LIFE CYCLE PERFORMANCE OF REFRIGERATION SYSTEMS IN THE DUTCH FOOD AND BEVERAGES SECTOR

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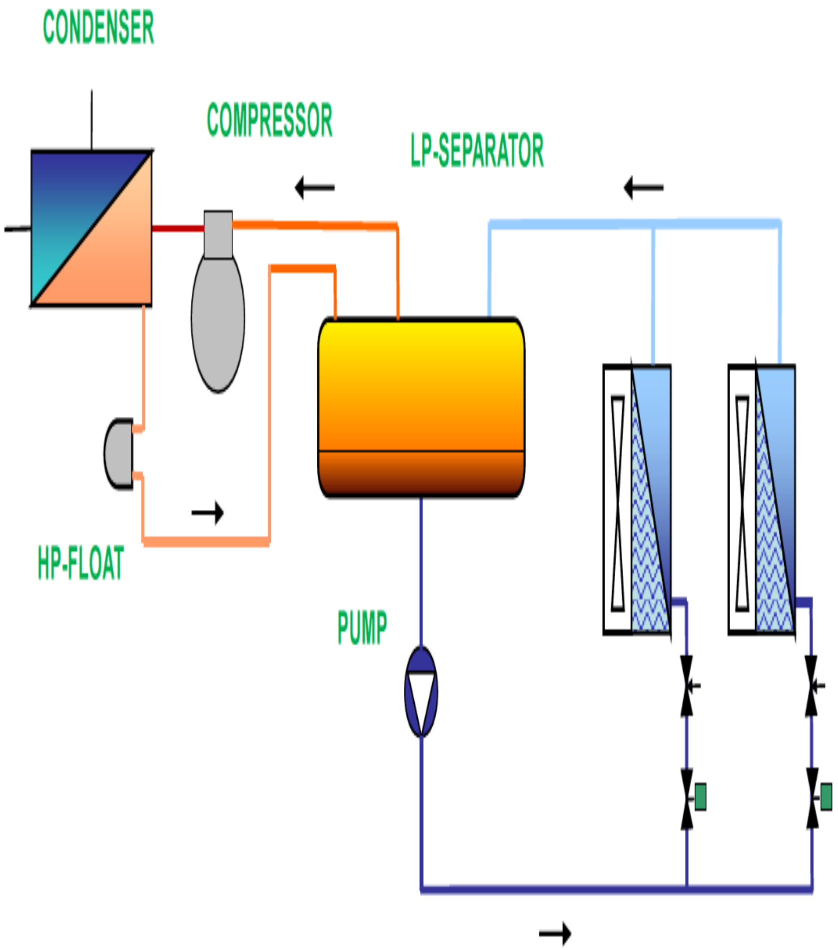
Content

