the production process in a given model facility. The ratio of HFC-134a to SF_6 for usage rate (kg of cover gas/ton of metal processed) as a cover gas in the production process is 0.5:1, resulting in significant annual cost savings. It is assumed that facilities incur annual costs of $32,908 each for the die casting and primary production facilities and $147,005 for the recycle/remelt facility.
- **Annual Revenue:** The price of HFC-134a is roughly 50% lower than that of SF_6.Cost savings associated with avoided SF_6 purchases were estimated to be $131,633 each for both die casting and primary production model facilities and $588,018 for the recycle/remelt model facility.

Table L-2: Engineering Costs for Alternative Cover Gas—HFC-134a

Model Facility Type	Option Lifetime (years)	Type of Gas Abated	Technical Effectiveness	Abatement Amount (tCO2e)	Capital Cost (2010 USD)	Annual Revenue (2010 USD)	Annual Costs (2010 USD)
Die casting	15	SF_6	43%	104,230	—	$131,633	$32,908
Recycle/remelt	15	SF_6	9%	465,605	—	$588,018	$147,005
Primary production	15	SF_6	43%	104,230	—	$131,633	$32,908

Replacement with Alternative Cover Gas—Novec™ 612

Research has shown that candidate fluorinated compounds such as Novec 612 can be a cover gas substitute for SF_6 (Milbrath, 2002; Ricketts, 2002; Hillis, 2002). The use of Novec™ 612 as an alternative cover gas represents an advantage over SO_2 because, like other fluorinated gases, Novec™ 612 has potentially fewer associated health, safety, odor, and corrosive impacts. Novec™ 612 is a zero GWP gas and therefore has a reduction efficiency of 100% compared with SF_6. Novec™ 612 is assumed to be technically applicable to all model facilities. The maximum market penetration for this option is assumed to be 45% of the emissions of SF_6 for die casting and primary production facilities and 10% for the recycle/remelt facility. Table L-3 summarizes engineering costs for use of Novec™ 612 as an alternative cover gas in each type of facility.

- **Capital Costs**: The assumed capital spending requirements for implementing a Novec™ 612 system were based on cost information from the case study published by USEPA SF_6 Emission Reduction Partnership (USEPA, 20xx), and recycle/remelt specific cost research from industry sources (Meridian, 2011). Capital costs are assumed to be primarily the cost of computerized mass flow control cabinets and piping material cost and installation. The total capital cost was $245,390 for the die casting facility, $33,128 for the recycle/remelt facility, and $496,916 for the primary production facility.
- **Annual O&M Costs:** Annual costs represent the costs of purchasing the necessary quantity of the alternative cover gas for use in the production process in a given model facility. The ratio of Novec™ 612 to SF_6 for usage rate (kg of cover gas/ton of metal processed) as a cover gas is 0.3:1, resulting in significant annual cost savings. It is assumed that facilities incur annual costs of $60,754 each for the assumed die casting and primary production facilities and $271,393 for the recycle/remelt facility.
- **Annual Revenue:** Novec™ 612 is roughly 50% more expensive than SF_6 by volume. However, given the usage rate of 0.3:1, the use of Novec™ 612 represents a significant decrease in gas purchase costs for a facility. Cost savings associated with avoided SF_6 purchases were estimated to be $131,633 each for both die-casting and primary production model facilities and $588,018 for the recycle/remelt model facility.

Table L-3: Engineering Costs for Alternative Cover Gas—Novec™ 612

Model Facility Type	Option Lifetime (years)	Type of Gas Abated	Technical Effectiveness	Abatement Amount (tCO_2e)	Capital Cost (2010 USD)	Annual Revenue (2010 USD)	Annual Costs (2010 USD)
Die casting	15	SF_6	45%	107,139	$245,390	$131,633	$60,754
Recycle/remelt	15	SF_6	10%	478,601	$33,128	$588,018	$271,393
Primary production	15	SF_6	45%	107,144	$496,916	$131,633	$60,754

Table L-4: Alternative Cover Gas Cost and Use Ratio

Gas Type	Bulk Gas Cost (2010 USD/kg)	Cover Gas Use Ratio (Gas/SF_6)	Reduction Efficiency (compared with SF_6)
SF_6	$29	1	—
SO_2	$4	1	100%
HFC-134a	$15	0.5	95%
Novec™ 612	$45	0.3	100%

