CENTRE ENERGETIQUE ET PROCEDES

Inventory of Direct and Indirect GHG Emissions from Stationary Air Conditioning and Refrigeration Sources, with Special Emphasis on Retail Food Refrigeration and Unitary Air Conditioning

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Nomenclature

A	surface	m^2
F	radiation transfer coefficient	
h	air enthalpy	kJ/kg
h_i	inner heat exchange coefficient	$W/m^2.K$
h_o	outer heat transfer coefficient	$W/m^2.K$
k	thermal conductivity	W/m.K
nd	number of air exchanges in room per 24 hours	
$Q_{defrost}$	extra heat from defrost	W
Q_{fan}	fan motors	W
$Q_{heat\text{-}wires}$	anti-sweat heaters	W
$Q_{infiltration}$	infiltration load	W
$Q_{lighting}$	heat dissipation load	W
Q_{load}	total load	W
$Q_{radiation}$	radiation load	W
Q_{wall}	conduction load	W
T	temperature	°C or K
t	insulation thickness	m
U	global heat exchange coefficient	$W/m^{2\cdot}K$
V	volumetric air flow rate	m^3/s

Greek symbols

ε	surface emissivity	
ρ	density	kg/m^3
σ	Stefan Boltzmann's constant	

Subscript

air,ent	entrapped air
air,ex	air exchange volume
c	condensation (or cold for COP)
case	display cabinet
CR	cold room
e	evaporation

Abbreviation

COP	coefficient of performance

1. Description of commercial refrigeration and stores

1.1. Store categories using refrigeration equipment

Commercial refrigeration equipment is used in different types of stores, for cooled beverage delivery, and food preservation at medium or low temperature. Refrigerating equipment numbers and technologies differ significantly with store types.

Each type or category of store is characterized by a typical structure defined by the average sales surface area, the number of refrigeration equipment, the length of refrigerated cases. Global numbers are established based on Californian statistical data or ratios taken from overall USA numbers.

In order to define a typical store lay out, a field study has been carried out in the state of California over a large number of stores, brands, and sale products. Based on the field survey and technical literature analyses, sixteen categories of stores using refrigerating equipment are identified. A total number of 122 stores have been visited during the survey. Table 1.1 presents these categories as well as well the corresponding visited number. Complete list with brand name is reported in Annex 1.

***Note**:* Carbonated soda fountains and vending machines are refrigerating equipment studied independently. They are used in many different stores.

Table 1.1. Store categories based on field survey.

Type	Number of stores visited and described
Grocery stores (food dedicated)	38
Large Supermarkets	16
Minimarkets	3
Pharmacies	10
Convenient stores	12
Liquor stores	5
Butcheries, Pork-butcheries	4
Fishmonger stores	2
Bakeries and Pastries	1
Small size Gas Stations	14
Large size Gas Stations	4
Hotels	8
Motels	5
Bars and Restaurants	1
Carbonated Soda Fountains	-
Vending machines	-
Total	**122**

1.2. Grocery stores or grocery supermarkets

A grocery store is a store established primarily for the retailing of food. A total number of 38 groceries have been visited. The main brands are Albertsons, Ralphs, Wholefood, and Safeway. These stores present an average sales area of 2,500 m² (sales area ranging between 1,000 m² and 4,000 m²), the share of refrigerated display case surface is nearly constant for a given brand name.

1.2.1. Large supermarkets

Supermarkets are large grocery stores that store products other than food, such as clothing or household items. The main brands visited are: Walmart, Target, Costco Wholesale, … (supermarkets where food is not the major product for sale and with very large surface). The sales area varies between 6,000 m² and 16,000 m², hence presenting an average sales area of 8,500 m². The share of refrigeration is significantly lower than that of a grocery store.

1.2.2. Minimarkets

The mainly visited brands are Smart &Final, foods co. The sales area varies between 300 m² and 1,000 m².

1.2.3. Convenience stores

A convenience store is a small store or shop often located along busy roads. The main visited brands are seven/eleven and AM/PM stores, as well as local stores. An average sales area of 150 m² resulted from survey data processing (visited convenience stores presented sales area varying between 100 and 300 m²).

1.2.4. Liquor stores

A liquor store is the American and Canadian name for a type of convenience stores, which specializes in the sale of alcoholic beverages in the countries where its consumption is regulated. This category presents an average sales area identical to a convenience store. However, a category is dedicated to liquor stores because survey data processing demonstrated that installed refrigeration equipment and systems differ from those found in usual convenience stores.

1.2.5. Pharmacies

The pharmacy is a retail shop where medicine and other articles are sold. The main visited brands are: Wall green, CVS pharmacy, and Rite aid. The sales area varies from 600 m² to 1,000 m². An average sales area of 800 m² is therefore chosen for this category.

1.2.6. Gas stations

A filling station, fueling station, gas station, service station or petrol station is a facility that sells fuel and lubricants for motor vehicles. Most of the visited gas stations had convenience stores selling food and beverages of different sizes. Therefore, two categories are dedicated to gas stations according to the store size and refrigeration load. A first category includes small gas stations, and another one includes mid-size gas stations and gas stations related to commercial

centers (for example, Walmart Gas station). The principal brands present in the survey are: 76, Chevron, Mobile, Exxon, Arco,…

1.2.7. Hotels

Hotels of different sizes have been visited during the survey, starting from 1-storey to 12-storey hotels. The principal brands visited are Best Western, Hilton, Marriott, Crowne Plaza, Holiday Inn,… In order to cover the wide range of hotels, a typical hotel lay–out is defined in terms of room numbers. The typical room number is estimated based on the US Census numbers for hotels and hotel rooms and is found equal to 100 rooms. For a hotel description, the kitchen description is also taken into account.

1.2.8. Motels

The data processing concerning motels is identical to that presented in the hotel section. It is not appropriate to merge these two categories mainly because of significant differences in their kitchen refrigeration features. The visited motel chains are: America's Best Value Inn, Super Motel and Comfort Inn Sunset,...

1.2.9. Bars and restaurants

Bars and restaurants have refrigerating equipment for food conservation and beverage cooling. During the survey, it was not easy to access this equipment for a technical description. The layout of the hotel, which has a restaurant and a bar, is quite similar in terms of refrigeration equipment, except for the ice dispenser at each floor.

1.2.10. Bakeries

Bakeries primarily produce bread and related products, which are then transported to numerous selling points throughout a region. They normally sell beverages and snacks. An average sales area of 125 m² is estimated based on survey data processing.

1.2.11. Butcheries

Butcheries are stores dedicated to prepare meats and other related goods for sale. Several butcheries have been visited (El Cochinito Meat Market, Economy Meat, Veronica Meat Market, Meat Market Carniceria Latina). This category presented an average area of approximately 125 m².

1.2.12. Fishmonger Stores

A fishmonger who sells fish and seafood. This category presents an average area identical to butcheries.

1.2.13. Vending machines

After the data processing, it was more appropriate to group the vending machines in one category to avoid double counting. Since statistics on vending machines present on the Californian market are available, it is possible to evaluate their contribution in commercial energy consumption and refrigerant emissions.

1.2.14. Carbonated Soda Fountains (CSD Fountains)

Data related to CSD fountains have been processed identically to vending machines data, and a category is dedicated to group them.

1.3. Identification of refrigeration systems

1.3.1. Refrigeration systems

Three main technologies of refrigeration systems are used in stores: stand-alone equipment, condensing units, and centralized systems [LIT96].

Stand-alone or plug-in equipment is often a display case where the refrigeration system is integrated into the cabinet and the condenser heat is rejected to the sales area of the supermarket. The purpose of plug-in equipment is to display ice cream or cold beverages such as beer or soft drinks.

Condensing units are small-size refrigeration equipment with one or two compressors and a condenser installed on the roof or in a small machine room. Condensing units provide refrigeration to a small group of cabinets installed in convenience stores and small supermarkets.

Centralized systems consist of a central refrigeration unit located in a machine room. There are two types of centralized system: direct and indirect systems. In a direct system (DX), racks of compressors in the machine room are connected to the evaporators in the display cases and to the condensers on the roof by long pipes. In an indirect system, the central refrigeration unit cools a heat transfer fluid (HTF) that circulates from the evaporator in the machinery room and the display cases in the sales area. The quest for increased energy efficiency and the phase-out of ozone depleting substances have considerably affected refrigeration system design for supermarkets. The traditional CFC and HCFC refrigerants are replaced today with R-404A, R-134a, etc. A number of technical solutions have been tested:

- low GWP refrigerants such as ammonia, propane, and CO_2
- charge minimization by using indirect systems
- improvement of leak tightness of components
- better servicing and beginning of recovery of refrigerants at end of life of equipment.

Still the current centralized direct system is the dominant technology in the US and globally for supermarkets.

1.3.2. Refrigerated cabinets and rooms

Refrigerating equipment is sorted under 3 cabinet technologies: stand-alone equipment or self contained system (SA), display cases (DC) and walk-in coolers (WI).

Display cases and walk-in cabinets can be connected either to centralized system or to condensing unit depending on the equipment size and on the store category, whereas stand-alone equipment are by definition self-contained refrigerating systems.

For each cabinet technology, different types or designs have been identified based on the survey feedback. Technical characteristics and thermal equation have been issued for each type.

1.4. Survey of current refrigeration cases

A survey of 115 stores has been performed from June to November 2007 in order to collect data on existing store structures and types of refrigeration systems and cabinets. The results of this survey provided an abundance of information and allowed estimates to be made of current electricity consumption for the operation of refrigeration cabinets either as direct consumption by the cabinets (lighting, fans, anti-sweat heaters, defrosting) or by refrigeration compressors and condenser fans in order to provide refrigeration to these cabinets. The survey was performed for both remotely operated cases (DC and WI) and self-contained refrigerated equipment (SA).

1.4.1. Survey contents and data collection

Display cases (DC) and stand-alone equipment (SA) include low temperature single-deck, low temperature multi-deck, low and medium temperature glass door, medium temperature single-deck, medium temperature multi-deck, service cases, and specialty cases. Specifications include the make and model, case length, blown air temperature, saturated suction temperature, and all are included in the database.

The product display has been divided into the following categories: dairy, deli, meat product, beverage, bakery, frozen food, and ice cream. In many instances, a cabinet can be used for several of these products. Where the product displayed affects the operating temperatures or refrigeration loads, a separate entry (in the data base) for the case is provided for each product. If the specified temperatures and refrigeration loads are the same for multiple products, the products used are noted in the description.

Survey data have been collected and regrouped as a function of the refrigeration cabinet type. Hence, surveys are presented separately for display cases, stand-alone equipment, walk-in and storage rooms.

During the survey, store data have been recorded and included store's brand name, location and average sales area. For the presently manufactured refrigeration equipment, several information have been collected as presented thereafter:

- Brand name of the equipment manufacturer
- Equipment model number: *ex:* for a TRUE equipment, GDM–35
- Temperature level (medium, low)
- Equipment position: horizontal, vertical, semi-vertical
- Open or closed type equipment
- For closed type, the number of doors is recorded whereas for open type, the total length of the equipment is estimated.
- Equipment capacity and dimensions: capacity in cf or liters, height, width and length.
- Refrigerant type and charge.
- Product type (dairy, deli, bakery, salads, floral, meat, drinks, ice cream…).

The purpose of remote or self-contained refrigerated display cases in a store is to provide temporary storage for perishable foods prior to sale. Most of the design characteristics and general shape and layout of display cases are based on marketing specifications and constraints. The configuration of display cases falls into essentially four different categories.

- **Tub**: The tub case is often used for the storage and display of frozen foods and meats. Tub cases operate at a very uniform temperature and require the lower refrigeration capacity per

foot of any display case type. The primary disadvantage of the tub is a low product storage volume per square foot of sales area.

- **Open-front multi-deck**: This case type possesses the largest storage volume per square foot of floor area, because of the use of an upright cabinet and shelves. Refrigeration capacity required for multi-deck cases is very high, including a large latent load portion due to the entrainment of ambient air in the air curtain passing over the opening of the case.
- **Glass door reach-in**: The reach-in case has glass doors over the opening of the case; these must be opened for product removal and stock. Reach-in cases are used in supermarkets primarily for frozen foods, because of their ability to contain the cold refrigerated air, which reduces the "cold aisle" problem.
- **Single-deck or service**: Open single-deck cases are commonly used for display of fresh meat products. The service display case is a single-deck case equipped with sliding doors in the back for access by serving people and a glass front to show product to customers. Cases of this type are commonly seen in the deli and meat departments of supermarkets.

Display cases have been developed and refined for specific merchandising applications, and cases of each type listed above exist specifically for the storage and display of specific food types.

To allow definition of baseline refrigeration equipment, survey data have been processed based on technical data of leading refrigeration cabinet manufacturers in the United States. Data processing showed capacities and dimensions found in the stores that could be different from data gathered on websites of equipment manufacturers. To take into account these differences, interpolations have been made on the refrigeration capacity as well as the input power.

When an equipment description is identical to a model listed in the table (except for its manufacturer), input power and refrigerant data are directly applied to the studied equipment.

1.4.2. Stand-alone equipment

One objective of the survey is to define baseline stand-alone equipment models depending on description parameters stated above. Leading manufacturers of stand-alone equipments are: True Manufacturing, Beverage Air, and Hussmann Corporation. The stand-alone cases listed have been categorized into 23 models presented in Table 1.2, each model having a number starting from 1 to 23.

1.4.3. Display cases

Leading refrigeration equipment manufacturers of display cases are: Hussmann Corporation, Hill Phoenix, Tyler Refrigeration Corporation, and Kysor Warren. 14 baseline display case models are defined in Table 1.3, each model having a number starting from 1 to 14.

1.4.4. Walk-ins

Selections include storage walk-ins, walk-in boxes with glass doors (e.g., dairy, beverage and floral boxes), preparation areas that may be fully enclosed or have one side open to the sales area, and other perimeter zones that are air conditioned from the refrigeration system (e.g., bakery prep areas, pharmacy, etc.). Specifications include the make and model (for components in the library), size, temperature, location, reach-in doors, walk-in doors,

refrigeration load, lighting, evaporator coils, defrost type and control, fans, and internal loads. For walk-in (WI), 5 baseline categories are found and listed in Table 1.4.

Table 1.2. Baseline stand-alone equipments list.

Number	Brand Name	Model	T° level	Open/ closed	Position	Door #	Capacity (liters)	Length (m)	Height (m)	Width (m)	Product type	Refrig type	Refrig charge (g)	Cooling Capacity (HP)	Product T(°C)	Evaporation T(°C)
SA_1	(TRUE)	GDM-7	Medium	closed	Vertical	1	200	0.8	1.0	0.6	drinks, salads, deli, dairy	R134A	300	0.2	2.0	-13
SA_2	(TRUE)	GDM-10	Medium	closed	Vertical	1	300	0.8	1.4	0.7	drinks, salads, deli, dairy	R134A	300	0.2	2.0	-13
SA_3	(TRUE)	GDM-23	Medium	closed	Vertical	1	600	0.8	2.0	0.7	drinks, salads, deli, dairy	R134A	300	0.33	2.0	-13
SA_4	(TRUE)	GDM-35	Medium	closed	Vertical	2	1000	1.6	2.0	1.0	drinks, salads, deli, dairy	R134A	300	0.5	2.0	-13
SA_5	(TRUE)	GDM-72	Medium	closed	Vertical	3	2000	2.4	2.0	2.0	drinks, salads, deli, dairy	R134A	550	0.5	2.0	-13
SA_6	(TRUE)	TCGR-50	Medium	closed	S-Vertical	2	800	1.6	1.2	1.3	salads, deli, bakery	R134A	300	0.5	2.0	-13
SA_7	Hussman	SHM	Medium	open	S-Vertical			1.8	1.2	0.6	drinks, salads, deli, dairy	R134A	800	0.5	2.0	-13
SA_8	(TRUE)	TAC-48	Medium	open	Vertical		1000	1.2	2.0	1.2	drinks, salads, deli, dairy	R404A	1000	1	2.0	-13
SA_9	Hussman	DDS8	Medium	open	Vertical			2.4	2.5	2.1	drinks, salads, deli, dairy	R22	1400		2.0	-13
SA_10	(TRUE)	THF-41FL	Low	closed	Horizontal	2	300	1.6	1.0	0.8	frozen	R134A	1200	0.75	-20.0	-35
SA_11	(TRUE)	GDM-23F	Low	closed	Vertical	1	600	0.8	2.0	0.7	frozen	R404A	600	0.75	-20.0	-35
SA_12	(TRUE)	GDM-35F	Low	closed	Vertical	2	1000	1.6	2.0	1.0	frozen	R404A	1000	1	-20.0	-35
SA_13	(TRUE)	GDM-72F	Low	closed	Vertical	3	2000	2.4	2.0	2.0	frozen	R404A	2500	1.5	-20.0	-35
SA_14	Bev_Air	FC-45	Medium	closed	Vertical	2	1200	1.6	2.0	0.7	Floral	R134A	600	0.33	2.0	-13
SA_15	Hussman	ISMGG	Medium	open	Horizontal			1.7	1.0	1.0	deli, dairy	R22	2300		2.0	-13
SA_16	Hussman	ISFGG	Low	open	Horizontal			1.7	1.0	1.0	frozen	R22	2300		2.0	-13
SA_17	(TRUE)	GDM41/45	Medium	closed	Vertical	2	1200	1.6	2.0	0.8	drinks, salads, deli, dairy	R134A	500	0.5	2.0	-13
SA_18	(TRUE)	GDM 12	Medium	closed	Vertical	1	340	0.8	1.6	0.7	drinks, salads, deli, dairy	R134A	250	0.2	2.0	-13
SA_19	Bev_Air	MT12	Medium	closed	Vertical	1	400	0.8	1.6	0.6	boissons	R134A	300	0.2	2.0	-13
SA_20	Bev_Air	UR30	Medium	closed	Vertical	1	700	0.8	0.9	0.7	boissons	R134A	200	0.2	2.0	-13
SA_21	LEER	Model 45	Low	closed	Vertical	2	1200	1.6	2.0	1.2	Ice maker	R134A	300	0.33	-25.0	-35
SA_22	Bev_Air	DD68	Medium	closed	Horizontal	2	800	1.6	1.0	0.7	Beer	R134A	300	0.33	2.0	-13
SA_23	(TRUE)	GSM	Medium	closed	Vertical	1	700	0.8	2.0	0.8	Tour Patissier	R134A	300	0.5	2.0	-13

Table 1.3. Baseline display cases list.