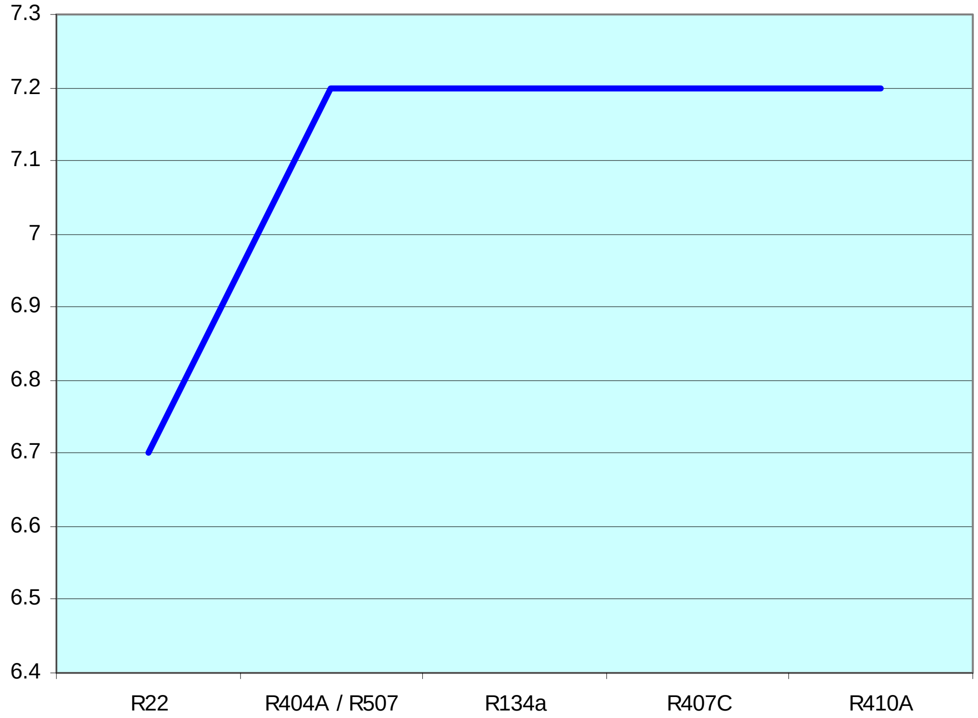
Food and beverages



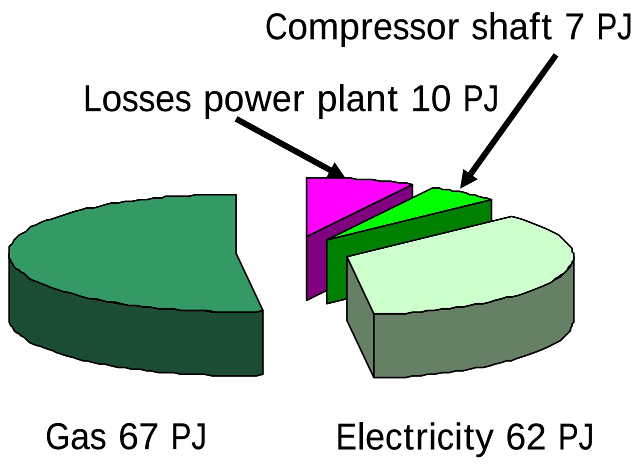
Example of the lay-out of a liquid overfeed system for cold storage application.

Food and Beverages Sector in NL

Sector information



Leakage rate of refrigerants in sector [%]



Refrigeration 17 PJ
Total sector 129 PJ

Pennartz and van den Bovenkamp (2011)

Food and Beverages Sector in NL

Sector information

Average operating hours per year [h]	Installed cooling capacity [MW]	Percentage NH3 plants [%]	Percentage R22 plants [%]	Percentage HFC plants [%]	kg NH3/kW cooling	kg R22/kW cooling	kg HFC/kW cooling
4393	2782	43	34	23	1.1	1.1	0.7

Pennartz and van den Bovenkamp (2011)

Food and Beverages Sector in NL

Current refrigerant inventory

	kg NH3/kW cooling	kg HFC/kW cooling
Direct expansion systems		1.5
Direct expansion systems with secondary fluid distribution		0.3
Liquid overfeed systems	1.3	2.0
Liquid overfeed systems with secondary fluid distribution	0.2	0.6

Food and Beverages Sector in NL

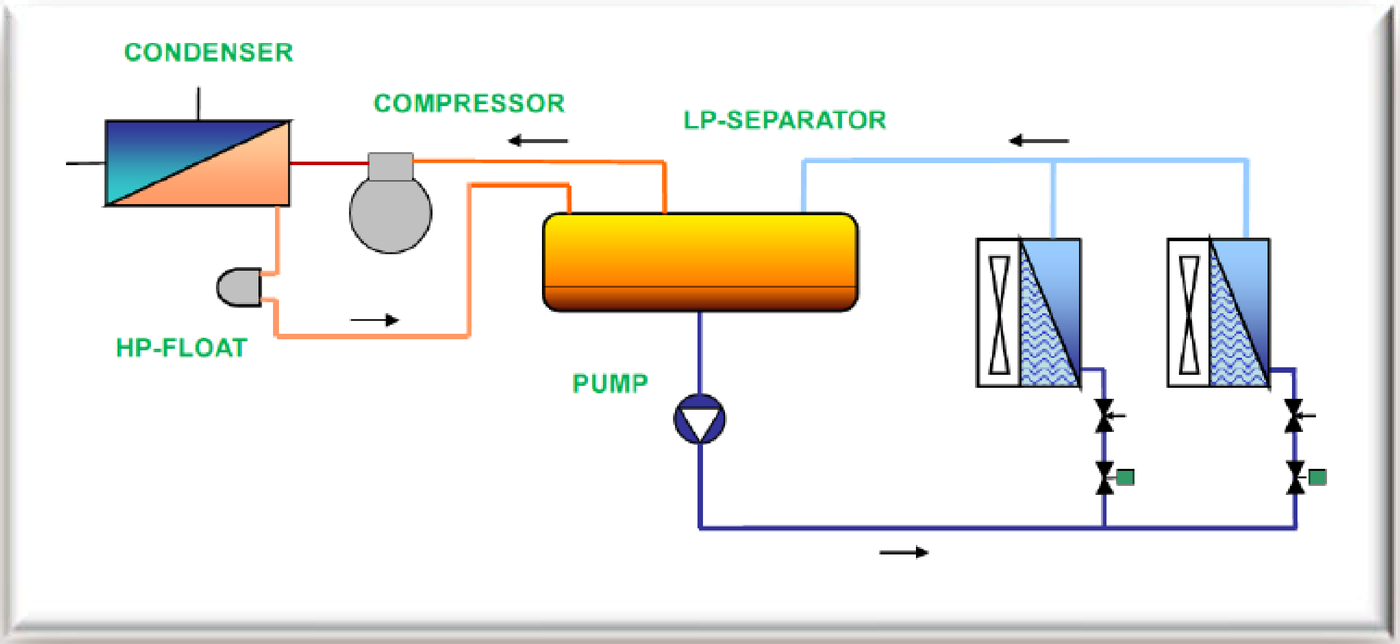
Used refrigerants and leakage rates (based on 1984 refrigeration plants from 193 companies)