Table L-5: Calculating Break-even Costs for Alternative Cover Gas Abatement Options

Model Facility Type	SO_2 Break-Even Cost (2010 USD/tCO_2e)	HFC 134a Break-Even Cost (2010 USD/tCO_2e)	Novec™ 612 Break-Even Cost (2010 USD/tCO_2e)
Die casting	−$0.27	−$0.97	−$0.26
Recycle/remelt	−$0.89	−$0.97	−$0.65
Primary production	−$0.27	−$0.97	−$0.11

Appendix M: Photovoltaic Cell Manufacturing

This section presents detailed information on the cost parameters for the abatement measures considered in the PV manufacturing sector.

Thermal Abatement

This analysis assumes that the emissions reduction efficiency of this option is 95% (an average developed based on destruction or removal efficiencies seen from Fthenakis, 2001; Beu, 2005; and USEPA, 2009). Based on expert judgment it was assumed that the average lifetime of this system and other noncentral abatement systems discussed in this analysis is seven years.

The engineering cost estimates per facility and assumptions about the technology for this technology are:

- **Capital Costs.** Thermal abatement system capital costs cover the cost of the abatement unit with ducting and water recirculation ($157,000 per unit) as well as hook up costs ($35,550) and natural gas infrastructure costs ($35,550) (Fthenakis, 2001; Burton, 2003). It is assumed that one unit is needed per tool at a facility. The total facility costs a model facility are $5.7 million.
- **Annual O&M Costs.** Annual costs per tool are summarized in the Table M-1 below (Burton, 2003). Total annual costs for a model facility are estimated to be $328,860.
- **Annual Revenue**. It is assumed that no cost savings are associated with this technology.

Table M-1: Annual Cost per Tool for Thermal Abatement Systems

Category	Cost (2010 USD)
Water/waste water/maintenance	$2,370
Consumables	$5,330
Electricity	$2,610
Natural Gas	$2,840

Catalytic Abatement

Cost assumptions for this technology are as follows:

- **Capital Costs:** Capital costs are associated with the purchase and installation of the abatement systems (Burton, 2003). One unit costs $217,010, and the installation costs $59,250, leading to an estimated facility capital cost of $6.9 million.
- **Annual O&M Costs:** It is assumed that facilities incur annual costs per tool for water ($3,790), waste chemicals ($60), catalyst replacement ($12,580), and electricity ($1,780) (Burton, 2003). A model facility runs an annual cost for catalytic abatement of $455,280.
- **Annual Revenue:** It is assumed that no cost savings are associated with this technology.

Plasma Abatement

This analysis assumes that the emissions reduction efficiency of this option is 97% (Fthenakis, 2001; Hattori et al., 2006). It is also assumed that a plasma abatement system is needed on each tool chamber (with an average assumed 3.5 chambers per tool). The assumptions for costs of plasma abatement systems are as follows:

- **Capital Costs:** It is assumed that plasma abatement technology requires capital costs that cover the purchase and installation of the system, which costs $41,478 per chamber, equating to a one-time cost of $ 1.8 million per facility (Fthenakis, 2001; Burton, 2003).
- **Annual O&M Costs:** Facilities with plasma abatement systems are assumed to incur an annual operation cost of $1,190 per chamber that covers general maintenance and use of the systems. The total facility annual cost is $51,850 (Fthenakis, 2001; Burton, 2003).
- **Annual Revenue:** It is assumed that no cost savings are associated with this technology.

NF_3 Remote Chamber Clean

Beu (2005) states that remote clean systems offer a reduction of 95% of emissions. Once the remote clean systems are installed, they will last for the lifetime of a facility, or 25 more years as estimated using facility age information from the DisplaySearch PV Database.

Cost assumptions include the following:

- **Capital Costs:** It is assumed that PV facilities are not "NF_3 ready"; in other words these facilities are not assumed to have the current infrastructure to handle the direct installation of NF_3 remote systems because this is a relatively new technology. Therefore, it is assumed that facilities incur capital costs, in addition to system costs, associated with items such as gas hookups and necessary hardware such as manifolds and values. (These costs are detailed in Table M-2 below.) The facility cost is estimated to be $9.2 million.
- **Annual O&M Costs:** Facilities operating NF_3 remote clean systems are subject to annual costs associated with the use of NF_3 versus a traditional gas such as C_2F_6, general maintenance, and annual F_2 scrub costs. The annual facility cost for NF_3 remote clean is estimated to be $3.4 million (Burton, 2003)
- **Annual Revenue:** It is assumed that no cost savings are associated with this technology.