Number	Brand Name	Model	T° level	Type	Position	Door #	Length (m)	Height (m)	Width (m)	Cooling Capacity (BTUh/FT)	Cooling Capacity (W/m)	Refrig Charge (Lb/FT)	Refrig Charge (kg/m)	Product type	T evaporation (°C)	Tproduct (°C)
DC-1	TYLER	N6D	Medium	open	Vertical		1.2;1.8;2.4;3.6	2.0	1.0	1270	1222	1	1.55	Dairy/Dely/Produce/Juice	-13	2
DC-2	HUSSMAN	RM	Medium	closed	Vertical	1;2;3	0.8	2.1	1.1	324	312	0.35	0.52	Dairy/Deli/beverages	-13	2
DC-3	HUSSMAN	E2	Medium	open	1/2Vert		1.2;1.8;2.4;3.6	1.2	1.2	945	909	0.23	0.34	Deli/Pizza/Floral/Juice	-13	2
DC-4	HUSSMAN	SMGV	Medium	closed	1/2Vert		1.2;1.8;2.4;3.6	1.3	1.1	210	202	0.19	0.28	Meat/delicatessen	-13	2
DC-5	TYLER	NM/NMG	Medium	open	Horizontal		1.8;2.4;3.6	1.0	1.0	432	416	0.26	0.39	Meat/deli/Produce	-13	2
DC-6	HUSSMAN	F6L	Low	open	Vertical		1.2;1.8;2.4;3.6	2.0	1.2	1755	1688	0.44	0.66		-35	-20
DC-7	HUSSMAN	RLN	Low	closed	Vertical	2;3;4;5	0.8	2.1	2.0	503	484	0.34	0.51	Frozen	-35	-20
DC-8	TYLER	NFNG	Low	closed	Horizontal		2.4;3.6	0.9	1.0	366	352	0.28	0.42	Frozen	-35	-20
DC-9	TYLER	NPW	Medium	open	Horizontal		2.4;3.6	0.8	1.8	776	747	0.51	0.76	Produce	-13	2
DC-10	HUSSMAN	P2X	Medium	open	Vertical		1.2;1.8;2.4;3.6	1.9	1.0	910	875	0.38	0.57	Fruits/Produce	-13	2
DC-11	HUSSMAN	F2XLG	Low	open	1/2Vert		1.2;1.8;2.4;3.6	1.4	1.2	2050	1972	0.44	0.66	Frozen meat/Seafood	-35	-20
DC-12	HUSSMAN	DSFM	Medium	closed	1/2Vert		1;2;3;4;	1.2	1.0	500	481	0.33	0.49	Seafood	-13	2
DC-13	Hussman	FI	Low	open	Horizontal		2,4;3,6	0.9	1.5	480	462	0.34	0.51	Frozen	-35	-20
DC-14	ZeroZone	RMCP30FL	Medium	closed	Vertical	2;3;4;5	0.8	2.1	0.9	1220	1174	0.43	0.64	FLORAL	-13	2

Table 1.4. Baseline walk-in cases list.

Number	T° level	Type O/C	Type R/C	Door #	Length (m)	Height (m)	Width (m)	Product DH (kg/kJ)	Product mass flow (kg/m3 24h)	Product T(°C)	Tevaporation (°C)
WI-1	Medium	open	0		1	2.5	3	45	20	2	-13
WI-2	Medium	closed	0	12	1	2.5	3	45	20	2	-13
WI-3	**Low**	closed	0	12	1	2.5	3	55	15	-20	-35
CSR-1	Medium	closed	1		1	3.5	6	45	20	2	-13
CSR-2	low	closed	1		1	3.5	6	55	15	-20	-35

Once the baseline refrigeration equipment, self-contained or remote refrigerated equipment are described, it is possible to draw typical layouts for the 16 store categories defined in Section 1.1. The next section presents the grocery supermarket layout based on equipment listed in Tables 2 to 4.

1.5. Typical grocery store lay-out

A representative grocery supermarket layout is shown in Figure 2. Refrigerated fixtures are located throughout the store, because of the large amount of perishable food products that are sold. These fixtures fall into 3 categories, stand-alone equipment, display cases, and walk-in storage coolers. Stand-alone equipment and display cases are located on the sales floor and are designed to refrigerate food products while providing a place to merchandise them. Walk-in coolers are used to store food products during the time period between receiving the product and placing the product out for sale.

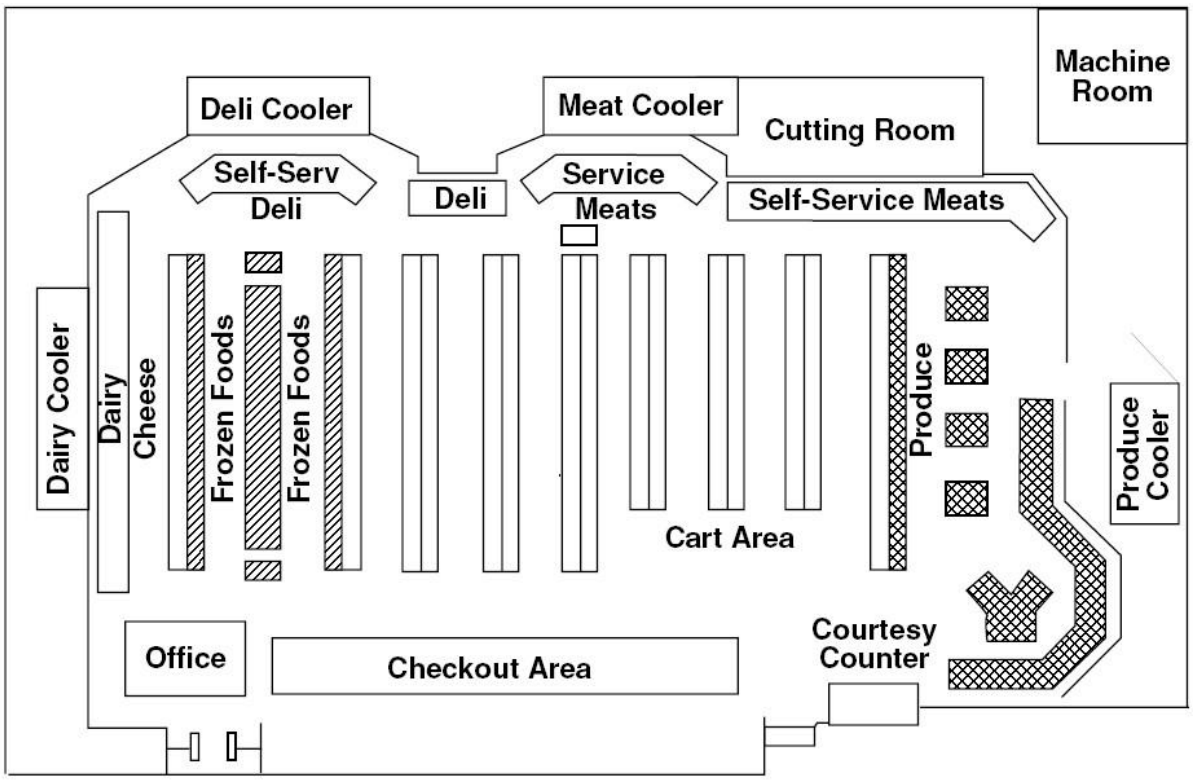

Figure 1.1. Lay out of the refrigerated fixtures in a supermarket [ORNL04].

A typical arrangement of refrigerating equipment in a grocery is shown in Figure 1.1. Display cases, of a variety of configurations and products, are generally used in the sales area and are located at the periphery of the store near their associated walk-ins. The survey data processing enabled the definition of a typical grocery refrigeration configuration presented in Tables 1.5, 1.6, and 1.7.

Table 1.5. Self-contained refrigerating equipments found in a grocery store.

Stand Alone equipments		
Description	**Model**	**Number of equipment**
Medium temperature self contained closed vertical case for drinks salads, deli and dairy with a capacity of 200 liters	SA-1	3
Medium temperature self contained closed vertical case for drinks salads, deli and dairy with a capacity of 300 liters	SA-2	2
Medium temperature self contained closed vertical case for drinks salads, deli and dairy with a capacity of 600 liters	SA-3	1
Medium temperature self contained open vertical case for drinks salads, deli and dairy with a capacity of 1000 liters	SA-8	1
Medium temperature self contained open vertical case for drinks salads, deli and dairy with a capacity of 2000 liters	SA-9	1
Medium temperature self contained open horizontal case for deli and dairy with a capacity of 1500 liters	SA-15	1
Medium temperature self contained closed vertical case for drinks salads, deli and dairy with a capacity of 1200 liters	SA-17	1
Medium temperature self contained closed vertical case for drinks salads, deli and dairy with a capacity of 340 liters	SA-18	1
Self contained Ice maker with a capacity of 1200 liters	SA-21	1

Table 1.6. Display cases equipments found in a grocery store.

Display cases equipments		
Description	**Model**	**Length (m)**
Medium temperature Open-front multi-deck vertical display case for dairy, deli, juice and drinks	DC-1	75
Medium temperature Glass door reach-in multi-deck vertical display case for dairy, deli, juice and drinks	DC-2	7
Medium temperature Open-front single-deck semi-vertical display case for deli, pizza floral and juices	DC-3	15
Medium temperature Glass door reach-in single-deck semi-vertical display case for meat and delicatessen	DC-4	20
Medium temperature Open Tub case for meat and delicatessen	DC-5	10
Low temperature Open-front multi-deck vertical display case for frozen products	DC-6	4
Low temperature Glass door reach-in multi-deck vertical display case for frozen products	DC-7	86
Medium temperature Open Tub case for produce	DC-9	17
Medium temperature Open-front multi-deck vertical display case for produce	DC-10	27
Medium temperature Open-front single-deck semi-vertical display case for seafood	DC-12	5
Low temperature Open Tub case for frozen products	DC-13	17
Medium temperature Glass door reach-in multi-deck vertical display case for floral	DC-14	3

Table 1.7. Walk-in and cold rooms found in a grocery store.

Walk In and Storage Rooms		
Description	**Model**	**Length (m)**
Medium temperature Open-front multi-deck walk in for dairy, deli, juice and drinks	WI-1	4
Medium temperature Glass door reach-in multi-deck walk in for dairy, deli, juice and drinks	WI-2	12
Low temperature Glass door reach-in multi-deck walk in for dairy, deli, juice and drinks	WI-3	12
Medium temperature Cold Storage room	CR-1	60
Low temperature Cold Storage room	CR-2	18.5

1.6 Typical layout of small stores

Similarly to grocery stores, the survey data processing enabled the definition of a typical refrigeration layout for each of the 15 categories defined previously. These layouts are described in Tables 1.8, 1.9, and 1.10.

Table 1.8. Self-contained refrigerating equipment distribution for different store categories.

Stand Alone	SA-1	SA-2	SA-3	SA-4	SA-5	SA-6	SA-7	SA-8	SA-9	SA-10	SA-11	SA-12	SA-13	SA-14	SA-15	SA-16	SA-17	SA-18	SA-19	SA-20	SA-21	SA-22	SA-23
Grocery	3	2	1	0	0	0	0	1	1	0	0	0	0	0	1	0	1	1	0	0	1	0	0
Large Supermarket	2	2	0	3	0	0	0	0	0	2	1	0	0	2	0	1	1	0	0	0	2	0	0
Pharmacy	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	1	0	0
Convenience	0	0	0	2	0	0	0	0	1	2	0	0	0	0	0	0	0	0	1	0	1	0	0
Liquor Store	0	1	0	1	1	0	0	0	0	3	0	0	0	0	0	0	1	0	1	0	1	0	0
Minimarket	1	2	1	0	0	0	0	1	0	1	1	0	1	0	1	0	0	0	0	0	2	0	0
Small Gas Stat	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Center Gas Stat	1	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	1	0	1	0	1	0	0
Hotel	2	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	4	1	0
Motel	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0
Butchery	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fishmonger Store	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Bakery	0	0	0	2	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
Restaurants Bar	2	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0
Vending Machine	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Soda Fountain	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0

Table 1.9. Distribution of refrigerated display cases for different store categories.

Display Case	DC-1	DC-2	DC-3	DC-4	DC-5	DC-6	DC-7	DC-8	DC-9	DC-10	DC-11	DC-12	DC-13	DC-14
Grocery	75	7	15	20	10	4	86	0	17	27	0	5	17	3
Large Supermarket	0	10	8	0	6	0	11	0	0	1	0	0	1	0
Pharmacy	0	1	0	0	0	0	3	0	0	0	0	0	0	0
Convenience	1	0	0	2	0	0	1	0	0	3	0	0	0	0
Liquor Store	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Minimarket	4	0	0	0	0	0	3	0	0	2	0	0	2	0
Small Gas Stat	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Center Gas Stat	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hotel	0	0	0	3	0	0	0	0	0	0	0	0	0	0
Motel	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Butchery	0	0	2.5	2.5	0	0	0	0	0	0	0	0	0	0
Fishmonger Store	0	0	5	0	0	0	0	0	0	0	0	0	0	0
Bakery	0	0	0	5	0	0	0	0	0	0	0	0	0	0
Restaurants Bar	0	0	0	3	0	0	0	0	0	0	0	0	0	0
Vending Machine	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Soda Fountain	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 1.10. Distribution of walk-in and cold storage rooms for different store categories.

Walk IN	WI-1	WI-2	WI-3	CR1	CR2	Sales Area (m²)
Grocery	4	12	12	60	19	2500
Large Supermarket	0	6	9	27.5	9	8500
Pharmacy	3	8	4	0	0	800
Convenience	0	9	2	0	0	150
Liquor Store	0	14	0	0	0	153
Minimarket	0	14	21	27.5	9	1145
Small Gas Stat	0	2	0	0	0	25
Center Gas Stat	0	7	2	0	0	100
Hotel	0	0	0	6	3	
Motel	0	0	0	0	0	
Butchery	0	0	0	3	0	125
Fishmonger Store	0	0	0	3	0	125
Bakery	0	0	0	0	0	125
Restaurants Bar	0	0	0	6	3	
Vending Machine	0	0	0	0	0	
Soda Fountain	0	0	0	0	0	

2. Method for Energy Consumption Calculation

2.1. Introduction

Supermarkets represent one of the largest energy-intensive building groups in the commercial sector, consuming 2 to 3 million kWh annually per store [BAX03]. Several studies have shown that annual electricity consumption ranges from 1 to 1.5 million kWh per store for refrigeration [LIT96]. A typical electricity usage of a grocery in the U.S. shows that 39% is used for refrigeration, 23% for lighting, 11% for cooling, 4% for ventilation, 13% for heating, and 10% for miscellaneous applications (cooking, water heating, …) as shown in Figure 2.1.

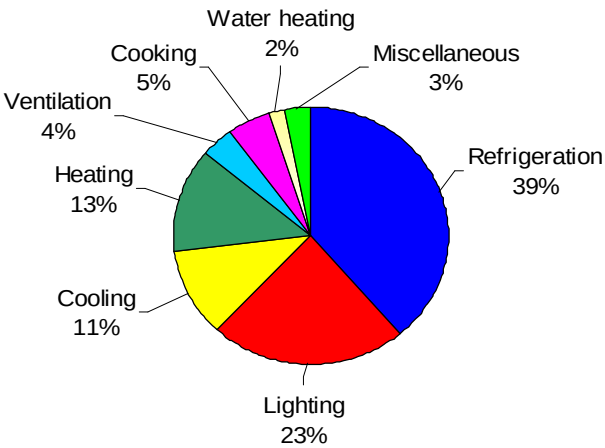

Figure 2.1. Typical electrical energy usage in a grocery store in USA [LIT96].

Recent field tests tend to confirm that this figure is still a good estimate. Data from a field test in a 50,000 ft²-store in Southern California indicate annual usage of about 1,500,000 kWh for all refrigeration including case lights, fans, heaters, etc [ORL04].

The approach for energy consumption calculation in commercial refrigeration, detailed in this report, is qualified as “bottom – up approach”. In order to simulate energy efficiency improvement of refrigeration equipment, each element in the energy consumption chain has to be considered and described in detail.

The energy consumption calculation is based on the evaluation of refrigeration loads, hour by hour, on a given year, taking into account weather conditions (temperature and humidity) of the 8 California climatic zones.

Each type of store (16 families) have been calculated independently, when the layout of refrigeration equipment in each store has been issued.

2.2. Energy consumption calculation

The method for energy consumption calculation is illustrated by the following algorithm. The method is applied for each type of store.

The cooling capacity of display cases is provided by a large vapor compression refrigeration system. The operating characteristics and energy requirements of the refrigeration system are directly related to the refrigeration capacity necessary to maintain display case temperature.

There are two principal temperature levels in supermarkets: medium temperature for preservation of chilled food and low temperature for frozen products. Chilled food is maintained between 1°C and 14°C, while frozen food is kept between -12°C to -18°C, depending on the country. The evaporation temperature, for a medium-temperature system, varies between –15°C and -5°C, and for a low-temperature system, the evaporation temperatures are in the range of –30°C to -40°C. Variations in temperature are dependent upon products, display cases and the chosen refrigeration system [LIT96].

2.3. Heat load, refrigeration capacity

The heat load of the case is the amount of heat that must be removed from the display case in order to maintain the product in the case at the desired storage temperature. The refrigeration capacity is equal or superior to the heat loads to maintain the product temperature. The refrigeration capacity of a display case is most often given at a specific blown air temperature at the outlet of the evaporator, since this value is easier to measure (and control) than the temperature of the stored product. The standard rating condition to specify the refrigeration capacity of a display case is for operation in an indoor environment with a 75°F dry-bulb temperature and a relative humidity of 55 percent. The heat loads of a refrigerated cabinet are coming from convection, conduction, radiation, and advection.

- *Conduction*

Ambient heat that passes through the walls of the display case is intercepted by the air flowing around the perimeter of the display case.

- *Radiation*

Thermal radiation heat transfer occurs between the interior of the display case and the surrounding ambient environment.

- *Convection (air entrainment)*

The air curtain passing across the opening of the display case mix with and entrain part of the surrounding ambient air, which is then returned to the case evaporator. The heat load due to the entrained air consists of both sensible and latent heats. Ambient air entrainment occurs in all display case types, but represents the largest portion of the refrigeration load for open, multi-deck cases.

- *Internal loads*

Heat energy is generated by the use of electric energy in the display case for the following auxiliaries:

- Lights: fluorescent light features are installed in the display cases for illumination of the product. Heat from the ballasts may also enter the case if the ballast is installed in the refrigerated portion of the case.
- Fan motors: the electric energy associated with the fans used to circulate air around the display case.
- Anti-sweat heaters: are installed in glass doors and on other surfaces that operate at a temperature below the ambient dew-point temperature. If heaters are not installed, condensation and possibly frost will form on these surfaces.

  The contribution of each load source will vary according to display case type. The refrigeration load of open multi-deck display cases is dominated by air entrainment. Internal electric loads represent a significant portion of the refrigeration load of reach-in

frozen food cases. For single-deck and tub cases, radiation heat transfer accounts for a large fraction of the heat loads.
The impact of each of these thermal loads on the refrigeration capacity depends upon the case type. For example, air infiltration is the most significant portion of heat loads for open, multi-deck cases, while radiation is the largest part of the heat load for tub-type cases. The door anti-sweat heaters represent a major share of the refrigeration load for frozen food door reach-in cases.