	R22	R404A/R507	R134a	R407C	R410A
Percentage of total refrigerant weight [%]	61.4	31.3	4.6	1.9	0.5
Percentage of total plants [%]	40.0	48.6	7.2	3.0	0.8
Refrigerant leakage [%]	6.7	7.2	7.2	7.2	7.2
GWP [kg CO_2] 100 yr	1790	3700/3800	1370	1700	2100

Pennartz and van den Bovenkamp (2012)

Cold storage application

Cooling capacity = 550 kW
Evaporation temperature = -6° C (indirect = -13° C)
Condensation temperature = 40° C (no heat recovery: variable)
Isentropic efficiency compressor = 0.613 (ammonia = 0.700)
Running time: 2500 hours/year
Minimum temperature difference in hex = 5 K



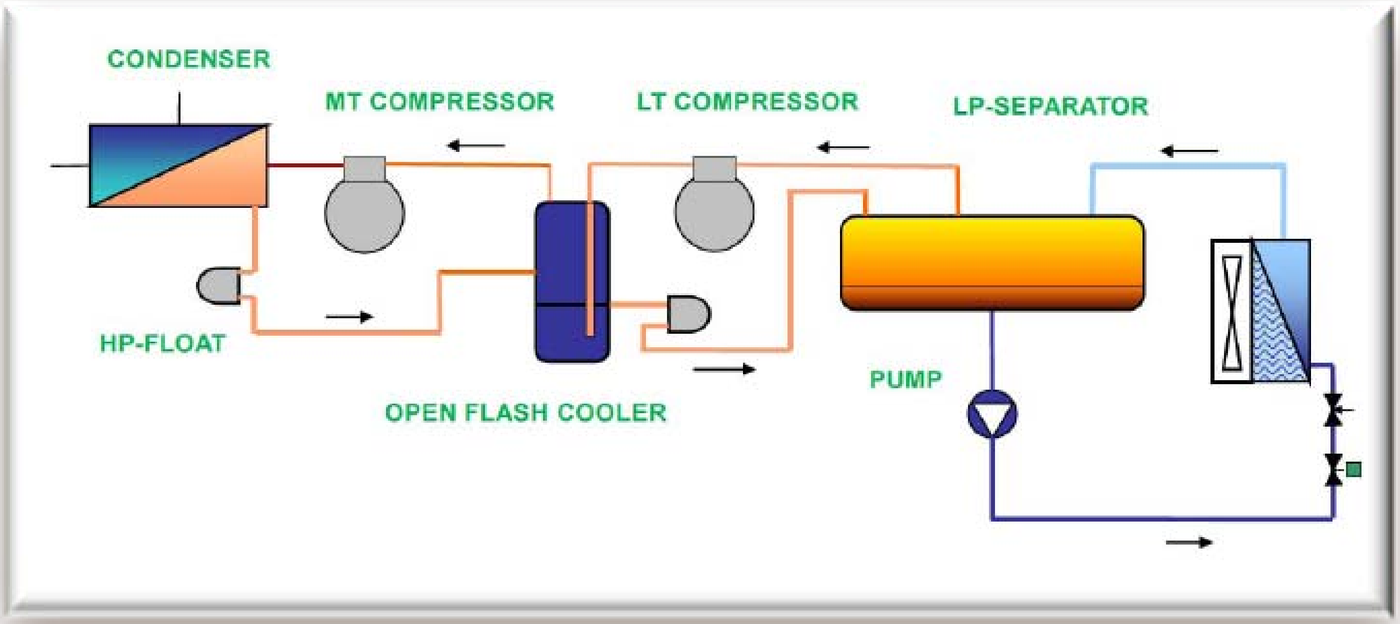
Cold storage application

Alternative systems considered

	System	Refrigerant inventory
1	Reference: Direct evaporation of R22	825 kg R22
2	Direct evaporation of R404A	825 kg R404A
3	Direct evaporation of HFO1234yf	825 kg HFO1234yf
4	Direct evaporation of R290 and secondary fluid for distribution (Kfo)	165 kg R290
5	Direct evaporation of R404A and secondary fluid for distribution (Kfo)	165 kg R404A
6	Direct evaporation of HFO1234yf and secondary fluid for distribution	165 kg HFO1234yf 2
7	Liquid overfeed of R717 and CO2 for distribution	110 kg R717 + 1100 kg CO2
8	Liquid overfeed of HFO1234yf and CO2 for distribution	330 kg HFO1234yf + 1100 kg CO2
9	Liquid overfeed of R717	715 kg R717
10	Liquid overfeed of R404A and secondary fluid for distribution	330 kg R404A
11	Liquid overfeed of HFO1234yf and secondary fluid for distribution	330 kg HFO1234yf
12	Liquid overfeed of R717 and secondary fluid for distribution	110 kg R717

Freeze storage application

Cooling capacity = 550 kW
Evaporation temperature = -27° C (indirect = -34° C)