Table M-2: Capital Costs Per CVD Chamber for Making a Facility NF_3 Ready (Burton, 2003)

Activity	Capital Cost (2010 USD)
Labor/gas hookup	$3,980
NF_3 manifold, vales, etc.	$16,5910
Toxic monitor	$7,700
Stainless steel line (double walled)	$10,310

Appendix N: Flat Panel Display Manufacturing

This section presents detailed information on the cost parameters that yield break-even costs for each option are provided below.

Central Abatement System (CAS)

Based on information in the Samsung CDM Project Design Document, the assumed lifetime of a CAS is fifteen years. The estimated reduction efficiency of a CAS is 77% (per various monitoring reports from both the Samsung and LG CDM projects).

It is assumed that one CAS is needed per production line. Costs, as presented in the Samsung CDM Project, are:

- **Capital Costs.** Capital costs for the systems cover the purchase of the system (one needed per facility). The cost of the system is estimated to be $4.5 million.
- **Annual O&M Costs.** Annual costs cover needed parts ($1.2 million per facility), labor ($900,000 per facility), electricity ($162,000 per facility), and needed chemicals ($135,000 per facility) and water ($72,000 per facility).
- **Annual Revenue**. It is assumed that no cost savings are associated with this technology.

Thermal Abatement System

This analysis assumes that the emissions reduction efficiency of this option is 95% (an average developed based on destruction or removal efficiencies (DREs) seen from Fthenakis, 2001; Beu, 2005; and USEPA, 2009). Based on expert judgment it was assumed that the average lifetime of this system, and other non-central abatement systems discussed in this analysis is seven years.

The engineering cost estimates per facility and assumptions about the technology for this technology are:

- **Capital Costs.** Thermal abatement system capital costs cover the cost of the abatement unit with ducting and water recirculation ($157,000 per unit) as well as hook up costs ($35,550) and natural gas costs ($35,550) (Fthenakis, 2001; Burton, 2003). It is assumed that one unit is needed per tool at a facility. The total facility costs a model facility are $5.7 million.
- **Annual O&M Costs.** Annual costs per tool are summarized in the Table N-1 below (Burton, 2003). Total annual costs for a model facility are estimated to be $328,860.
- **Annual Revenue**. It is assumed that no cost savings are associated with this technology.

Table N-1: Annual Cost per Tool for Thermal Abatement Systems

Category	Cost (2010 USD)
Water/waste water/maintenance	$2,370
Consumables	$5,330
Electricity	$2,610
Natural gas	$2,840

Catalytic Abatement System

Catalytic abatement systems are based on destruction via catalyst, so they must be process/stream specific to achieve the 99% emission reductions quoted in literature (Fthenakis, 2001). Because catalytic destruction systems operate at relatively low temperatures, their use results in little or no NO_x emissions and the required amounts of water are low as well. Due to the high cost of catalyst replace, these systems are assumed to be the least widely used type of abatement.

Cost assumptions for this technology are:

- **Capital Costs.** Capital costs are associated with the purchase and installation of the abatement systems (Burton, 2003). One unit costs $217,010, and the installation costs $59,250, leading to estimated facility capital costs of $6.9 million.
- **Annual O&M Costs.** It is assumed that facilities incur annual costs per tool for water ($3,790), waste chemicals ($60), catalyst replacement ($12,580), and electricity ($1,780) (Burton, 2003). A model facility runs annual costs for catalytic abatement of $455,280.
- **Annual Revenue.** It is assumed that no cost savings are associated with this technology.

Plasma Abatement System

This analysis assumes that the emissions reduction efficiency of this option is 97% (Fthenakis, 2001; Hattori et al., 2006). It is also assumed that a plasma abatement system is need on each tool chamber (with an average assumed 3.5 chambers per tool). The assumptions for costs of plasma abatement systems are:

- **Capital Costs.** It is assumed that plasma abatement technology requires capital costs that cover the purchase and installation of the system, which are $62,220 per chamber, equating to onetime costs of $ 1.8 million per facility (Fthenakis, 2001; Burton, 2003).
- **Annual O&M Costs.** Facilities with plasma abatement systems are assumed to incur annual operation costs of $1,190 per chamber that cover general maintenance and use of the systems. Total facility annual costs for $51,850 (Fthenakis, 2001; Burton, 2003).
- **Annual Revenue.** It is assumed that no cost savings are associated with this technology.