- Defrosting: The conditions of air in cold storage rooms or in display cases affect the refrigerating capacity of the coil. At surface temperature lower than the dew point temperature of the air, the water vapor contained in the humid air will condense on surfaces, and at surface temperature lower than 0°C frost will deposit on the surfaces. The frost formation that is seen on evaporator surfaces is an important factor in the operation of refrigeration systems. Without periodic removal, the frost will accumulate and eventually block the airflow passages of the evaporator, resulting in loss of cooling capacity. The usual operation for supermarket refrigeration systems is to defrost the display cases on a scheduled basis. Several different methods are employed for defrosting: off-cycle defrosting, electric defrosting.

▪ *Off-Cycle defrost*ing

Refrigeration to the case is shut off and the evaporator warms above the melting temperature of the frost. This method is commonly used for display cases operating at the highest blown air temperatures (34 to 37°F), because frost loading is relatively small. Off-cycle defrosting is also used where the product is not sensitive to air temperature change, such as milk and other dairy products. For frozen food or meat, off-cycle defrosting is not appropriate.

▪ *Electric defrosting*

Electric heaters are installed at the inlet of the evaporator so that the circulated air can be heated. The warm air passes through the evaporator where it provides the heat needed to melt the frost. Although it is the most energy consuming application, electric defrosting remains used in all refrigeration systems and is considered the most reliable defrosting method.

Defrosting has a significant impact both for energy consumption and product temperatures because of the air and product temperature rises during defrosting and has to be lowered quickly after defrosting leading to a significant overcapacity for rapid “pull down” of temperatures. If not performed correctly, the product can be damaged. The number of defrosting cycles required for a refrigeration case depends on its type. Open, multi-deck display cases will require several, while tub and reach-in cases normally have only one defrosting per day. Defrosting schedule is normally controlled by a time clock that initiates defrosting for each case at specific times each day.

2.4. Thermal modeling of display cases

The average air temperature, inlet and return air temperatures, evaporating temperature, electrical data for fans, heating wires, defrosting heaters and light, coil volume, diameter of tubs and refrigeration loads at 22°C – 65% RH and at 25°C – 60% RH for each cabinet have been put into a database. The refrigeration loads in display cases are dependent on indoor conditions in the supermarket; a higher indoor temperature and relative humidity increase the cooling demand and the energy requirement. An energy balance of an open vertical cabinet is shown in Figure 2.2 where heat losses from infiltration, radiation, conduction, lighting, the fan, heating wires, and defrosting are presented.

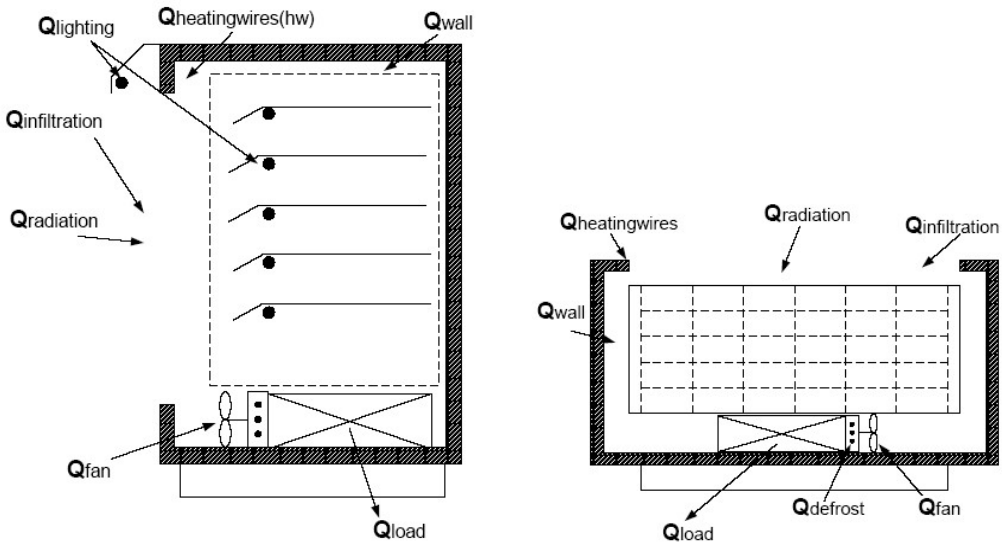

Figure 2.2. Energy balance of vertical (left) and horizontal (right) display cases.

The following equations state the expressions of different loads accounted for in the cooling load calculations as a function of the display case and the store temperature.

Starting with the conduction load expressed in Equation 2.1:

$$\dot{Q}_w = U_{case} A_{case} \left(T_{store} - T_{case} \right) \tag{2.1}$$

Where $U_{case} = \dfrac{1}{\dfrac{1}{h_i} + \dfrac{t}{k} + \dfrac{1}{h_o}}$ and A_{case} corresponds to the total surface of the cabinet exchanging by conduction with the surrounding store ambience. h_i and h_o represent the inner and outer convective heat exchange coefficients respectively, t and k the insulation thickness and thermal conductivity respectively.

The radiation load is also considered and can be evaluated applying Equation 2.2:

$$\dot{Q}_{radiation} = \frac{\sigma \left(T_w^4 - T_{case}^4 \right)}{\left[\left(\dfrac{1-\varepsilon_w}{\varepsilon_w A_w} \right) + \left(\dfrac{1}{A_w F_{case,w}} \right) + \left(\dfrac{1-\varepsilon_{case}}{\varepsilon_{case} A_{case}} \right) \right]} \tag{2.2}$$

Where the subscript w refers to the store wall, σ Stefan Boltzmann's constant and ε the surface emissivity.

The infiltration load depends on the amount of store air entrained in through-frozen-food cabinets. This amount is usually expressed as a ratio of the cabinet blown airflow rate. The percentages of the store air entrapment into the cabinets and freezer rooms are found in literature or evaluated through extensive measurements and parametric analyses for specific

blown air velocities. For instance, for an open cabinet, air entrapment is taken equal to 7 or 8% of the blown airflow rate, while it is approximately equal to 1% for closed cabinets. Equation 2.3 states the infiltration load expression:

$$\dot{Q}_{infiltration} = \rho_{air} V_{air,ent} \left(h_{store} - h_{case} \right) \tag{2.3}$$

Where the subscript *air,ent* refers to entrapped air, V the volumetric air flow rate and h air enthalpy at store or case temperature.

Dissipations of heat from installed equipment should also be taken into account such as lamps and ballasts ($\dot{Q}_{lighting}$), fan motors ($\dot{Q}_{fan}$), anti-sweat heaters ($\dot{Q}_{heating-wires}$) and extra heat from defrost ($\dot{Q}_{Defrost}$). The total load is obtained by summing all of the above evaluated quantities as expressed in Equation (2.4):

$$\dot{Q}_{load} = \dot{Q}_{wall} + \dot{Q}_{infiltration} + \dot{Q}_{radiation} + \dot{Q}_{lighting} + \dot{Q}_{fan} + \dot{Q}_{heating-wires} + \dot{Q}_{Defrost} \tag{2.4}$$

The load calculation of a stand-alone equipment is identical to a closed cabinet display load calculation.

2.5. Thermal modeling of cold storage room

The capacity demand for cold storage is due to four factors: heat transmission, exchange of air, cooling or freezing of products and internal heat generation [GRA03]. Heat transmission through walls, floor, and ceiling is dependent on the overall heat transfer coefficient and the temperature difference between the room and the surroundings. The heat transmission has been defined as shown in Equation 2.5:

$$\dot{Q}_{cond} = \Sigma \left(U_{CR} A_{CR} \left(T_{store} - T_{CR} \right) \right) \tag{2.5}$$

The exchange of air in cold rooms depends on the frequency of door openings and the size of the room. The exchange of air increases the refrigeration load of the room. The influence of incoming air in the room can be calculated from Equation 2.6:

$$\dot{Q}_{airex} = \rho_{air} \dot{V}_{airex} \left(h_{store} - h_{CR} \right) \tag{2.6}$$

Where $\dot{V}_{airex}$ is an average volume flow of incoming air that is defined in (Granryd 2003) as presented in Equation 2.7:

$$\dot{V}_{airex} = V_{CR} \frac{nd}{24.3600} \tag{2.7}$$

nd is the number of air exchanges in the room per 24 hours. Temperatures and the frequency of door openings influence the number of air exchanges. Results from experiments are presented in Table 2.1 [GRA03].

Table 2.1. Number of air exchanges from ARIAS.

Room Volume (m^3)	Medium T (°C)	Low T (°C)
7	38	30
10	31.5	24.5
20	21.5	17
40	14.5	11.5
100	9	7
500	3.5	2.7
1000	2.5	2.7
3000	1.35	1.05

The enthalpy difference for freezer rooms has been assumed to be 45 [kJ/kg], which is the average between the enthalpies of different products at temperatures -15°C and –18°C. Similarly, the enthalpy difference for the cold room has been assumed to be 55 [kJ/kg], which is the average between the enthalpies of different products at temperatures 17°C and 1°C. The mass flow has been assumed to be 20 kg/m^3 per 24 hours [ARIA05] for cold rooms and 15 kg/m^3 per 24 hours for freezer rooms. Internal heat generation from lighting and people also affects the refrigeration load of the cold room. The heat generated by lighting has been assumed to be 15 W/m^2 and the heat from people to be 200 W.

2.6. Coefficient of performance

Many factors have an impact on the coefficient of performance (COP):

- Level of temperature for product or beverage conservation
- Temperature differences at the condenser and evaporator coils
- Compressor efficiency
- Type of refrigerant
- Configuration of the refrigeration system (one or two compression stage, sub-cooling or not)

For energy calculation along the year, the coefficient of performance has been considered as a function of these variable values. The expression of the COP for the theoretical cycle of Carnot is:

$$COP_c = \frac{Te}{Tc - Te} \qquad (2.8)$$

Where *Te* and *Tc* are respectively evaporating temperature and condensing temperature expressed in Kelvin. These temperatures are linked to product temperature and ambient temperature. Product conservation temperature is supposed to be fixed along the year. Typical temperature difference at the evaporator and the condenser are presented in Table 2.2.

Table 2.2. Temperature difference in heat exchangers.

Difference of temperature in heat exchangers	DTev evaporator	DTcd condenser
Centralized System / medium temperature	15 K	12 K
Centralized System / low temperature	17 K	10 K
Condensing Units / medium temperature	15 K	12 K
Condensing Units / low temperature	17 K	12 K
Stand-alone equipment / medium temperature	15 K	15 K
Stand-alone equipment / low temperature	15 K	15 K

In centralized systems, the evaporating temperature is the same for all display case connected to the same compressor rack. The evaporating temperature varies usually between –10°C and –12°C for medium temperature display cases. Product temperature conservation ranges from 0°C to +10°C. Moreover, the control for evaporator feeding in refrigerant is usually performed by an electromagnetic valve. The superheat control is not optimized and leads to poor efficiency of the evaporator coil. In consequence, temperature difference between air and refrigerant is high.

Because of pressure drops in suction line of the compressor rack, the pressure at the suction port is lower, and the equivalent saturating temperature is between –12°C and –15°C. The air flow rate on the evaporator is low, for noise reduction.

For the calculations, the temperature chosen is **–13°C** for medium-temperature compressor rack, and –35°C for low-temperature compressor rack.

The coefficient of performance can be expressed with the theoretical Carnot COP and the cycle efficiency. The cycle efficiency depends mainly on the compressor efficiency, the cycle architecture, and the refrigerant properties. For each type of refrigeration system (centralized, condensing units, stand alone), cycle efficiencies have been calculated for the refrigerant in use. Compressor efficiencies have been taken from manufacturer data (Copeland, Carlyle)

Table 2.3. Cycle efficiency (COP / COPc).

	Cycle efficiency
Centralized System / medium temperature	45 %
Centralized System / low temperature	42 %
Condensing Units	40 %
Stand-alone equipment	25 %

The additional power consumption of the condenser fan is integrated in the cycle efficiency. In centralized systems, the input power for condenser ventilation is 7% of compressor rack input power for medium-temperature system, and 8% of compressor rack input power for low-temperature system [BIG02, FAY00].

In supermarkets, the condensation pressure is controlled to a minimum level, to keep the pressure sufficiently high in order that the thermo expansion valves (TxV) feed correctly the evaporators. In winter time, with low outdoor temperature, it is possible to reduce the condensing pressure, taking advantage of a lower pressure ratio for the compressors. This is possible when expansion valves are designed for a wider range of pressure differences. The impact on the cycle efficiency, when the head pressure control is activated, has been taken into account for the different scenarios of energy consumption.

Finally the equation of the coefficient of performance is a function of the outdoor temperature:

$$COP = \frac{Tev}{(Text + DT_{cd}) - Tev} \cdot \eta c \qquad (2.9)$$

with *DTcd* (temperature difference at the condenser) as functions of the out door temperature (*Text*), the floating head pressure control (*FHPC*), the technology of the refrigerating system (*Tech*), and the level of the evaporating temperature (*Tev*) (see Table 6).

$$DTcd = f(Text; FHPC; Tech; Tev) \qquad (2.10)$$

The cycle efficiency (η_c) is a function of the technology (*Tech*) and the level of temperature for centralized systems (*Tev*) (see Table 7). Two other variables are considered for the cycle efficiency: the floating head pressure control (*FHPC*) and the outdoor temperature (*Text*).

Because ventilation is reduced when outdoor temperature is low, in winter time for example, the additional input power of the condenser fan decreases. The cycle efficiency includes the additional power input of the condenser fans, which varies according to the outdoor temperature. In consequence, the cycle efficiency must be correlated to the outdoor temperature and the head pressure control.

$$\eta c = f(Text; FHPC; Tech; Tev) \tag{2.11}$$

2.7. Store distribution in climatic zones

Global calculations for energy consumption are done for different climatic conditions. The outdoor temperature has an impact on the coefficient of performance of the refrigerating system (8), (10). Depending on the climatic zone of the supermarket and the other stores, the hourly variation of temperature will have an impact on the energy consumption.

8 climatic zones have been defined. Temperature variations during one typical year are known and registered hour by hour in weather stations. The distribution of stores and supermarkets in the different climatic zones has been done proportionally to the population living in each zone.

Figure 2.3 presents the average temperature (24 hours averaged) for 3 weather stations in California.

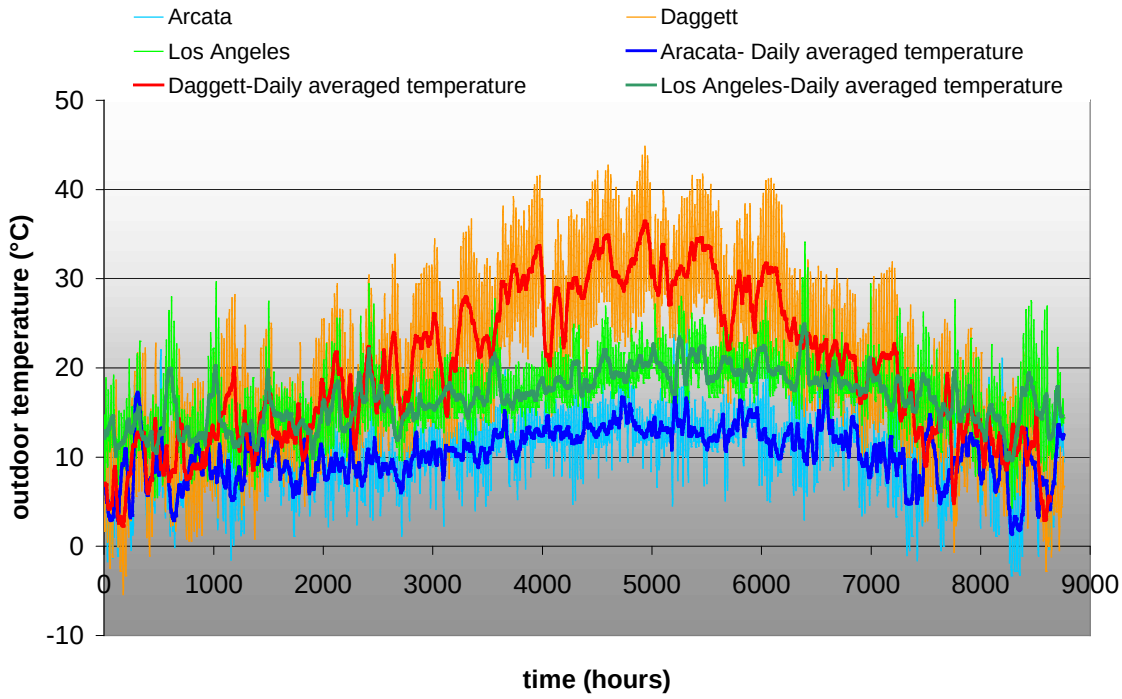

Figure 2.3. Temperature evolution in one year – 3 weather station measurements.

Figure 2.4 presents the 8 climatic zones, and the population distribution in these zones. Los Angeles, with 36% of the population, is the first for the number of inhabitants. The distribution of the different stores studied in the commercial refrigeration sector is supposed to be the same as the population distribution.

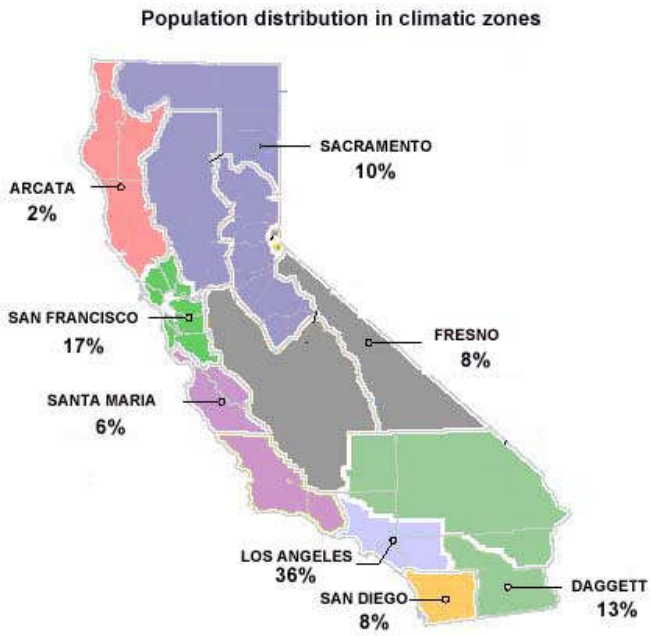

Figure 2.4. Climatic zones and population distribution.

3. Energy Savings

The quest for increased energy efficiency and the phase-out of ozone depleting substances (ODS) have changed the refrigeration system design for some new supermarkets. A great potential for energy efficiency improvement as well as limitation of green House gas emissions have been assessed by many research laboratories as well as commercial chains or equipment manufacturers. Energy saving technologies such as heat recovery, floating head pressure, defrosting control, energy efficient lighting, high efficiency motors, and efficient control have been implemented in many supermarkets to reduce energy consumption. The objective of these technical options is to develop energy-efficiency solutions in refrigerated cases, while enhancing food safety without hampering merchandizing facets.