Condensation temperature = 40° C (no heat recovery: variable)
Isentropic efficiency compressor = 0.613 (ammonia = 0.700)
Running time: 4000 hours/year
Minimum temperature difference in hex = 5 K



Freeze storage application

Alternative systems considered

	System	Refrigerant inventory
1	Reference: 2-stage liquid overfeed of R22	1100 kg R22
2	2-stage liquid overfeed of R404A	1100 kg R404A
3	2-stage liquid overfeed of HFO1234yf	1100 kg HFO1234yf
4	2-stage liquid overfeed of R717	715 kg R717
5	2-stage liquid overfeed of R404A and secondary fluid for distribution	330 kg R404A
6	2-stage liquid overfeed of HFO1234yf and secondary fluid for distribution	330 kg HFO1234yf 2
7	2-stage liquid overfeed of R717 and secondary fluid for distribution	110 kg R717
8	2-stage liquid overfeed of R404A and CO2 for distribution	330 kg R404A + 1100 kg CO2
9	2-stage liquid overfeed of HFO1234yf and CO2 for distribution	330 kg HFO1234yf 2 + 1100 kg CO2
10	2-stage liquid overfeed of R717 and CO2 for distribution	110 kg R717 + 1100 kg CO2
11	Liquid overfeed of R717 cascaded with liquid overfeed CO2	110 kg R717 + 1100 kg CO2
12	Liquid overfeed of R717 cascaded with direct evaporation of CO2	110 kg R717 + 825 kg CO2

Plant characterization – Energetic performance

$$COP = \frac{\dot{Q}_{LT}}{\dot{W}_{LT} + \dot{W}_{MT}}$$

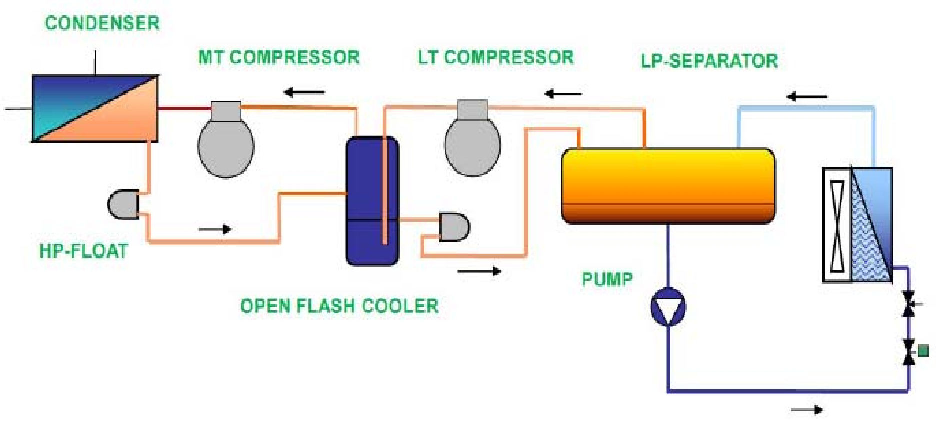
$$P_{cond\_fan} = 0.027 * (\dot{Q}_{LT} + \dot{W}_{LT} + \dot{W}_{MT})$$

$$P_{evap\_fan} = a * (\dot{Q}_{LT} + \dot{Q}_{MT})$$

$$COPS = \frac{\dot{Q}_{LT}}{\dot{W}_{LT} + \dot{W}_{MT} + P_{cond\_fan} + P_{evap\_fan} + P_{refrigerant\_pump}}$$

$$PEU = \frac{\dot{Q}_{LT}}{COPS} * 8760 * (\text{Refrigeration\_load\_ratio}) * \frac{1}{\eta_{elec}}$$