NF_3 Remote Chamber Clean

NF_3 Remote Chamber Clean technology offers a reduction of 95% of emissions (Beu, 2005). Once the remote clean systems are installed, they will last for the lifetime of a facility, or 21 more years as estimated using facility age information from the DisplaySearch Equipment Database.

Cost assumptions include:

- **Capital Costs.** It is assumed that FPD facilities are not “NF_3 ready,” or in other words, these facilities are not assumed to have the current infrastructure to handle the direct installation of NF_3 remote systems. This assumption is based on the fact that this is a relatively new technology. Therefore it is assumed that facilities incur capital costs, in addition to system costs, associated with things such as gas hookups needed hardware such as manifolds and values. (These costs are detailed in Table N-2.) The facility costs are estimated to be $9.2 million.

Table N-2: Capital Costs Per CVD Chamber for Making a Facility NF_3 Ready (Burton, 2003)

Activity	Capital Cost (2010 USD)
Labor/gas hookup	$3,980
NF_3 manifold, vales, etc.	$16,591
Toxic monitor	$7,700
Stainless steel line (double walled)	$10,310

- **Annual O&M Costs.** Facilities operating NF_3 remote clean systems are subject to annual costs associated with the use of NF_3 versus a traditional gas such as C_2F_6, general maintenance, and annual F_2 scrub costs. Facility costs annually for NF_3 remote clean are estimated to be $3.3 million (Burton, 2003).
- **Annual Revenue.** It is assumed that no cost savings are associated with this technology.

Gas Replacement

In the gas replacement option, the replacement gas is often used/consumed more efficiently during CVD chamber cleaning than the original gas, which, combined with the differences in GWP, yields an assumed emissions reduction efficiency of 77%. As with NF_3 remote clean, once a gas is replaced, the "new" process will last for the lifetime of a facility.

- **Capital Costs.** Facilities replacing gases for chamber cleans face a capital expenditure that reflects the aggregate cost the new gas hookup as well as engineer time cost for implementation. These costs, which were based on information from NM0317, are estimated to be $1.2 million per facility.
- **Annual O&M Costs.** There are no annual costs associated with this technology.
- **Annual Revenue.** Facilities face an annual cost savings which reflects the cost of replacing SF_6 with NF_3, and using smaller amounts of a clean gas overall. The costs of these gases are estimated to be $20 per kilogram of NF_3 (Prather and Hsu, 2008) and $16 per kilogram of SF_6 (Rothlisberger, 2011). An average amount of gas consumed per facility, and hence reduction amounts, were estimated based on WLICC data (Bartos, 2010).

Appendix O: Description of the Input Data Used in DAYCENT Simulations

Data Type	Description	Source
Daily Weather	Daily weather for 1901 – 2010 at 0.5°resolution in latitude by longitude. This includes daily minimum temperature, daily maximum temperature, and daily precipitation.	The original data source was the MsTMIP project's 6 hour CRU + NCEP combined data. This was aggregated to daily, and all non-land cells were removed. http://nacp.ornl.gov/MsTMIP.shtml
Soils	This data is the same as was used for previous the DAYCENT global simulations. The data is at 0.5°resolution in latitude by longitude and includes sand, silt, clay, bulk density, pH, number of soil layers.	FAO, 1996. The Digitized Soil Map of the World Including Derived Soil Properties, CDROM. Food and Agriculture Organization, Rome.
Agricultural cells to simulate	This mask was computed from the fraction of agricultural area. The fraction of agricultural area is provided at 5 minute resolution in latitude by longitude. This data was aggregated it to 0.5°resolution by latitude and longitude then we selected cells where fraction of cropland area ≥ 5% of the grid cell area.	Agricultural Lands in the Year 2000. Described in the publication, Ramankutty et al. (2008), "Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000", Global Biogeochemical Cycles, Vol. 22, GB1003, doi:10.1029/2007GB002952.
Crop masks for maize, winter wheat, spring wheat, winter barley, spring barley, sorghum, and soybean	Crop-specific masks indicating where to simulate each crop. Each crop mask is a subset of the agricultural cells to simulate, described above. This data was provided at 0.5° resolution in latitude by longitude. Note: Although separate crop masks were provided for winter and spring wheat, there was almost no difference between these masks. Likewise for winter and spring barley. The main difference between winter and spring varieties was the planting and harvest dates (see below).	These files were produced by Mirella Salvatore at the FAO, and Aaron Berdanier. Personal communication
Irrigated Areas by crop type	Crop-specific data with the fraction of cropland area that is irrigated. This data was provided at 0.5°resolution in latitude by longitude for all years between 1985 and 2008. Irrigation was simulated for modern agriculture (year 1951 or later) for cells where the irrigated fraction > 0.0 for any year between 1985 and 2008. The fraction of cropland irrigated in 2008 was used in the post-processing step to aggregate model results.	These files were produced by Mirella Salvatore at the FAO, and Aaron Berdanier. Personal communication