3.1. Heat recovery systems

The refrigeration system in a supermarket always rejects heat to the environment through the condensers. It is possible to use the rejected heat for heating the store in the winter season. Heat rejected from condensers can also be used to heat service water and premises in cold climates, which is a good measure to improve energy usage in new efficient refrigeration cycle design. Heat recovery leads to a reduction in costs and in the usage of fossil fuels for heating.

3.2. Floating head pressure

A drawback of the heat recovery system is the high condensing temperatures that increase the energy consumption of the refrigeration system. In the so-called floating head pressure condensing systems, the condensing temperature follows with the ambient temperature. The system is implemented with electronic expansion valve (or multiple-orifice expansion valve) operating over a wide range of pressure differences and allowing for low condensing temperature at low ambient temperatures. A reduction of condensing temperatures increases the coefficient of performance of refrigeration systems.

3.3. Installing glass doors in open cases

Display cases commonly carry large refrigeration loads, especially vertical open display cabinets. The reason is that this kind of cabinet displays a large amount of food on a small surface in the store with a large open front area. The heat and moisture exchanged between the products in the cabinet and the store environment affect the refrigeration load, defrost and condensation, on walls and products. Infiltration causes about 60 to 70% of the cooling load for a typical open vertical display cabinet [ARIA05].

The refrigeration loads associated with the glass door reach-in case are normally less than those of the multi-deck, but greater than for the tub case. Glass door cases are, however, equipped with anti-sweat electric heaters in the doors to prevent fogging and decreased visibility of the product.

Installing glass doors in display cases reduces the infiltration and energy consumption of the cabinets. The reason for the absence of the doors in a display case is to avoid placing an obstacle between the customer and the product, which may hinder the customer impulse to purchase a new product. Results from a laboratory test that evaluated glass doors on a open five-deck display case show a reduction of the total cooling load of the case by a 68% [FAR02].

3.4. Hot Gas Defrost

Discharge refrigerant gas is piped from the compressor rack to the display case where the refrigerant is condensed by melting the frost. The piping is arranged so that the liquid refrigerant is returned to the compressor rack for distribution to other display cases in the system. Hot gas defrosting is the fastest method to remove frost and tends to have the least impact on case air and product temperatures. Hot gas is the most costly defrosting method to implement because of the extensive piping and controls needed.

4. Results for energy consumption

4.1. Energy consumption in the commercial refrigeration sector

Results for energy consumption are presented first for supermarkets only, and second for all the commercial refrigeration sector, including small stores and vending machines.

4.1.1. Results for grocery supermarkets

4.1.1.1 One typical grocery supermarket

Before deriving the calculation for California State, one typical supermarket located in the Los Angeles (LA) climatic zone is presented. Table 4.1 gives the cooling capacity distribution, for medium and low temperature systems, and for each technology of display cases and walk-in coolers.

Table 4.1. Cooling capacity in a typical grocery supermarket.

Cooling Capacity	Medium temperature	Low temperature	Total
Centralized System (kW)	233.3	125.7	359.0
Condensing Units (kW)	17.5	11.7	29.2
Stand-alone (kW)	13.0	1.4	14.5
Total (kW)	**263.8**	**138.8**	**402.7**

90% of the total cooling capacity of refrigeration equipment is the centralized system. Stand-alone display cases totalize 14.5 kW of cooling capacity, which is 3.5 % of the refrigeration capacity in the grocery supermarket.

Refrigerant charge is 965 kg including stand-alone equipment and condensing units. Centralized system is filled with around 900 kg of refrigerant, representing 94% of the total amount. The evaluation of the refrigerant charge is presented in details in section 5.2 for refrigerant emission inventory.

4.1.1.2 Energy consumption for one supermarket in LA climatic zone

Energy consumption is calculated hour by hour, for each climatic zone. Results for one supermarket in LA climatic zone are presented in Table 4.2.

Table 4.2. Annual energy consumption for 1 grocery supermarket in LA climatic zone.

Grocery supermarket (GWh/year)	Centralized System	Condensing Units	Stand-alone
Compressor for refrigeration	1.154	0.122	0.068
Auxiliary components	0.722	0.074	0.03
AC additional energy consumption	0	0	0.019
Total (GWh)	1.876	0.196	0.117
	2.189 GWh		

The energy consumption of refrigeration compressors is 1.154 GWh/year. Auxiliary components (fans, lighting, anti-sweat heaters, and defrosting heaters) totalize 0.722 GWh. As mentioned by different studies, (Wal03, Bax03, ORL04, Lit96) field tests on energy consumption measurement in a supermarket have concluded on numbers in the same order of magnitude.

4.1.1.3 Derivation to California State

Taking into account the different climatic zones, and the distribution of the stores in these zones, the energy consumption is derived to California (Table 4.3).

Table 4.3. Annual energy consumption for grocery supermarkets in California.

Grocery supermarkets in CA (GWh/year)	Centralized System	Condensing Units	Stand-alone
Compressor for refrigeration	9,033	952	522
Auxiliary components	5,583	569	233
AC additional energy consumption	0	0	125
Total (GWh)	14,616	1,521	880
	17,018 GWh		

Annual energy consumption of commercial refrigeration equipment in grocery supermarkets, including auxiliary electric loads, is 17,018 GWh in California. 86% is due to centralized systems, and 5% of the total energy consumption is due to stand-alone display cases.

4.1.2. Results including the other small stores using refrigeration equipment

Table 4.4. Annual energy consumption for commercial refrigeration sector in California, including small stores.

Total commercial ref. (GWh/year)	Centralized System	Condensing Units	Stand-alone
Compressor for refrigeration	9,033	6,210	11,120
Auxiliary components	5,583	3,561	7,389
AC additional energy consumption	0	0	2,571
Total (GWh)	14,616	9,771	21,080
	45,467 GWh		

When all types of stores are added to grocery supermarkets, the annual energy consumption grows to 45,467 GWh. The share by technology of refrigeration equipment is presented on Figure 4.1.

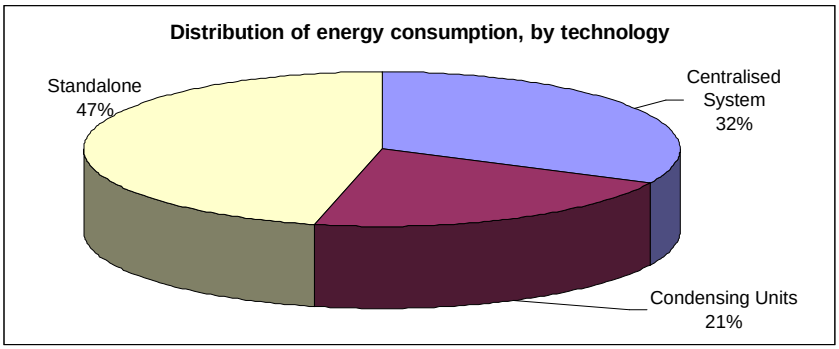

Figure 4.1. Distribution of energy consumption by technology, in commercial refrigeration.

Because of the high number of stand-alone equipment in small stores, including vending machines, and the poor efficiency of their refrigerating systems, this technology is first for energy consumption in the commercial refrigeration sector. It costs 21 TWh per year in California. Centralized systems, only used in supermarkets, are more energy efficient and represent 32% of the global energy consumption. But in terms of refrigerant bank and refrigerant emissions, the situation is reversed and centralized systems are responsible for nearly 80% of refrigerant emissions in the commercial refrigeration sector.

4.2. Technical options for energy savings

5 technical options for energy savings have been evaluated.

- **Technical option 1:** night curtain are installed on each open display case. The ambient air induction is reduced, and the thermal load on the refrigeration system decreases. Night hours have been considered from 10 pm to 4 am. Moreover, during night hours, lighting is off in all display cases.
- **Technical option 2:** all open display cases are replaced by glass door display cases, even for medium temperature products. Ambient air induction is significantly reduced (by factor 7), decreasing the thermal load of the display case and the energy consumption of the refrigeration system.
- **Technical option 3:** auxiliary components are replaced by new technologies, with improved energy efficiency (LED lighting, DC current fan, high efficiency heater…)
- **Technical option 4:** the floating head pressure control is done on every centralized system in supermarkets. Depending on the climatic zone, the impact is more or less significant on the annual energy consumption.
- **Technical option 5:** all options combined: 100% glass door + high efficiency electrical components + floating head pressure control.

4.2.1. Technical option 1: Night curtain installed on every open display case

4.2.1.1 Grocery supermarkets

Table 4.5 presents the results for one typical supermarket in LA climatic zone.

Table 4.5. Energy consumption for one grocery supermarket – Technical option 1.

Operating Mode	Night curtains		
Grocery supermarket (GWh/year)	Centralized System	Condensing Units	Stand-alone
Compressor for refrigeration	1.049	0.119	0.062
Auxiliary components	0.74	0.074	0.031
AC additional energy consumption	0	0	0.017
Total	1.789	0.193	0.11
		2.092	
Energy Savings (GWh ; %)		0.097	4.4%

Energy savings, thanks to night curtains installed on every open display case in a supermarket is 97 MWh/year, 4.4% of the energy consumption without night curtain.

Table 4.6. Energy consumption for all supermarkets in California – Technical option 1.

Operating Mode	Night curtains		
Grocery supermarkets in CA (GWh/year)	Centralized System	Condensing Units	Stand-alone
Compressor for refrigeration	8,213	929	483
Auxiliary components	5,723	576	238
AC additional energy consumption	0	0	118
Total	13,936	1,505	840
		16,281	
Energy Savings (GWh ; %)		736	4.3%

Deriving the calculation for all supermarkets in California, the energy saving associated to the installation of night curtain is 736 GWh/year.

4.2.1.2 All commercial refrigeration equipment (small stores and supermarkets) in California

Table 4.7. Energy consumption in commercial refrigeration sector – Technical option 1.

Operating Mode	Night curtains		
Total commercial ref. (GWh/year)	Centralized System	Condensing Units	Stand-alone
Compressor for refrigeration	8,213	6,111	11,056
Auxiliary components	5,723	3,580	7,398
AC additional energy consumption	0	0	2,559
Total	13,936	9,691	21,013
		44,640	
Energy Savings (GWh ; %)		827	1.8%

Considering now all refrigeration equipment, the additional savings is limited (736 to 827 GWh), because most of stand-alone equipment is already closed with glass doors and the night curtain technical option has no effect on this equipment.

4.2.2. Technical option 2: Open display cases closed with glass doors

The impact of night curtain is limited to 6 hours in the night. Moreover this period of time is one where coefficient of performance increases thanks to quite low outdoor temperatures. A radical change in display case technology could be to close all open display cases with doors, medium-temperature ones included.

4.2.2.1 Grocery supermarkets

Table 4.8. Energy consumption for one grocery supermarket – Technical option 2.

Operating Mode	Add doors		
Grocery supermarket (GWh/year)	Centralized System	Condensing Units	Stand-alone
Compressor for refrigeration	0.729	0.113	0.047
Auxiliary components	0.794	0.077	0.033
AC additional energy consumption	0	0	0.013
Total	1.523	0.19	0.093
		1.806	
Energy Savings (GWh ; %)		0.383	17.5%

Closing all the display cases, the energy savings for one year is 17.5%: 383 MWh per supermarket

Table 4.9. Energy consumption for all supermarkets in California – Technical option 2.

Operating Mode	Add doors		
Grocery supermarkets in CA (GWh/year)	Centralized System	Condensing Units	Stand-alone
Compressor for refrigeration	5,703	883	366
Auxiliary components	6,141	597	256
AC additional energy consumption	0	0	85
Total	11,844	1,480	708
		14,032	
	Energy Savings (GWh ; %)	2,986	17.5%

Deriving the scenario to California, the energy saving is nearly 3 TWh per year.

4.2.2.2 All commercial refrigeration equipment (small stores and supermarkets) in California

Table 4.10. Energy consumption in commercial refrigeration sector – *Technical option 2.*

Operating Mode	Add doors		
Total commercial ref. (GWh/year)	Centralized System	Condensing Units	Stand-alone
Compressor for refrigeration	5,703	5,846	10,866
Auxiliary components	6,141	3,636	7,423
AC additional energy consumption	0	0	2,506
Total	11,844	9,483	20,795
		42,122	
	Energy Savings (GWh ; %)	3,345	7.4%

Most of stand-alone equipment is already equipped with glass doors. The impact on energy savings is significant mainly in supermarkets. Nevertheless, for the complete commercial refrigeration sector, the energy savings are 7.4% compared to the base line.

4.2.3. Technical option 3: Cabinet lighting, anti-sweat heater and ventilation: low energy consuming technologies

4.2.3.1 Grocery supermarkets

Table 4.11. Energy consumption for one grocery supermarket – Technical option 3.

Operating Mode	Eco for auxiliary components		
Grocery supermarket (GWh/year)	Centralized System	Condensing Units	Stand-alone
Compressor for refrigeration	1.064	0.107	0.062
Auxiliary components	0.532	0.05	0.023
AC additional energy consumption	0	0	0.017
Total	1.596	0.157	0.102
		1.855	
	Energy Savings (GWh ; %)	0.334	15.3%

Auxiliary components are energy consumers, first by their own electrical load, and second by the additional heat load to the display case. This additional heat load increases the cooling capacity of the refrigeration system, and its energy consumption.

Improved technologies are available to retrofit lighting, ventilation, and anti-sweat heaters. Technical option 3 gives the range of energy savings if all auxiliary components were replaced.

Table 4.12. Energy consumption for all supermarkets in California – Technical option 3.

Operating Mode	Eco for auxiliary components		
Grocery supermarkets in CA (GWh/year)	Centralized System	Condensing Units	Stand-alone
Compressor for refrigeration	8,323	833	479
Auxiliary components	4,117	384	180
AC additional energy consumption	0	0	114
Total	12,440	1,217	773
	14,430		
Energy Savings (GWh ; %)		2,588	15.2%

Energy savings thanks to high efficiency auxiliary components is around 15% compared to the base line. In California, the annual savings are 2.6 TWh for this technical option.

4.2.3.2 All commercial refrigeration equipment (small stores and supermarkets) in California

Table 4.13. Energy consumption in commercial refrigeration sector – Technical option 3.

Operating Mode	Eco for auxiliary components		
Total commercial ref. (GWh/year)	Centralized System	Condensing Units	Stand-alone
Compressor for refrigeration	8,323	5,495	9,666
Auxiliary components	4,117	2,345	5,655
AC additional energy consumption	0	0	2,219
Total	12,440	7,841	17,539
	37,821		
Energy Savings (GWh ; %)		7,647	16.8%

Technical option 3 is applied to each type of display cases. Stand-alone equipment can benefit of the technical changes. Deriving the scenario to California, for commercial refrigeration sector, energy savings for one year are 7.6 TWh, nearly 17% of the base line consumption.

4.2.4. Technical option 4: Floating head pressure on centralized systems

4.2.4.1 Grocery supermarkets

Table 4.14. Energy consumption for one grocery supermarket – Technical option 4.

Operating Mode	Floating head pressure (Eco)		
Grocery supermarket (GWh/year)	Centralized System	Condensing Units	Stand-alone
Compressor for refrigeration	1.08	0.11	0.068
Auxiliary components	0.722	0.074	0.03
AC additional energy consumption	0	0	0.019
Total	1.802	0.184	0.117
	2.103		
Energy Savings (GWh ; %)		0.086	3.9%

Table 4.14 presents the energy consumption for one supermarket in LA climatic zone, when floating head pressure control is activated. The interest of this control, and the energy savings associated are strongly dependent on the temperature changes during the year. In a climatic zone where maximum and minimum temperatures are not far from each other, the interest of a floating head pressure is limited. In LA climatic zone, the energy saving is 3.9%.

Table 4.15. Energy consumption for all supermarkets in California – Technical option 4.

Operating Mode	Floating head pressure (Eco)		
Grocery supermarkets in CA (GWh/year)	Centralized System	Condensing Units	Stand-alone
Compressor for refrigeration	8,260	840	522
Auxiliary components	5,583	569	233
AC additional energy consumption	0	0	125
Total	13,843	1,408	880
	16132		
Energy Savings (GWh ; %)		886	5.2%

The derivation of energy consumption in California, taking into account 8 climatic zones, give a better result with 5.2 % of energy savings thanks to the floating head pressure control.

4.2.4.2 All commercial refrigeration equipment (small stores and supermarkets) in California

Table 4.16. Energy consumption in commercial refrigeration sector – Technical option 4.

Operating Mode	Floating head pressure (Eco)		
Total commercial ref. (GWh/year)	Centralized System	Condensing Units	Stand-alone
Compressor for refrigeration	8,260	5,478	11,120
Auxiliary components	5,583	3,561	7,389
AC additional energy consumption	0	0	2,571
Total	13,843	9,039	21,080
	43,963		
Energy Savings (GWh ; %)		1,505	3.3%

Floating head pressure cannot be applied to stand-alone equipment, which are located in an air conditioned area. The global impact of this technical option, on complete commercial refrigeration sector is lowered to 3.3%, representing 1.5 TWh per year.

4.2.5. Technical option 5: All options combined

The last scenario is the combination of three factors: closing all open display cases, low energy consuming components, and floating head pressure.

4.2.5.1 Grocery supermarkets

In a typical supermarket, located in LA climatic zone, the annual energy savings is 37%, meaning 811 MWh less consumed (see Table 4.17).

Table 4.17. Energy consumption for one grocery supermarket – Technical option 5.

Operating Mode	Add doors + eco Aux + FHP		
Grocery supermarket (GWh/year)	Centralized System	Condensing Units	Stand-alone
Compressor for refrigeration	0.587	0.087	0.041
Auxiliary components	0.575	0.052	0.025
AC additional energy consumption	0	0	0.011
Total	1.162	0.139	0.077
	1.378		
Energy Savings (GWh ; %)		0.811	37.0%

Table 4.18. Energy consumption for all supermarkets in California – Technical option 5.

Operating Mode	Add doors + eco Aux+Eco FHP		
Grocery supermarkets in CA (GWh/year)	Centralized System	Condensing Units	Stand-alone
Compressor for refrigeration	4,489	669	317
Auxiliary components	4,448	403	195
AC additional energy consumption	0	0	73
Total	8,937	1,073	585
	10,594		
Energy Savings (GWh ; %)		6,423	37.7%

For all supermarkets in California, the maximum energy savings are 6.4 TWh per year when all technical options are applied.

4.2.5.2 All commercial refrigeration equipment (small stores and supermarkets) in California

Table 4.19. Energy consumption in commercial refrigeration sector – Technical option 5.