1000 MWh = 3.6 TJ



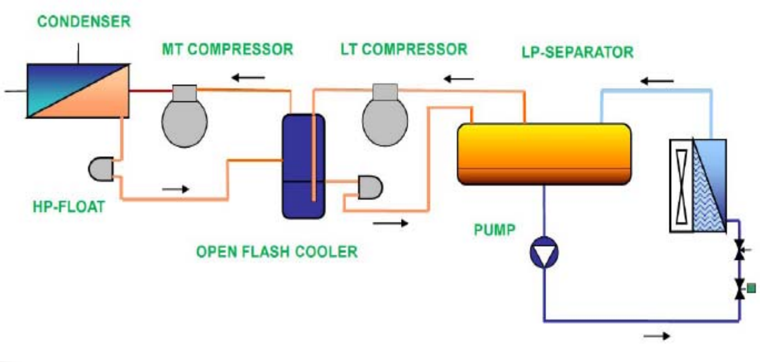
Plant characterization – Global warming / cost estimation

$$TEWI = GWP\ L_{annual}\ m_{charge}\ n + GWP\ m_{charge}\ (1-\alpha_{recovery}) + n\ E_{annual}\ \beta,$$

$$Cost = a * \dot{Q}^{b}$$

	Compressors				Condensers	
	R404A	HFO1234yf	CO2	R717	R404A	R717
a	824	1231	3827	1225	83.217	378.27
b	-0.4017	-0.4674	-0.7195	-0.4148	-0.0032	-0.2171

Cost=Cost(compressor+condenser)*3.5



Cold storage application

Seasonal averaged

Altern.	$\dot{W}_{LT}$ [kW]	Q_{cond} [kW]	P_{cond_fan} [kW]	P_{aux} [kW]	COP [-]	COPS [-]	PEU [TJ]	TEWI [ktonCO2 eq.]	TEWI [%direct emissions]	Invest. costs [kEuro]]	TCO [kEuro/year]
1	135.2	685.2	18.5	51.5	4.50	3.12	4.00	6.95	33.8	338.9	104.5
2	138.1	688.1	18.6	51.6	4.46	3.10	4.06	9.77	52.4	341.1	105.8
3	130.4	680.4	18.4	51.4	4.66	3.20	3.89	4.54	0.1	335.1	102.3
4	166.4	716.4	19.4	62.9	3.56	2.50	4.91	5.74	0.3	348.5	121.4
5	174.8	724.8	19.6	63.1	3.39	2.43	5.09	6.95	15.0	353.2	125.1
6	165.4	715.4	19.3	62.8	3.58	2.51	4.88	5.70	0.0	348.0	120.9
7	135.2	685.2	18.5	58.9	4.39	2.93	4.15	4.85	0.0	366.2	110.0
8	155.1	705.1	19.0	62.5	3.84	2.64	4.66	5.44	0.0	343.1	116.5
9	113.1	663.1	17.9	52.7	5.35	3.48	3.55	4.14	0.0	360.0	98.8
10	174.8	724.8	19.6	63.1	3.42	2.43	5.09	7.95	26.0	353.2	125.1
11	165.4	715.4	19.3	62.8	3.58	2.51	4.88	5.70	0.0	346.4	120.7
12	144.5	694.5	18.7	62.2	4.09	2.76	4.43	5.16	0.0	368.9	115.1

TCO (Total Cost of Ownership):
Depreciation period: 20 years
Interest: 8%
Energy costs: 150 €/MWh

Cold storage application

Ranking of systems

Without heat recovery

Altern.	CSR [ktonCO2 eq.]	TCO [k€/year.]	Safety [Class.]	**Total score**
3	11.2	10.5	5.5	**8.2**
9	12.0	12.0	1.0	**8.2**
1	6.5	9.6	7.1	**6.6**
7	10.6	7.3	2.5	**6.4**
8	9.5	4.6	8.5	**6.1**
6	9.0	2.8	9.6	**5.5**
12	10.0	5.2	2.5	**5.5**
11	8.9	2.8	8.5	**5.3**
4	**8.9**	**2.5**	**7.2**	**5.0**
2	**1.0**	**9.1**	**7.1**	**4.5**
5	**6.5**	**1.0**	**12.0**	**4.5**
10	**4.6**	**1.0**	**10.7**	**3.6**