Data Type	Description	Source
Initial Year of Cultivation	Fraction of area in agriculture for years 1700-2007 at 0.5° resolution in latitude by longitude. We computed the first year when the fraction of agricultural area was 50% of the fraction of cropland area in 2000 – this determined the year of plow-out for the cell.	Global Cropland and Pasture Data from 1700-2007. This is a beta release of an updated version of our original historical cropland data set that spanned the 1700-1992 period. The original data set was described in the publication by Ramankutty and Foley (1999) in Global Biogeochemical Cycles. This release updates the data to the 1700-2007 time period. (http://www.geog.mcgill.ca/landuse/pub/Data/Histlanduse/, Accessed June 29, 2012).
Crop Specific Planting and Harvest Dates	Planting date (day of year) and harvest date (day of year) for each crop at 0.5° resolution in latitude by longitude: Barley (winter), Barley (spring), Maize (main season), Maize(second season), Sorghum (main season) , Sorghum second season), Soybeans, Wheat (winter), Wheat (spring)	Sacks, W.J., D. Deryng, J.A. Foley, and N. Ramankutty (2010). Crop planting dates: an analysis of global patterns. Global Ecology and Biogeography 19, 607-620. DOI: 10.1111/j.1466-8238.2010.00551.x.
Harvest type and residue removal rate by crop.	Harvest type and residue removal rate by crop at 0.5° resolution in latitude by longitude by crop. The harvest type designates a grain or non-grain harvest (for this exercise, all crops had grain harvests). The residue removal rate determines the percentage of residue removed from the field at time of harvest. Residue includes all above-ground plant material after grain is removed.	These files were produced by Mirella Salvatore at the FAO, and Aaron Berdanier. Personal communication
Tillage, planting, and weeding practices by country and by crop	Tillage, planting, and weeding practices by crop for developed countries (conventional), develop countries (conservation), and less developed countries. Crops are categorized as small grain (barley, wheat) or large grain (maize, sorghum, soybean). These practices determine the intensity of soil disturbance simulated for each event.	These files were produced by Mirella Salvatore at the FAO, and Aaron Berdanier. Personal communication
N application rates : includes fertilizer N and manure N	Annual N application rates including N fertilizer plus manure N (gN m^{-2} yr^{-1}) at 0.5° resolution in latitude by longitude by crop for years 1985 - 2008. N application rates from 1950 – 1984 were linearly interpolated between 0.0 in 1950 and the 1985 rate. N application rates for 2009 – 2035 were set to the 2008 rate. Note: There was no data about the relative amount of fertilizer N and manure N.	These files were produced by Mirella Salvatore at the FAO, and Aaron Berdanier, Personal communication

Data Type	Description	Source
Harvested Areas and Yields by crop type in year 2000.	Harvested Area (proportion of grid cell area) and Yield (tons/ha). The data is provided at 5 minute resolution in latitude by longitude. We aggregated the data to a 0.5°resolution. The measured yields were compared to simulated yields from the baseline simulation. The harvested area fraction was used in the post-processing step for aggregating model results.	Harvested Area and Yields of 175 crops (M3-Crops Data). Monfreda et al. (2008), "Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000", Global Biogeochemical Cycles, Vol.22, GB1022, doi:10.1029/2007GB002947.