Operating Mode	Add doors + eco Aux+Eco FHP		
Total commercial ref. (GWh/year)	Centralized System	Condensing Units	Stand-alone
Compressor for refrigeration	4,489	4,516	9,403
Auxiliary components	4,448	2,396	5,677
AC additional energy consumption	0	0	2,152
Total	8,937	6,911	17,231
		33,079	
Energy Savings (GWh ; %)		12,388	27.2%

For the complete commercial refrigeration sector, the maximum energy savings is 12.4 TWh per year, totalizing 27% of the base line consumption. Global annual energy consumption is evaluated at 33 TWh, and stand-alone equipment consumes more than half of this value.

4.2.6. Summary

4.2.6.1. Energy savings in supermarkets

Figure 4.2 presents the comparison of the energy savings, related to the base line, for different technical options applied to grocery supermarkets in California.

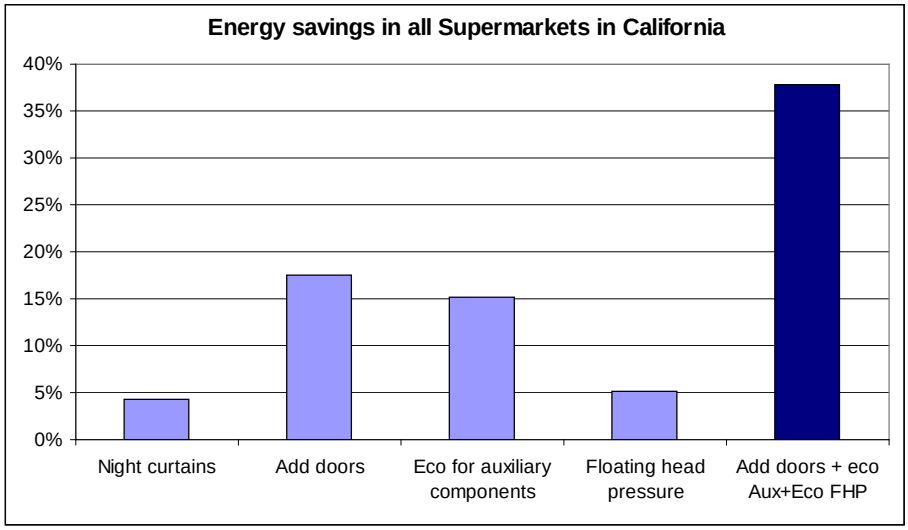

Figure 4.2. Energy savings / technical options applied in Californian supermarkets.

- Night curtains installed on open display cases have a limited impact on the energy consumption. Night period is short in time in supermarkets (6 hours only) and during this period, the coefficient of performance of the refrigerating system is improved thanks to quite low outdoor temperature, lowering the condensation temperature by the same time.
- Floating head pressure control is interesting in climatic zones with wide temperature differences along the year. Near the coast, where the temperature is more stable, the interest of this system is limited.
- In supermarkets, most of display cases are open, and heat loads due to air induction is around 70% of the total load. Closing the display cases permits to decrease the cooling

capacity and the energy consumption of the compressor racks. 17.5% of energy saving are possible with this change in technology.

- The other elements for energy consumption are the auxiliary components. High energy efficiency technologies exist and could reduce by 15% the energy consumption.
- All options applied together lead to 37% of energy savings in supermarkets

4.2.6.2. Energy savings in small stores (condensing units and standalone equipment)

Figure 4.3 presents the comparison of the energy savings, related to the base line, for different technical options applied to small stores in California. Stand-alone equipment and condensing units are the two refrigeration technologies used in small stores.

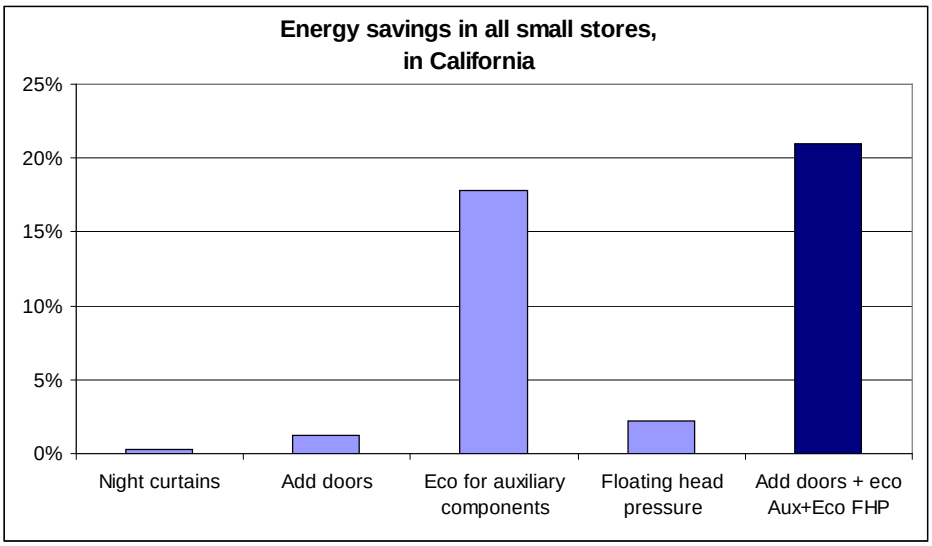

Figure 4.3. Energy savings / technical options applied in Californian small stores.

Most of stand-alone equipment is closed with glass doors (vending machines for example). Options of night curtains and closing the display cases are not applied on this stand-alone equipment. The impact on energy consumption is low.

Progresses to save energy on stand-alone equipment must be focused on auxiliary components and compressor efficiency, which is very poor today.

4.2.6.3. Energy savings in commercial refrigeration sector, all types of stores

Figure 4.4 presents the comparison of the energy savings, related to the base line, for different technical options applied to all types of stores using refrigeration equipment in California, whatever the technology.

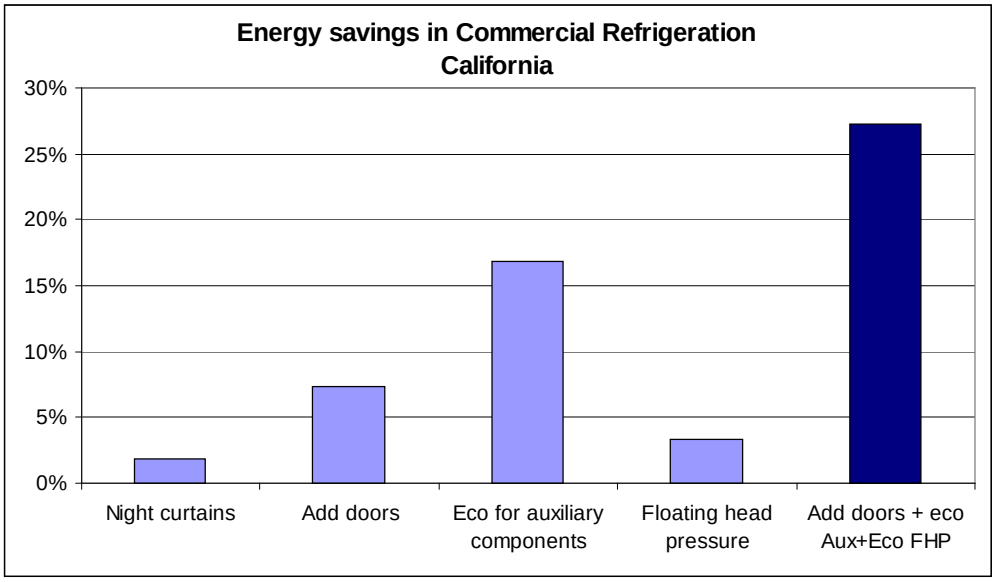

Figure 4.4. Energy savings / technical options applied in commercial sector.

Figure 4.5 presents for technical option 5, where all technical options are applied, the distribution in energy consumption by technology of refrigerating system.

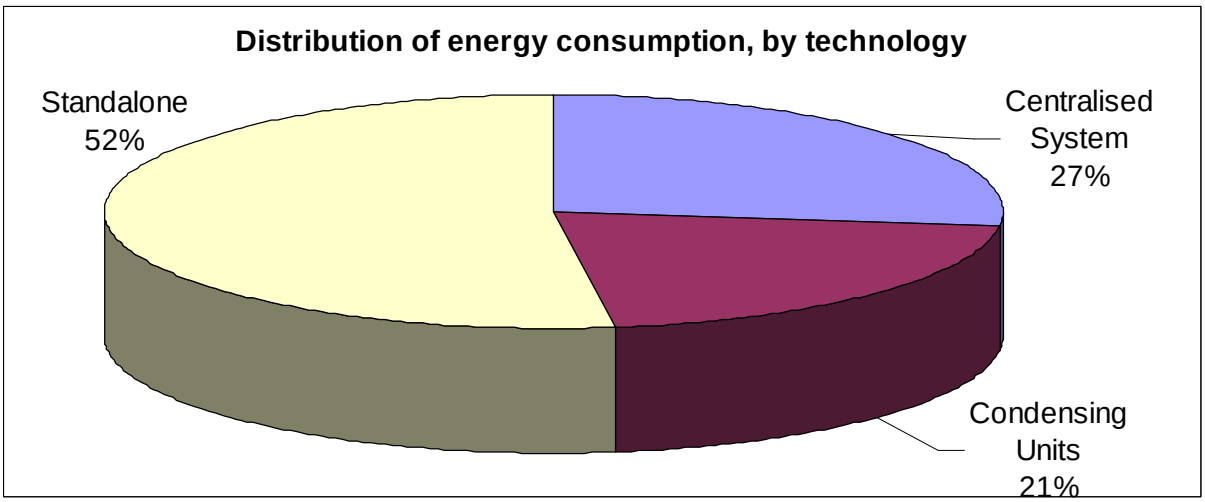

Figure 4.5. All technical options combined: energy consumption distribution.

It appears clearly that stand-alone equipment, by their high numbers in every type of stores, consumes more than 50% of the total energy consumption in commercial refrigeration sector. The poor efficiency of small hermetic compressor, and sometime heat exchanger designs not adapted, lead to a poor cycle efficiency (25%). Technical options to reduce energy consumption are more effective for centralized system. In technical option 5, the energy consumption of centralized systems is cut by nearly 40% compared to the base line.

5. Refrigerant inventory and emissions

5.1 Method of calculation

The calculation method is described in Annex 1.

5.2 Database for commercial refrigeration in California

The bank of refrigerants contained in grocery supermarkets is calculated based on the last 30 past years. The bank is the cumulated market of refrigerants filled in new refrigerating systems year after year, taking into account the average lifetime of the store (30 years for a supermarket) and the lifetime of the refrigeration system (15 years for centralized systems) before remodelling.

Calculations are performed from year 1990 to 2004, and forecasts are simulated until 2020. In order to initiate calculations as of 1990, the database has to include data from 1960 to 2020, assuming an average 30-year lifetime of grocery supermarkets and other small stores.

5.2.1 Grocery supermarkets

5.2.1.1 Number of stores in California

The numbers of grocery supermarkets in California from 1960 to 2020 have to be evaluated. Some statistical data coming from the US Bureau of Census have been used. Depending on the source, different numbers for a given year have been found, which are not coherent. The definition of supermarket store reported in the US Bureau of Census is as follows:

"Supermarkets and other general-line grocery stores: Establishments commonly known as supermarkets, food stores, grocery stores, and food warehouses, primarily engaged in the retail sale of a wide variety of grocery store merchandise. Customers normally make large, volume purchases from these stores."

Numbers of grocery supermarkets in State of California are available for a few years (1992, 1997, 2002, 2004). More data are available for USA, and can be helpful to evaluate California numbers, by using ratios based on GDP and population.Those rations have been used to complete the database back to 1960.

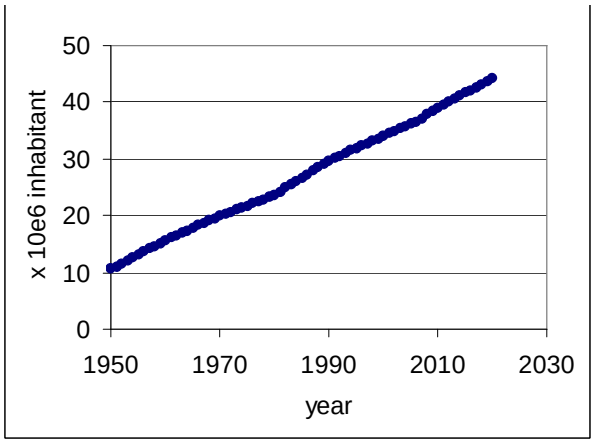

Figure 5.1. Population growth in California.

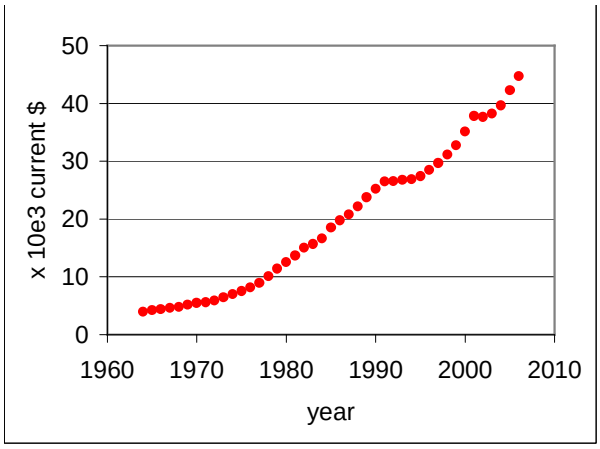

Figure 2.2. GDP/inhab. growth in California.

A ratio giving the evolution of the number of supermarkets and the population has been calculated with the available data and has also been correlated to the GDP to inhabitant ratio. Some assumptions have been established to derive the evolution of the number of supermarkets from 1960 to 2004.

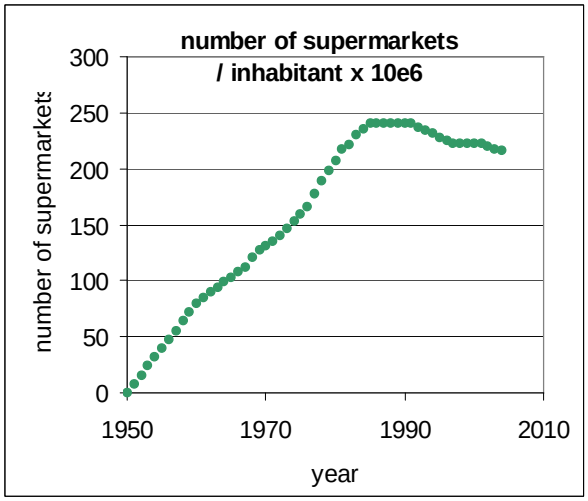

Figure 5.3. Population growth in California.

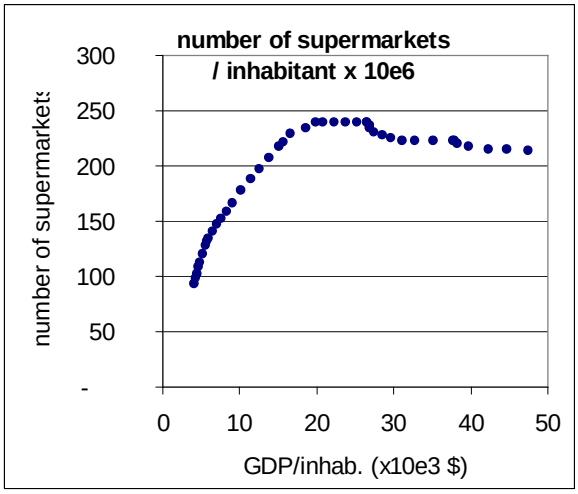

Figure 5.4. GDP/inhab. growth in California.

Figure 5.3 presents the evolution of the number of supermarkets per million of inhabitants. This ratio, established from the available data, indicates that in 1990 there were 240 grocery supermarkets for 1 million inhabitants in California. This ratio has decreased slightly in 2004, because of the population growth: 220 supermarkets per million of inhabitants in 2004.

First supermarkets have been built after the second world war. 1950 has been assumed as the initial year.

$$\alpha = \frac{supermarkets}{inhabitants} \cdot 10^6 \qquad [5.1]$$

Taking into account the GDP/inhabitant ratio, a second ratio has been established (see Figure 5.4) which gives the evolution of the number of supermarkets / million of inhabitants related to the GDP/inhabitant. Two cases have been considered: when the economy is growing rapidly (year 1950 to 1980), ratio α, defined in [1.1], is proportional to the GDP/inhabitant. When GDP/inhabitant has reached 18,000 $/inhabitant, a new trend is defined showing no link between the economical growth and the number of supermarkets per inhabitant.

When no data are available from statistic source, ratio α is used to determine the number of supermarkets in California.

From the evolution of the supermarket numbers in California, the openings of new stores per year can be determined. The average lifetime for a supermarket store is supposed to be 30 years before renewing.

An average area has been determined, thanks to the field survey in 54 supermarkets in California. Taking into account the distribution of the main brand names and the typical layout of their supermarkets, the average area of grocery supermarkets in California is 2,500 m^2. This

area is only the surface dedicated to food and beverage, refrigerated or not. Clothes, and other non-food items are not considered in the calculation of the average sales area.

According to this principle, large supermarkets with a total average area of 8,500m^2 are integrated with grocery supermarket numbers, considering only their food retail area, which is similar to a grocery in terms of refrigeration equipment.

Figure 5.5 presents the evolution of the number of grocery supermarkets in California, from 1950 to 2004.

Data from UC bureau of census gives a total number of 7,500 grocery supermarkets in California in the '90s.

The period from 1970 to 1990 is the period where the growth in supermarket openings is the highest. This growth is linked to the population growth (see Figure 5.1) and the ratio α.

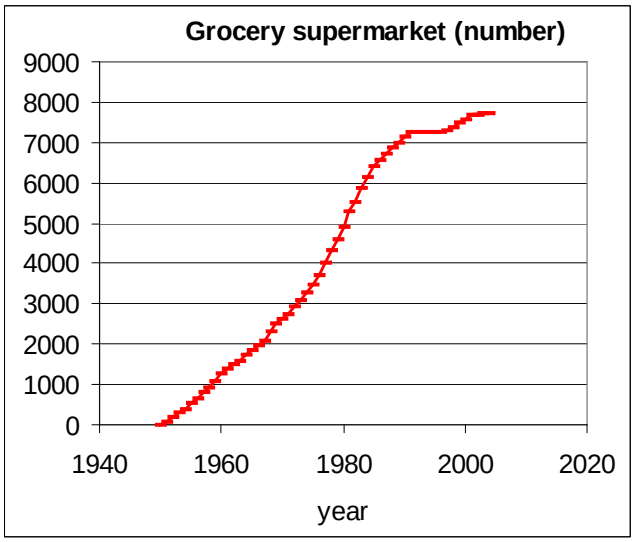

Figure 5.5. Supermarkets in California.