With heat recovery

Altern.	CSR [ktonCO2 eq.]	TCO [k€/year.]	Safety [Class.]	**Total score**
9	13.3	12.0	1.0	**8.6**
3	12.0	9.9	5.5	**8.2**
7	12.0	8.8	2.5	**7.3**
1	7.0	8.8	7.1	**6.4**
8	10.0	5.0	8.5	**6.4**
12	11.0	6.4	2.5	**6.2**
6	9.4	3.4	9.6	**5.9**
11	9.4	3.5	8.5	**5.7**
4	**9.3**	**3.2**	**7.2**	**5.3**
5	**6.4**	**1.0**	**12.0**	**4.5**
2	**1.0**	**7.8**	**7.1**	**4.1**
10	**4.4**	**1.0**	**10.7**	**3.6**

CSR (Corporate Social Responsability):
based on TEWI: lowest 12; highest 1
Safety (safety class & amount of refrigerant)
Total: (CSR+TCO+0.5*Safety)/2.5

Cold storage application

Ranking of systems

Without heat recovery

	System
9	Liquid overfeed of R717
3	Direct evaporation of HFO1234yf
7	Liquid overfeed of R717 and CO2 for distribution
1	Reference: Direct evaporation of R22
8	Liquid overfeed of HFO1234yf and CO2 for distribution
12	Liquid overfeed of R717 and secondary fluid for distribution
6	Direct evaporation of HFO1234yf and secondary fluid for distribution
11	Liquid overfeed of HFO1234yf and secondary fluid for distribution
4	Direct evaporation of R290 and secondary fluid for distribution (Kfo)
5	Direct evaporation of R404A and secondary fluid for distribution (Kfo)
2	Direct evaporation of R404A
10	Liquid overfeed of R404A and secondary fluid for distribution

With heat recovery

Altern.	CSR [ktonCO2 eq.]	TCO [k€/year.]	Safety [Class.]	**Total score**
9	13.3	12.0	1.0	**8.6**
3	12.0	9.9	5.5	**8.2**
7	12.0	8.8	2.5	**7.3**
1	7.0	8.8	7.1	**6.4**
8	10.0	5.0	8.5	**6.4**
12	11.0	6.4	2.5	**6.2**
6	9.4	3.4	9.6	**5.9**
11	9.4	3.5	8.5	**5.7**
4	**9.3**	**3.2**	**7.2**	**5.3**
5	**6.4**	**1.0**	**12.0**	**4.5**
2	**1.0**	**7.8**	**7.1**	**4.1**
10	**4.4**	**1.0**	**10.7**	**3.6**

CSR (Corporate Social Responsability):
based on TEWI: lowest 12; highest 1
Safety (safety class & amount of refrigerant)
Total: (CSR+TCO+0.5*Safety)/3.0

Cold storage application

Impact of refrigerant costs

With heat recovery; Refrigerant costs not included in TCO

	System
9	Liquid overfeed of R717
3	Direct evaporation of HFO1234yf
7	Liquid overfeed of R717 and CO2 for distribution
1	Reference: Direct evaporation of R22
8	Liquid overfeed of HFO1234yf and CO2 for distribution
12	Liquid overfeed of R717 and secondary fluid for distribution
6	Direct evaporation of HFO1234yf and secondary fluid for distribution
11	Liquid overfeed of HFO1234yf and secondary fluid for distribution
4	Direct evaporation of R290 and secondary fluid for distribution (Kfo)
5	Direct evaporation of R404A and secondary fluid for distribution (Kfo)
2	Direct evaporation of R404A
10	Liquid overfeed of R404A and secondary fluid for distribution

With heat recovery; Refrigerant costs included in TCO

Refrigerant costs [kEuro/year]	Altern.	CSR [ktonCO2 eq.]	TCO [k€/year.]	Safety [Class.]	**Total score**
0.09	9	12.0	12.0	1.0	**8.2**
11.11	3	11.2	5.9	5.5	**6.6**
0.20	7	10.6	7.2	2.5	**6.4**
1.66	1	6.5	8.9	7.1	**6.3**
0.01	12	10.0	5.2	2.5	**5.5**
4.63	8	9.5	2.7	8.5	**5.5**
2.22	6	9.0	1.8	9.6	**5.2**
0.29	4	8.9	2.4	7.2	**5.0**
4.44	**11**	**8.9**	**1.0**	**8.5**	**4.7**
0.14	**5**	**6.5**	**0.9**	**12.0**	**4.5**
0.68	**2**	**1.0**	**8.8**	**7.1**	**4.4**
0.27	**10**	**4.6**	**0.9**	**10.7**	**3.6**