5.2.1.2 Average area and refrigerant charge

The average area is 2,500 m^2, but this average area has changed during the last 50 years.

It is assumed that the average sales area dedicated to food has been multiplied by factor 2 in 30 years.

Figure 5.6 presents the evolution of the average area of grocery supermarkets as of 1950.

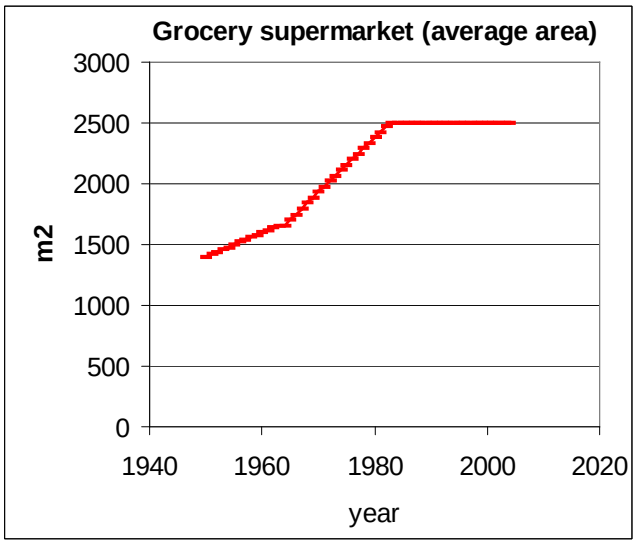

Figure 5.6. Average area of grocery supermarket.

The refrigerant charge has been determined from the calculation of the cooling capacity of the centralized refrigeration system. The typical layout of the grocery supermarket has been

established after the field survey. Each and every display case has been characterized by its cooling capacity and temperature level. Ratios of refrigerant charge per kW of cooling capacity are known for the technology of centralized system. Table 5.1 summarizes the results of calculations used for energy consumption calculations. Table 5.2 gives the ratio of refrigerant charge / cooling capacity for the different technologies of refrigeration systems met in a grocery supermarket.

Table 5.1. Cooling capacity of each refrigeration system for a typical grocery supermarket.

Cooling Capacity	Medium temperature	Low temperature	Total
Centralized System (kW)	233.3	125.7	359.0
Condensing Units (kW)	17.5	11.7	29.2
Stand-alone (kW)	13.0	1.4	14.5
Total	**263.8**	**138.8**	**402.7**

Table 5.2. Ratios for refrigerant charge.

Refrigerant charge / Cooling Capacity	Medium temperature	Low temperature
Centralized System in direct expansion	2 kg/kW	3.5 kg/kW
Centralized System with secondary loop	0.8 kg/kW	1.2 kg/kW
Condensing Units	1.4 kg/kW	2.4 kg/kW

Stand-alone equipment are not included in this table because the information for the refrigerant charge is known (from the manufacturer) for each type of display case considered.

Using the cooling capacity and the refrigerant charge ratios, the total refrigerant charge for a supermarket is determined. Table 5.3 gives the results. Currently in California, it is considered that the use of secondary loop systems or CO_2 cascade is not significant enough to be considered. On the contrary, forecasts will be done in order to evaluate the impact of a widespread use of secondary loop systems on refrigerant emissions.

Table 5.3. Refrigerant charge in a grocery supermarket.

Refrigerant charge	Medium temperature	Low temperature	Total
Centralized System	466 kg	440 kg	906 kg

During the field survey, in most of supermarket stores visited, it was impossible to visit the machinery room. Nevertheless some machinery rooms of a few supermarkets have been visited with the store manager. A first cross checking is possible with refrigerant charge indicated in one of those supermarkets. For confidentiality reasons, the brand name and the location of the reference supermarket are not mentioned. The compressor racks for medium temperature display cases and storage room were charged with 900 lb of R-507A. The compressor racks for low temperature equipment were charged with the same amount of refrigerant: 900 lb. This supermarket is representative of the typical grocery supermarkets described (see Section 5.1) and the refrigerant charge is 2 x 450 kg, nearly the same (see Table 5.3) as the one defined using the refrigerant ratio (see Table 51.2) and the cooling capacity (see Table 5.1). Those ratios have been elaborated on a number of field surveys made in the US and in Europe.

For calculations in RIEP, the average refrigerant charge (906 kg) is related to the grocery surface (2,500 m^2) and a coefficient of refrigerant charge per square meter is defined. This

coefficient, 0.36 kg/m^2 for year 2004, is the expression of the share of refrigerated (and frozen) food in a grocery supermarket. The change in food consumption habits during the last 50 years had an impact on the refrigeration ratio for a given sales area.

The assumption is made that the ratio of refrigerated sales area has increased by 50 % between 1960 and 1990 (see Figure 5.7).

In parallel, the average area of grocery supermarket was increasing (see Figure 5.6), meaning that the refrigerant charge in a typical supermarket was 400 kg in 1960, and is of 906 kg today.

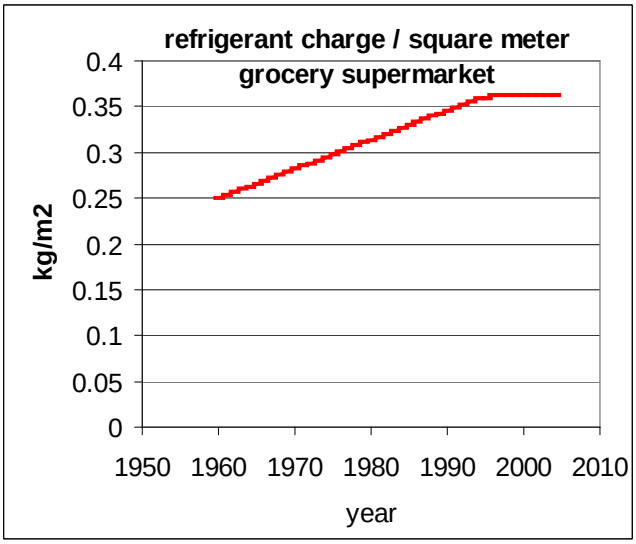

Figure 5.7. Refrigerant charge ratio (kg/m^2).

5.2.1.3 Refrigerant emission rates

The emissions of refrigerants are of two types: fugitive emissions during all the lifetime of the refrigeration equipment, including accidental emissions (rupture of pressure valve or liquid line), and end-of-life emissions when refrigerant recovery is not performed carefully (if performed).

The fugitive emission rate is an average value taking into account refrigerant losses of different types. This emission rate is established based on refrigerant annual consumption for a given store: the refrigerant quantity refilled annually in the system compensates all the refrigerant emissions.

Emission rate is estimated at **30 % per year** for centralized systems. This value is a conservative one, emissions could vary from 10 to 30 % [GAG97], [IPC05], [TOC06] but values have to be confirmed along the years. Complementary data are needed but are not easily disclosed by Commercial chains.

Refrigerant recovery at end of life has increased in the past 10 years due to the phase-out of CFCs. Figure 5.8 presents the refrigerant recovery efficiency evolution assumed for RIEP calculations.

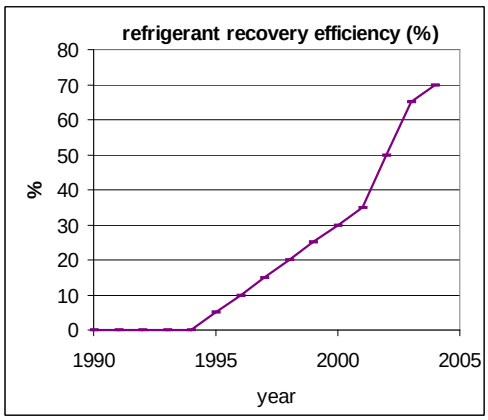

Figure 5.8. Refrigerant recovery efficiency at end of life.

5.2.1.4 Refrigerants in use

The refrigerant market share follows the regulations. Since 1995, CFCs are no longer used in new refrigeration systems. CFCs have been replaced first by HCFC blends for retrofitting of existing systems and in new systems. HCFCs will be banned in new refrigeration systems as of 2010. In the US, HFCs start to be used in centralized systems in 1999. Refrigerant shares are presented in Figure 5.9.

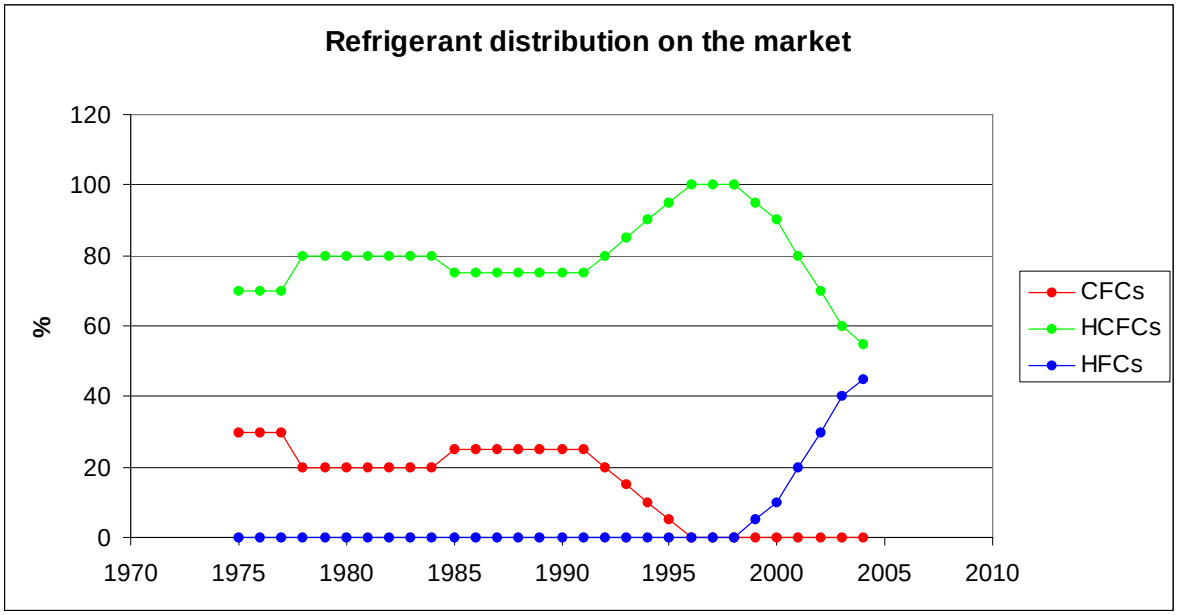

Figure 5.9. Refrigerant market shares (new equipment and remodelling).

Remodelling of the refrigeration system is supposed to be done at mid lifetime of the store, after 15 years. After 1995, this step is typically the time to retrofit CFCs refrigerant to HCFC blends. Retrofit of CFCs is supposed to be achieved in 2004.

5.2.2 Small stores

5.2.2.1 Number of stores in California

US bureau of Census data have been mainly used to evaluate the number of the different stores in California since 1960.

The same methodology is applied to each type of store when statistical data are not available. For small stores like bakeries, butcheries, fishmongers, and convenience stores another point has been considered: these small stores were common before the growth of supermarkets. For the last 20 years, the numbers of these small stores has been decreasing. They are replaced by larger sales area stores such as mini-markets, and supermarkets.

Stores, where refrigeration equipment is used, are summarized in Table 5.4. Those stores been described in Section 2 presenting energy consumption in commercial refrigeration.

Table 5.4. Stores reported in the data base.

Type of stores	Number of stores in 2004
Grocery stores (food dedicated)	7,737
Minimarkets	6,625
Pharmacies	4,846
Convenience stores	2,317
Liquor stores	3,466
Butcheries, Pork-butcheries	763
Fishmonger stores	184
Bakeries and Pastries	5,512
Small size Gas Stations	5,453
Large size Gas Stations	1,818
Hotels	5,458
Motels	5,817
Bars and Restaurants	66,306
Stand-alone equipment studied independently of their location of use	**Number of units in use in 2004**
Carbonated Soda Fountains	23,040
Vending machines	1,268,830

5.2.2.2 Refrigerant charge and type of refrigerant

The field survey has allowed identifying the typical layout of each small store using refrigerating equipment. This refrigerating equipment is not connected to a centralized system in the machinery room like in supermarkets. Stand-alone equipment, display cases and walk-in cooler connected to one or several condensation units are the typical technologies met in those stores. Table 5.5 presents the typical refrigerant charge evaluated for each type of store, based on the field survey.

Table 5.5. Refrigerant charges.

Type	Refrigerant Charge in stand alone equipments (kg)	Refrigerant Charge in condensing units (kg)
Bakeries	2.65	4.3
Bars & restaurants	2.5	19
Vending machines	0.3	-
Butcheries	0.3	9.7
Center gas stations	3.45	15.8
Convenience stores	4.9	29.2
CSD fountains	0.3	-
Fishmonger stores	0.6	13.4
Grocery supermarkets	7.4	56.5
Hotels	3.4	19.5
Liquor stores	5.8	16.8
Minimarkets	9.3	101.7
Motels	1.45	0
Pharmacies	2.35	37.3
Small gas stations	0.8	3.1

Note: Grocery supermarkets are considered in the list of stores because the use of stand-alone equipment in the sales area is significant. Moreover some walk-in coolers are not connected to the centralized system, but run with independent condensing units.
Stand-alone equipment and condensing units are not similar to centralized system in terms of energy efficiency, but also in terms of refrigerant type and refrigerant emissions. In order to be more accurate in the evaluation of refrigerant emissions, refrigerating equipment has been sorted and calculated by technology: stand alone equipment, condensing unit, and centralized system.

5.2.2.3 Refrigerant emission rate

Stand-alone equipment is characterized by short refrigerant circuit, the compressor and the condenser being integrated in the cabinet. Tube and fittings are usually brazed permitting to reduce fugitive emissions. Because of a small unitary refrigerant charge (less than 2 kg in most cases), refrigerant recovery at end of life is not done on stand-alone equipment.

Condensing units are more emissive systems. The charge of refrigerant can be significant, for example in mini-markets, where the number of display cases is high. Recovery at end of life should be improved.

Table 5.6. Emission rates and recovery efficiency.

Type	Emission rate (%)	Recovery efficiency (%)
Stand alone equipment	1	0
Condensing units	15	30

5.3 Refrigerant inventory from 1990 to 2004

5.3.1 Refrigerant demand

The refrigerant demand is the addition of refrigerant needs for servicing of all refrigerating systems in use, and the refrigerant needs for first charge of new refrigerating systems. Figures 5.10 to 5.12 present the refrigerant demand, by type, respectively for centralized systems, condensing units, and stand-alone equipment.

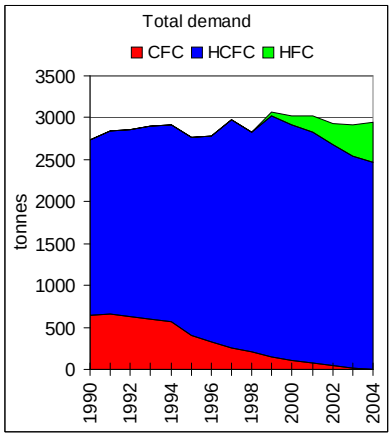

Figure 5.10. Refrigerant demand in centralized system (grocery supermarkets).

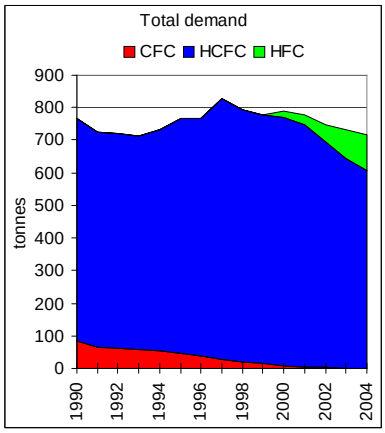

Figure 5.11. Refrigerant demand in condensing unit systems.

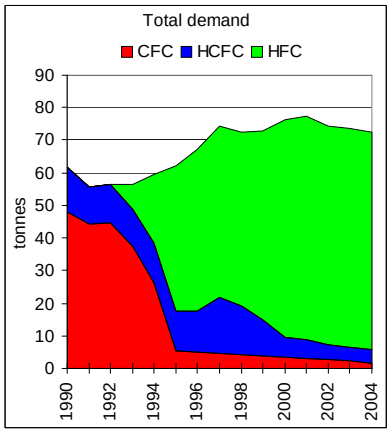

Figure 5.12. Refrigerant demand in stand-alone equipment.

Depending on the technology (centralized, condensing unit, stand alone) the refrigerant demand is significantly different. As indicated on Figure 5.14, centralized systems with 3,000 tonnes per year, represent nearly 80% of the refrigerant demand in the commercial refrigeration sector.

Refrigerant demand for stand-alone equipment is mainly for new equipment sold on the market, because servicing needs for this technology are low. In terms of refrigerant distribution, HFC are mainly dedicated to stand-alone equipment. In other technologies (centralized and condensing units) refrigerant needs are high for servicing, because of high emission rates of these systems (30% in centralized systems and 15% in condensing units).

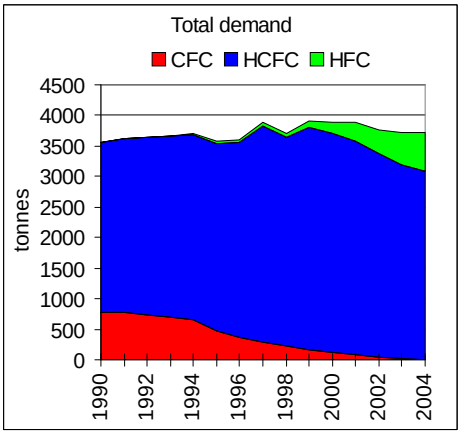

Figure 5.13. Refrigerant demand in commercial refrigeration.

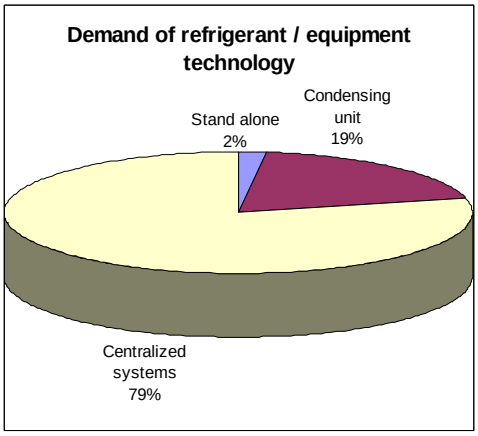

Figure 5.14. Distribution by refrigeration equipment technology.

HCFC demand, mainly R-22, represents 80% of the refrigerant market. 3,000 tonnes of HCFCs are used in the commercial refrigeration sector in 2004.

5.3.2 Refrigerant bank charged in refrigeration equipment

The refrigerant bank is the total amount of refrigerant charged in all refrigeration systems in use whatever their vintage, in commercial sector. Figures 5.15 to 5.17 present the refrigerant bank, by family, respectively in centralized systems, condensing units, and stand-alone equipment.