Freeze storage application

Seasonal averaged

Altern.	$\dot{W}_{LT}$ [kW]	$\dot{W}_{MT}$ [kW]	Q_{cond} [kW]	P_{cond_fan} [kW]	P_{aux} [kW]	COP [-]	COPS [-]	PEU [TJ]	TEWI [ktonCO2 eq.]	TEWI [%direct emissions]	Invest. costs [kEuro]]	TCO [kEuro/year]
1	118.6	115.9	784.5	21.2	64.2	2.45	1.89	10.25	15.01	20.7	368.8	217.0
2	123.7	128.0	801.7	21.6	64.7	2.30	1.80	10.86	19.38	35.2	377.5	228.5
3	118.7	116.5	785.2	21.2	64.2	2.44	1.89	10.27	12.00	0.0	367.7	217.3
4	104.7	96.5	751.1	20.3	63.3	2.84	2.13	9.08	10.59	0.0	382.6	197.8
5	141.6	157.3	848.9	22.9	74.7	1.92	1.52	12.82	16.97	12.1	393.3	264.4
6	136.1	142.5	828.6	22.4	74.1	2.05	1.60	12.10	14.12	0.0	381.7	250.7
7	120.9	117.7	788.6	21.3	73.0	2.38	1.80	10.70	12.48	0.0	392.7	227.2
8	130.7	154.8	835.4	22.5	65.6	2.02	1.62	12.05	16.00	12.5	384.9	250.1
9	125.6	140.3	815.9	22.0	65.1	2.15	1.71	11.36	13.25	0.0	388.3	238.3
10	111.3	116.1	777.4	21.0	64.0	2.50	1.93	10.00	11.67	0.0	389.8	214.8
11	104.7	120.2	774.9	20.9	64.0	2.53	1.95	9.91	11.56	0.0	407.3	215.0
12	104.7	120.2	774.9	20.9	62.2	2.53	1.96	9.85	11.49	0.0	407.3	213.9

TCO (Total Cost of Ownership):
Depreciation period: 20 years
Interest: 8%
Energy costs: 150 €/MWh

Freeze storage application

Ranking of systems

Without heat recovery

Altern.	CSR [ktonCO2 eq	TCO [k€/year.]	Safety [Class.]	Total score
4	12.0	12.0	1.0	8.2
12	10.9	9.3	2.7	7.2
11	10.8	9.2	2.7	7.1
10	10.7	9.2	2.7	7.1
3	10.3	8.8	4.1	7.0
9	8.7	5.3	9.5	6.2
7	9.7	7.1	2.7	6.0
1	6.5	8.8	5.5	6.0
6	7.6	3.3	9.5	5.2
8	5.3	3.4	12.0	4.9
5	4.0	1.0	12.0	3.7
2	1.0	6.9	5.5	3.6

With heat recovery

Altern.	CSR [ktonCO2 eq	TCO [k€/year.]	Safety [Class.]	Total score
4	12.0	12.0	1.0	8.2
12	10.8	9.7	2.7	7.3
11	10.8	9.6	2.7	7.2
10	10.7	9.6	2.7	7.2
3	9.8	8.5	4.1	6.8
7	9.7	8.0	2.7	6.4
9	8.2	5.5	9.5	6.1
1	6.5	8.6	5.5	6.0
6	7.1	3.8	9.5	5.2
8	4.4	2.9	12.0	4.4
5	3.3	1.0	12.0	3.4
2	1.0	6.1	5.5	3.3

CSR (Corporate Social Responsability):
based on TEWI: lowest 12; highest 1
Safety (safety class & amount of refrigerant)
Total: (CSR+TCO+0.5*Safety)/3.0

Freeze storage application

Ranking of systems

With heat recovery

Altern.	CSR [ktonCO2 ed	TCO [k€/year.]	Safety [Class.]	Total score
4	12.0	12.0	1.0	8.2
12	10.8	9.7	2.7	7.3
11	10.8	9.6	2.7	7.2
10	10.7	9.6	2.7	7.2
3	9.8	8.5	4.1	6.8
7	9.7	8.0	2.7	6.4
9	8.2	5.5	9.5	6.1
1	6.5	8.6	5.5	6.0
6	7.1	3.8	9.5	5.2
8	4.4	2.9	12.0	4.4
5	3.3	1.0	12.0	3.4
2	1.0	6.1	5.5	3.3

	System
4	2-stage liquid overfeed of R717
12	Liquid overfeed of R717 cascaded with direct evaporation of CO2
11	Liquid overfeed of R717 cascaded with liquid overfeed CO2
10	2-stage liquid overfeed of R717 and CO2 for distribution
3	2-stage liquid overfeed of HFO1234yf
7	2-stage liquid overfeed of R717 and secondary fluid for distribution
9	2-stage liquid overfeed of HFO1234yf and CO2 for distribution
1	Reference: 2-stage liquid overfeed of R22
6	2-stage liquid overfeed of HFO1234yf and secondary fluid for distribution
8	2-stage liquid overfeed of R404A and CO2 for distribution
5	2-stage liquid overfeed of R404A and secondary fluid for distribution
2	2-stage liquid overfeed of R404A