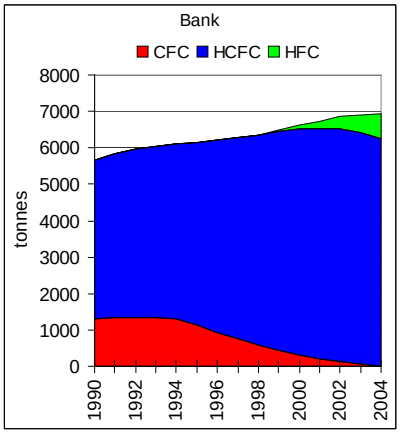

Figure 5.15. Refrigerant bank in centralized systems (grocery supermarkets).

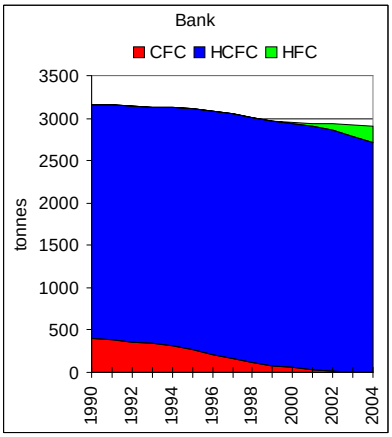

Figure 5.16. Refrigerant bank in condensing unit systems.

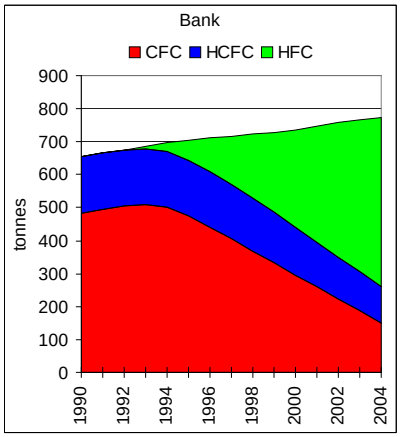

Figure 5.17. Refrigerant bank in stand-alone equipment.

Bank of refrigerants in centralized systems in supermarkets is nearly 7,000 tonnes in 2004 in California, and 90% of this bank are HCFCs. The introduction of HFC on the market, in new equipment, has begun in 1999.

In condensing units, the bank of refrigerant is around 3,000 tonnes, but is not growing any longer.

Stand alone equipment, working with small refrigerant unitary charges, were filled mainly with R-12 before 1992. No retrofit is performed on those systems. In 2004, the remaining bank of R-12 in stand-alone equipment is estimated at 200 tonnes. R-12 has been replaced by R-134a, which is in the main refrigerant in use, today, in stand-alone equipment.

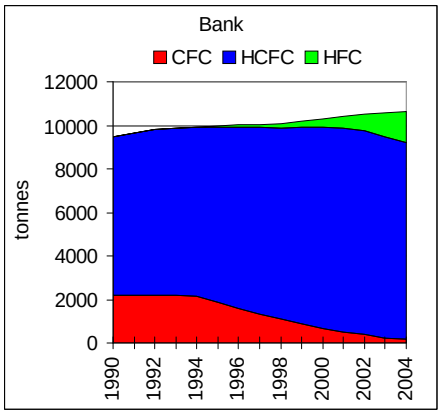

Figure 5.18. Refrigerant bank in commercial refrigeration.

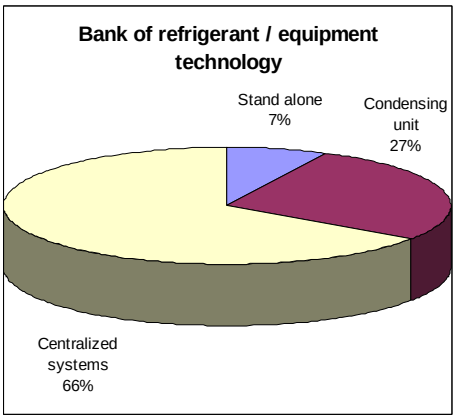

Figure 5.19. Distribution by refrigeration equipment technology.

Total refrigerant bank in the commercial refrigeration sector is estimated around 10,700 tonnes in 2004, mainly constituted of HCFCs.

5.3.3 Refrigerant emissions

Emissions represent both fugitives losses, and end of life emissions. Figures 5.20 to 5.22 present the refrigerant emissions, by type, respectively from centralized systems, condensing units, and stand-alone equipment.

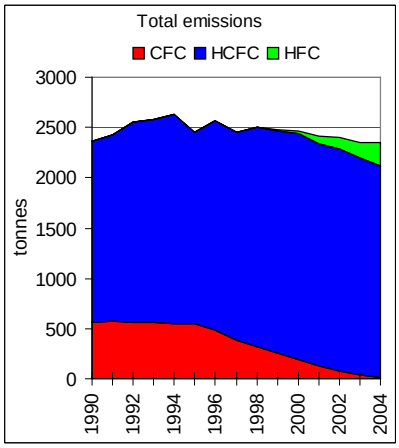

Figure 5.20. Refrigerant emissions in centralized systems (grocery supermarkets.)

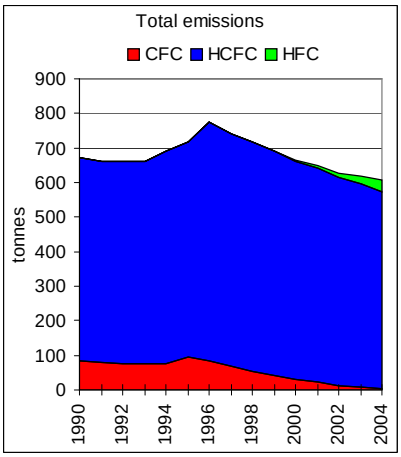

Figure 5.21. Refrigerant emissions in condensing unit systems.

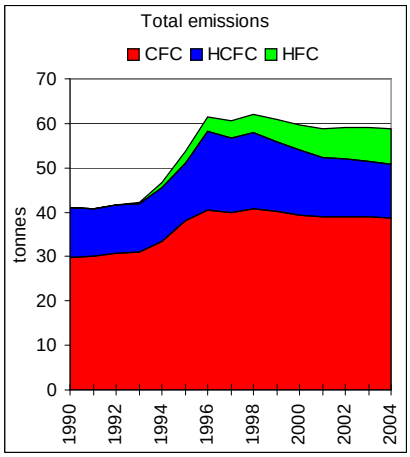

Figure 5.22. Refrigerant emissions in stand-alone equipment.

Lifetime of these refrigeration systems is estimated to be 15 years. For centralized systems, the real lifetime of the system is usually longer. But from1990 to 2020, many retrofit operations are and will be done, because first of the phase-out of CFCs, then followed by the phase out of HCFCs. After 15 years, the system is supposed to be renewed, which means, most of the time, refrigerant handling and emissions associated to this operation.

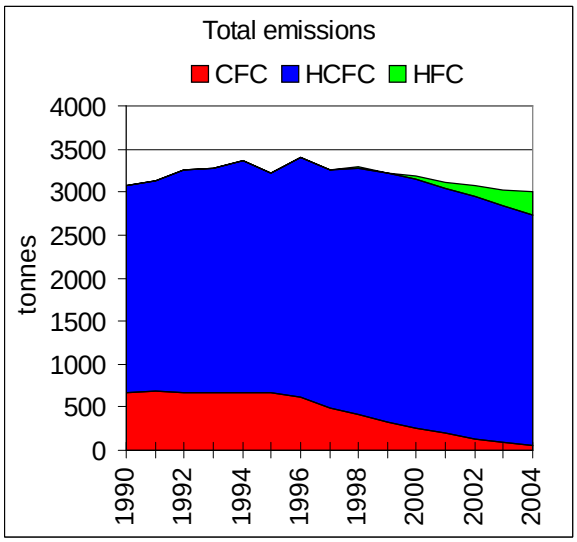

Figure 5.23. Refrigerant emissions in commercial refrigeration.

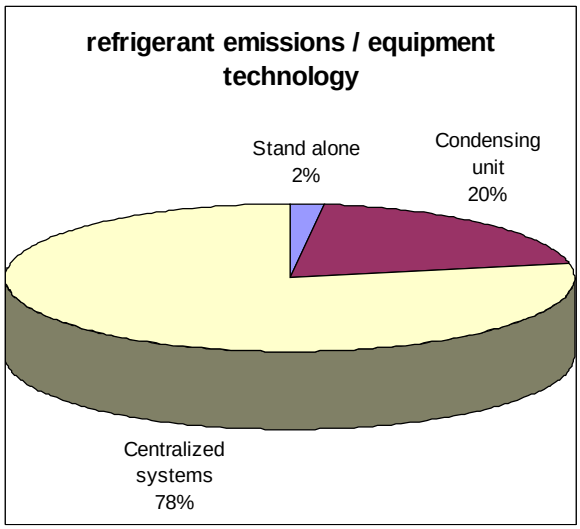

Figure 5.24. Distribution by refrigeration equipment technology.

5.3.4 CO_2 equivalent emissions of refrigerants

Refrigerant emissions expressed in CO_2 equivalent are based on GWP values from the 2nd Assessment Report. Figures 5.25 to 5.27 present the refrigerant emissions in CO_2 equivalent values, respectively from centralized systems, condensing units, and stand-alone equipment.

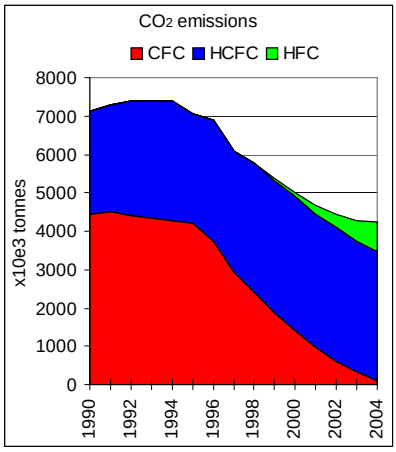

Figure 5.25. CO_2 emissions in centralized systems (grocery supermarkets).

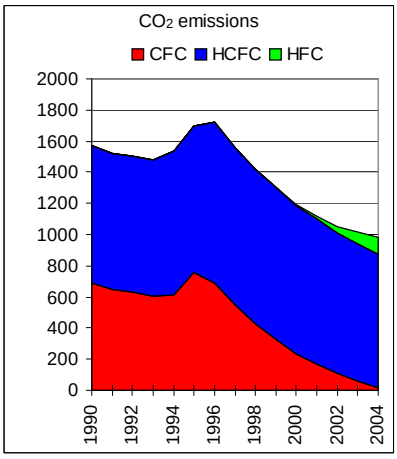

Figure 5.26. CO_2 emissions in condensing unit systems.

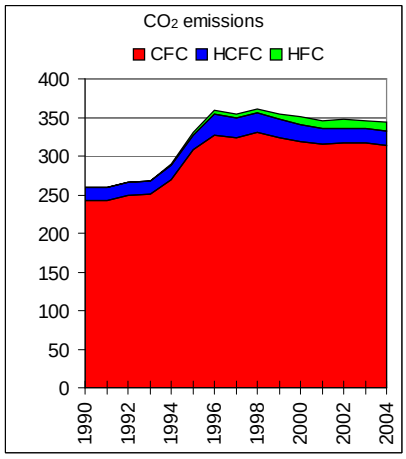

Figure 5.27. CO_2 emissions in stand-alone equipment.

From 1990 to1995, CFC emissions represent around 20% of refrigerant emissions in centralized systems in supermarkets. Because of its high GWP (GWP R-12: 8600), emissions of this CFC represent more than 55% of CO_2 equivalent emissions.

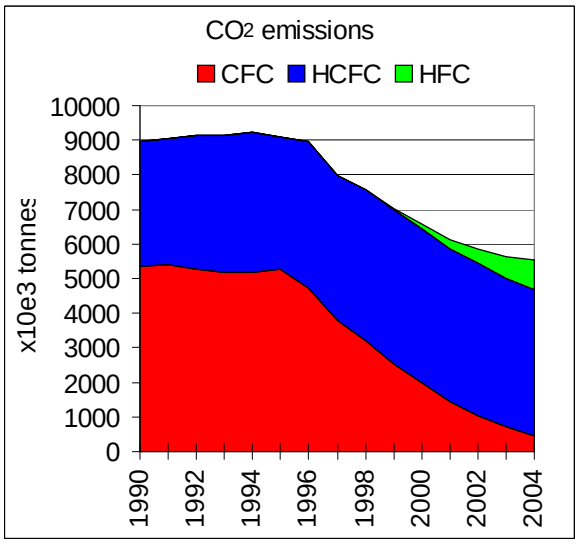

Figure 5.28. CO_2 emissions in commercial refrigeration.

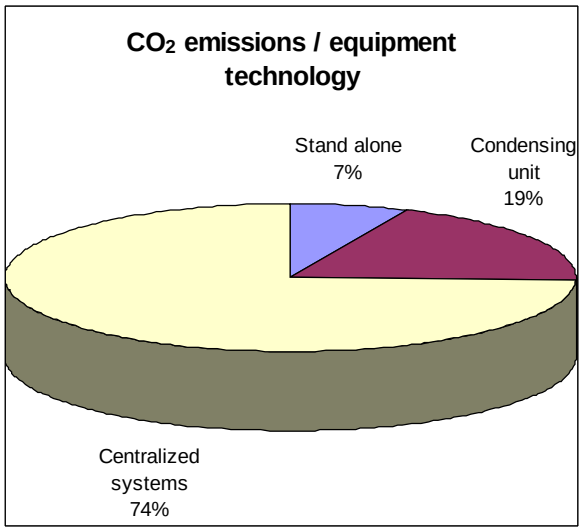

Figure 5.29. Distribution by refrigeration equipment technology.

Total CO_2 equivalent emissions have been decreasing since 1995, because of R-12 phase out. In 2004, CO_2 equivalent emissions in commercial refrigeration are more than 5 million tonnes CO_2. Centralized systems in supermarkets represent 74% of those emissions.

5.4 Scenario and projections to 2020

5.4.1 Assumptions for scenarios

Three scenarios have been simulated to evaluate the impact of technical changes and policies on refrigerants.

Scenario 1: business as usual (BAU)
No significant changes are considered. The regulation organizing the phase-out of HCFCs after 2010 is taken into account. The use of secondary loop systems is not accelerated. Emission rate and recovery efficiency are kept at the same level. There is no significant effort to retrofit R-22 systems.

Scenario 2: large introduction of secondary loop systems
Indirect refrigeration systems decrease the refrigerant charge and minimizing potential refrigerant leakage. Indirect systems have many forms: complete indirect system, partial indirect system, and indirect cascade system. Water solutions of glycols, alcohols and brines have long been used as secondary refrigerants. Other very promising developments are phase-change secondary refrigerant mainly CO_2.

Starting in 2008, secondary loop systems are progressively introduced. The use of CO_2 as secondary fluid is technically possible for both medium and low temperature systems. For now, this technology is only used for low temperature systems, where the pressure is limited to 1.2 MPa in operating conditions.

The assumptions made for the simulations in scenario 2 are as follows:
- 75% of new refrigeration systems are built with a CO_2 secondary loop for low temperature applications
- 50% of new refrigeration systems dedicated to medium temperature are secondary loop systems with water solutions of glycols
- Secondary loop systems have an emission rate of 10%, thanks to improved refrigerant containment in the machinery room
- The refrigerant charge is reduced (see Table 1.2) with secondary loop systems, R-404A is the refrigerant used in the machinery room
- R-22 retrofit with R-422A starts in 2008 and is totally done in 12 years
- Recovery efficiency is progressively increased to 80%
- The emission rate on new centralized systems is progressively reduced from 30% to 20% thanks to improved leak tightness of components, improvement in the leak search and data reporting when refrigerant losses are observed.

Scenario 3: introduction of low GWP refrigerants, reduction in cooling capacity and refrigerant charge.
Recent research on refrigerant has led to new molecule developments, permitting to reach very low GWP refrigerant. In 5 to 10 years, refrigerant blends with GWP lower than 500, for low temperature application, will possibly be available.

Simulations on energy consumption, when all display cases are closed, have shown significant decrease of the refrigeration needs. This scenario is evaluated in scenario 3.

The assumptions taken for the simulations in scenario 3 are:

- Identical to scenario 2, except the choice of R-404A in secondary loop system. A new refrigerant blend, called BLD1(blend 1) with a GWP of 500, is introduced progressively on the market, beginning in 2012. It replaces R-404A and R-507A in new refrigeration systems.
- The cooling capacity is cut by nearly 40%: all open display cases are replaced by display cases equipped with glass doors. The replacement of old display cases is done in 15 years, starting in 2008.

5.4.2 Refrigerant bank filled in refrigeration equipment

5.4.2.1 Case of centralized system in supermarket only

Figures 5.31 to 5.32 present, for each scenario, the refrigerant bank changes from 2000 to 2020 in centralized systems in supermarkets.

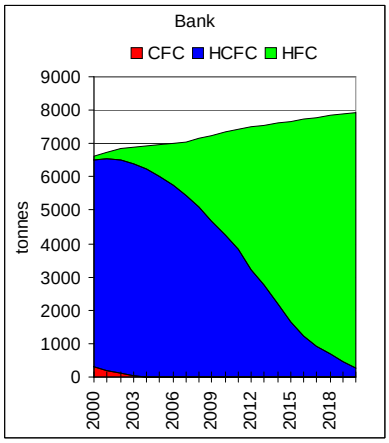

Figure 5.30. Scenario 1
Refrigerant bank changes.

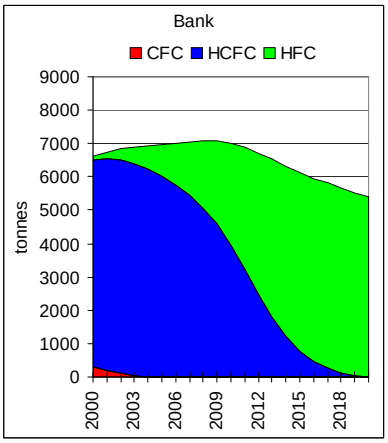

Figure 5.31. Scenario 2
Refrigerant bank changes.

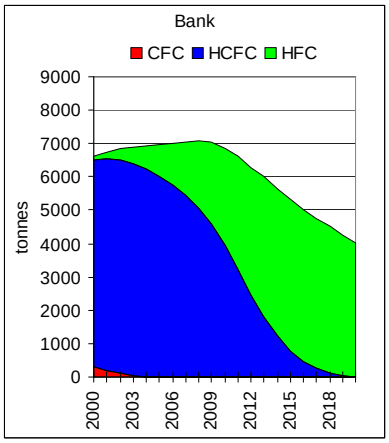

Figure 5.32. Scenario 3
Refrigerant bank changes.

In scenario 1, business as usual, the refrigerant bank continues to growth, and reaches 8,000 tonnes in 2020. In 2010, HCFC bank is still more than 50% of the total bank.