CSR (Corporate Social Responsability):
based on TEWI: lowest 12; highest 1
Safety (safety class & amount of refrigerant)
Total: (CSR+TCO+0.5*Safety)/2.5

Freeze storage application

Impact of refrigerant costs

With heat recovery; Refrigerant costs included in TCO

Altern.	CSR [ktonCO2 eq	TCO [k€/year.]	Safety [Class.]	Total score
4	12.0	12.0	1.0	8.2
12	10.8	9.7	2.7	7.3
11	10.8	9.6	2.7	7.2
10	10.7	9.6	2.7	7.2
7	9.7	8.0	2.7	6.4
3	9.8	6.6	4.1	6.2
9	8.2	4.9	9.5	5.9
1	6.5	8.3	5.5	5.9
6	7.1	3.3	9.5	5.1
8	4.4	2.8	12.0	4.4
5	3.3	1.0	12.0	3.4
2	1.0	6.0	5.5	3.3

	System
4	2-stage liquid overfeed of R717
12	Liquid overfeed of R717 cascaded with direct evaporation of CO2
11	Liquid overfeed of R717 cascaded with liquid overfeed CO2
10	2-stage liquid overfeed of R717 and CO2 for distribution
7	2-stage liquid overfeed of R717 and secondary fluid for distribution
3	2-stage liquid overfeed of HFO1234yf
9	2-stage liquid overfeed of HFO1234yf and CO2 for distribution
1	Reference: 2-stage liquid overfeed of R22
6	2-stage liquid overfeed of HFO1234yf and secondary fluid for distribution
8	2-stage liquid overfeed of R404A and CO2 for distribution
5	2-stage liquid overfeed of R404A and secondary fluid for distribution
2	2-stage liquid overfeed of R404A

Comparison with previous studies

Emission per kWh major difference

COLD STORAGE

	Energy			TEWI			TCO		
	This study [MWh/year]	Mieog [MWh/year]	[%]	This study [ktonCO2 eq./lifetime]	Mieog [ktonCO2 eq./lifetime]	[%]	This study [k€/year]	Mieog [k€/year]	[%]
1	625			8.55			128		
2	645	641	101	11.49	11.0	105	132	94	140
3	606	606	100	6.06	8.5	72	125	92	136
4	739			7.40			146		
5	782			8.82			153		
6	734	729	101	7.34	9.1	81	146	103	142
7	608	614	99	6.08	7.5	81	129	99	130
8	704			7.04			141		
9	544	518	105	5.44	6.3	86	118	91	130
10	782			9.83			153		
11	734	702	105	7.35	9.0	82	145	106	138
12	657	643	102	6.57	7.8	84	136	102	134
Average			**102**			**84**			**136**

FREEZE STORAGE

	Energy			TEWI			TCO		
	This study [MWh/year]	Mieog [MWh/year]	[%]	This study [ktonCO2 eq./lifetime]	Mieog [ktonCO2 eq./lifetime]	[%]	This study [k€/year]	Mieog [k€/year]	[%]
1	1475			17.81			259		
2	1602	1586	101	22.74	27.7	82	279	182	154
3	1483			14.84			260		
4	1285	1368	94	12.84	16.7	77	232	168	138
5	1866			20.67			320		
6	1721			17.21			297		
7	1490	1630	91	14.90	19.9	75	264	190	138
8	1770			19.64			305		
9	1629			16.29			284		
10	1405	1585	89	14.05	19.3	73	251	186	135
11	1396	1454	96	13.96	17.7	79	251	177	142
12	1389			13.89			250		
Average			**94**			**77**			**141**

Mieog & Verwoerd (2004)

Conclusions

Energy & Emissions (Reference is R22)

Energetic performance cold storage:	
Liquid overfeed ammonia	11% savings
Direct evaporation of HFO1234yf	3% savings
Emission reduction cold storage:	
Liquid overfeed ammonia	40% reduction
Direct evaporation of HFO1234yf	35% reduction
Energetic performance freeze storage:	
2-stage liquid overfeed ammonia	11% savings
Liquid overfeed NH3 cascaded CO2 direct exp	4% savings
Emission reduction freeze storage:	
2-stage liquid overfeed ammonia	29% reduction
Liquid overfeed NH3 cascaded CO2 direct exp	23% savings