In scenario 2, the introduction of secondary loop systems starting in 2008, allows reversing the growth of the bank. In 2020, around 2,500 tonnes of refrigerants are avoided compared to the BAU scenario.

In scenario 3, both secondary loop systems, and reduction of the refrigeration needs in the sales area (glass doors) have permitted to divide the BAU bank of refrigerants by a factor 2, at 4,000 tonnes, in 2020.

5.4.2.2 Commercial refrigeration sector, including small stores

Figures 5.33 to 5.34 present, for each scenario, the refrigerant bank changes from 2000 to 2020 in the commercial refrigeration sector.

In the business as usual scenario, the total bank in commercial refrigeration sector reaches 12,000 tonnes in 2020.

In scenario 2, the impact of secondary loop introduction in supermarkets is less significant in relative value, because of the refrigerant bank in condensing units. Technically, the use of

secondary loop systems is possible in small stores in replacement of condensing units, but the additional cost seems to be not acceptable for now.

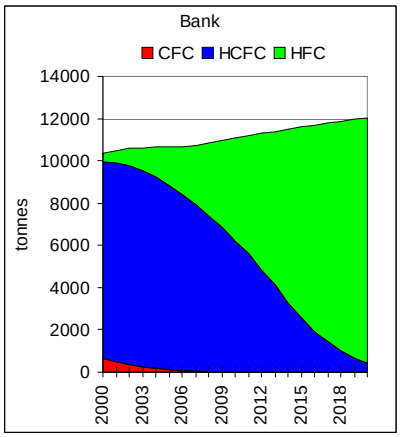

Figure 5.33. Scenario 1
Refrigerant bank changes.

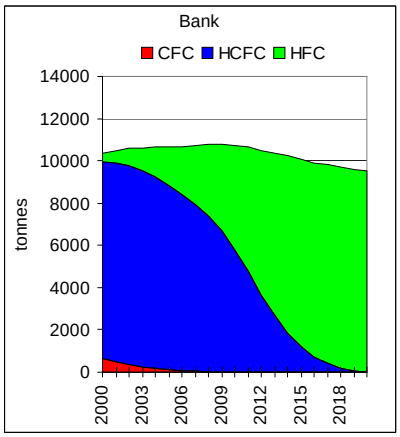

Figure 5.34. Scenario 2
Refrigerant bank changes.

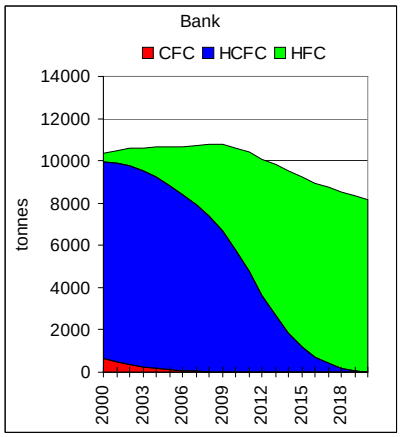

Figure 5.35. Scenario 3
Refrigerant bank changes.

In the commercial refrigeration sector, including small stores, the impact of measures taken in scenarios 2 and 3 are significant. In scenario (3), the refrigerant bank reduction is 25% in 2020.

5.4.3 Refrigerant emissions

5.4.3.1 Centralized systems in supermarkets only

The impact of changes in technology, moving to secondary loop systems, is both on the refrigerant charge and on the fugitive emission rate. As shown on Figure 5.37 (scenario 2) and Figure 5.38 (scenario 3), the level of HFC emissions is divided by 2 (scen. 2) and divided by a factor 3 in scenario 3.

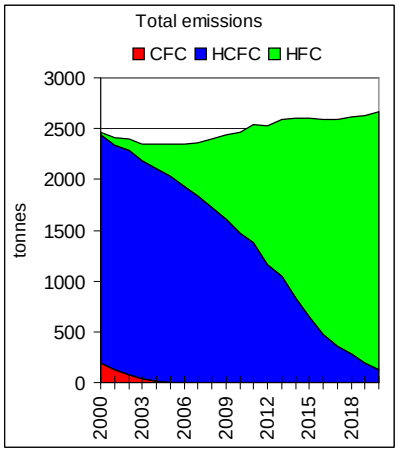

Figure 5.36. Scenario 1
Refrigerant emission changes.

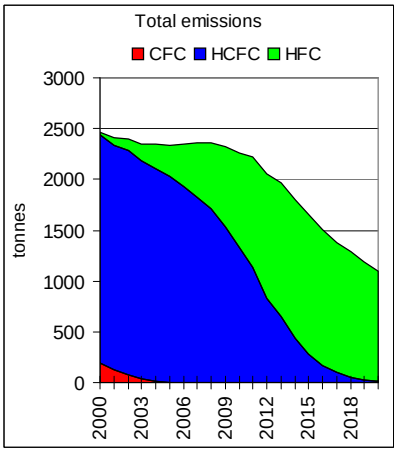

Figure 5.37. Scenario 2
Refrigerant emission changes.

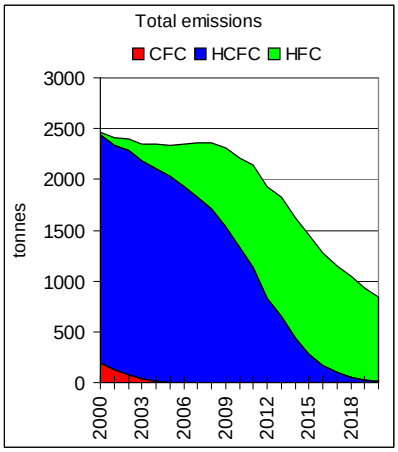

Figure 5.38. Scenario 3
Refrigerant emission changes.

5.4.3.2 Commercial refrigeration sector, including small stores

In scenarios 2 and 3, improvement of leak tightness and of recovery efficiency have also been considered for condensing units and stand-alone equipment. Figures 5.39 to 5.41 present the results in emission reductions for the commercial refrigeration sector, taking into account all technologies.

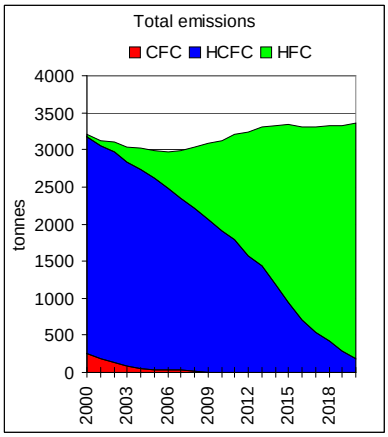

Figure 5.39. Scenario 1
Refrigerant emission changes.

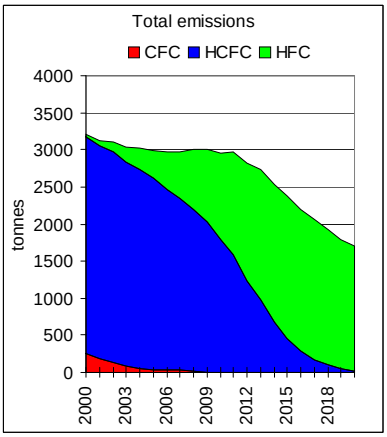

Figure 5.40. Scenario 2
Refrigerant emission changes.

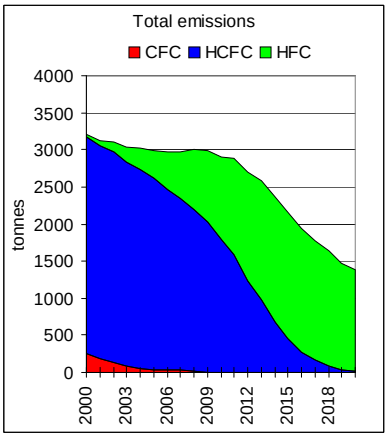

Figure 5.41. Scenario 3
Refrigerant emission changes.

In the business as usual scenario, the level of refrigerant emissions is stable between 3,000 tonnes and 3,500 tonnes per year. In scenario 2, after the introduction of secondary loop systems in supermarkets, refrigerant emissions are limited to 1,700 tonnes in 2020. When the cooling capacity is decreased (scenario 3), in addition of a secondary loop system, refrigerant emissions are lower: 1,400 tonnes in 2020.

5.4 Refrigerant CO_2 equivalent emissions

5.4.4.1 Centralized system in supermarkets only

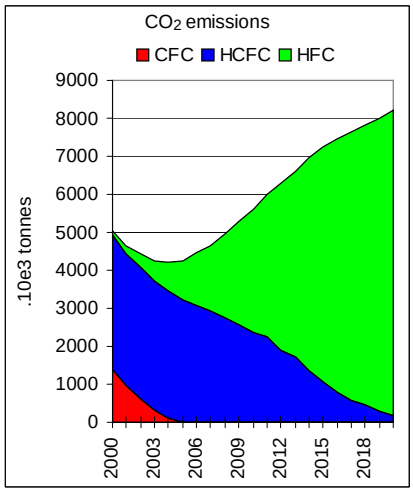

Figure 5.42. Scenario 1
CO_2 emission changes.

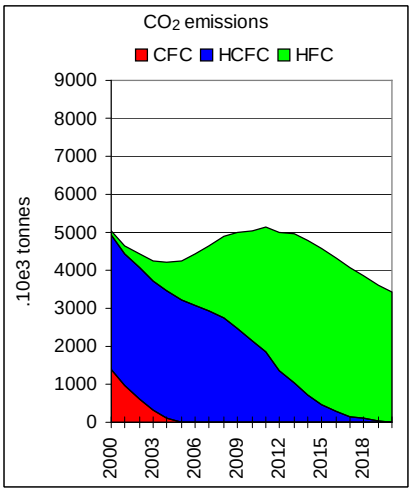

Figure 5.43. Scenario 2
CO_2 emission changes.

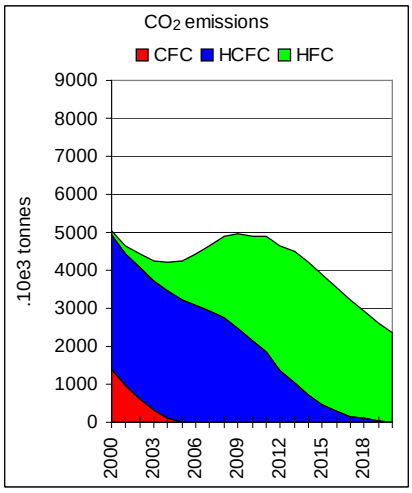

Figure 5.44. Scenario 3
CO_2 emission changes.

R-507A and R-404A have the highest GWP of HFC refrigerants currently used. The phase-out of HCFCs that had lower GWPs has an impact on CO_2 equivalent emissions. In scenario 1,

which is the current scenario for year 2000 to 2008, a minimum in CO_2 equivalent emissions is observed in 2004. After this date, the wide use of R-404A has a negative impact on CO_2 equivalent emissions. Those emissions could reach 8 millions tonnes in 2020, more than the values met in the period of use of CFCs (from 1990 to 1994) (see Digure1.25).

5.4.4.2 Commercial refrigeration sector, including small stores

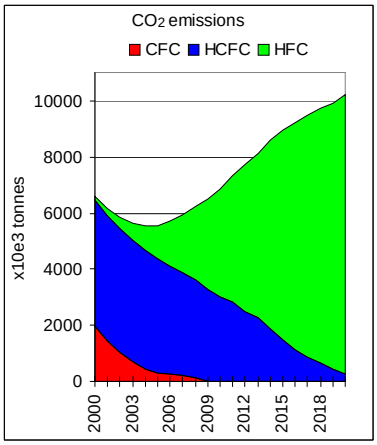

Figure 5.45. Scenario 1
CO_2 emission changes.

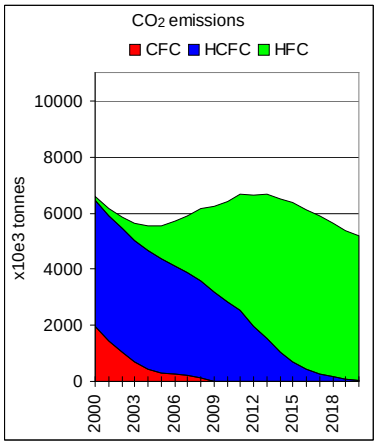

Figure 5.46. Scenario 2
CO_2 emission changes.

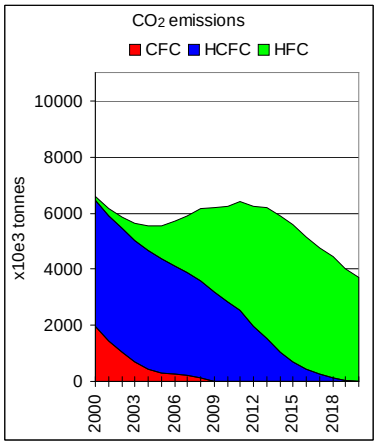

Figure 5.47. Scenario 3
CO_2 emission changes.

Changes in refrigerants, with low GWP blends, are supposed to start in 2012, only on new refrigeration systems. The simulation of scenario 3 does not consider a retrofit of existing systems with R-404A. Nevertheless, the reduction in CO_2 equivalent emissions is significant: less than 4 million tonnes in 2020, instead of 10 millions in scenario 1.

5.4.5 HCFC recovery and refrigerant demand

In 2010, the production of virgin HCFCs is banned. In developed countries, the use of HCFCs is still possible with recycled fluids, but the demand will have an impact on the refrigerant prices. Figures 1.48 to 1.50 give an evaluation of HCFC demand for servicing in commercial refrigeration, and, in parallel, the total amount of HCFCs recovered after end of life or retrofit operation.

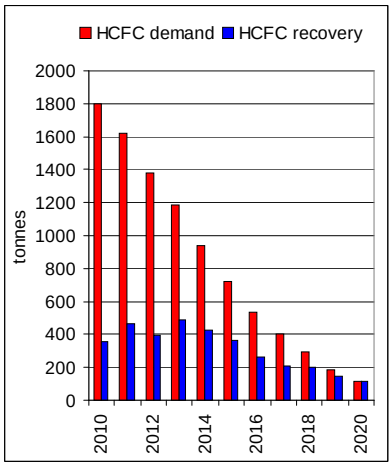

Figure 5.48. Scenario 1
R-22 demand and recovery.

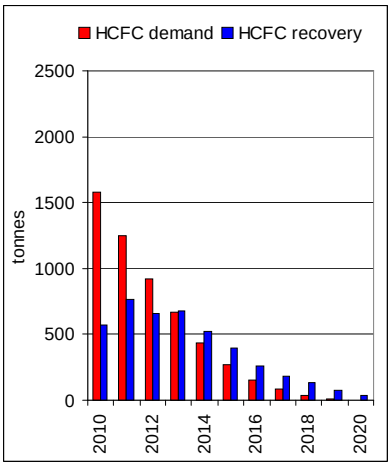

Figure 5.49. Scenario 2
R-22 demand and recovery.

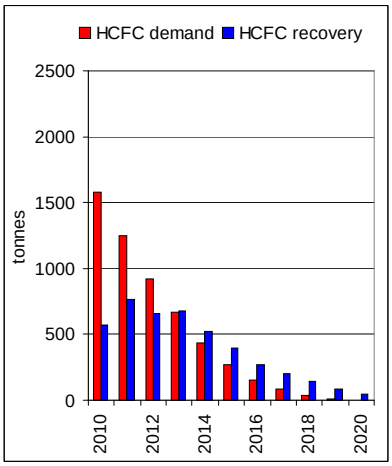

Figure 5.50. Scenario 3
R-22 demand and recovery.

In scenario 1, no retrofit has been consider before the end of life of systems, or before the renewing period (15years). Figure 1.48 shows clearly the lack in refrigerant for the period from 2010 to 2020: the recovery of R-22 is nearly 400 tonnes per year, when the refrigerant needs for servicing are 1800 tonnes in 2010 and 700 tonnes in 2015. Without any leak tightness improvement, and retrofit policy, the needs of HCFC will exceed the available recycled refrigerants or the change to intermediate blend has to be highly accelerated.

In scenarios 2 and 3 (Figures 1.49 and 1.50), retrofits of HCFC installations start in 2008 and generate additional refrigerant on the market after recycling. The demand for HCFCs is covered by recovery from 2013 to 2020. Before 2013, needs of R-22 for servicing ca not be covered by refrigerant recovery from the commercial sector only.

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7. ANNEX

Inventories of the worldwide fleets of refrigerating and air-conditioning equipment in order to determine refrigerant emissions. The 1990 to 2003 updating. ADEME/ARMINES Agreement 04 74 C0067–
Excerpts from the Final Report of December 2005 – Version 3, July 2006

Section 1 and Annexes 1 and 2 to Section 1

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1. Method of calculation, data and databases

1.1 Calculation method for emission prevision of refrigerants

The Tier 2 method, as defined in the IPCC guidelines [IPCC96, IPCC 06] proposes a calculation for HFC refrigerant emissions from equipment:

- during the manufacturing process,
- during the lifetime, and
- at the end of life of equipment.

This approach of looking at refrigerating equipment from cradle to grave (see Figure 1.1) covers all possible emissions but needs to be further worked out in order to give consistent results.

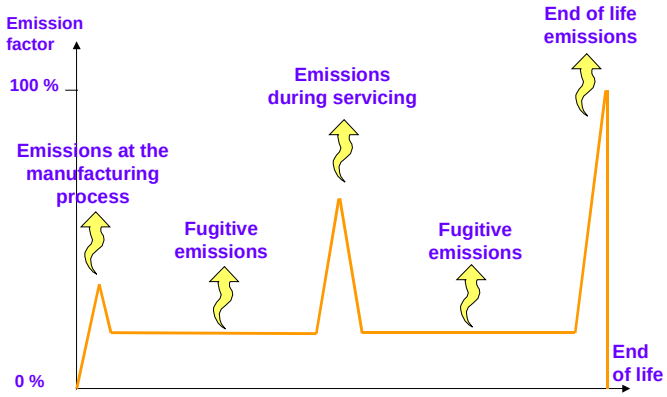

Figure 1.1 – Types of emissions from cradle to grave from refrigerating equipment.

The equations are coming from the draft version of the 2006 IPCC Guidelines (second draft, August 2006) and have taken into account the work done by the CEP during the last eight years. They are presented in Annex 1. The equations used are the same as the ones in the previous study [INV06], the main improvement being the introduction of retrofit, meaning that the lifetime of equipment is differentiate from the lifetime of the type of refrigerant charged in the equipment.

The same method is being used for the refrigerant inventories and emission forecasts for the French Government [BAR05, PAL04a, PAL04b, and PAL03] delivered to the CITEPA, which is the technical body in charge of French inventories of greenhouse gases to be delivered to UNFCCC.

♦ Emissions at the manufacturing process

When equipment is mass-produced, the direct emissions are usually very small. For field-assembled systems, the emissions during the installation phase are higher but not substantial. The main source of emissions related to charging and topping up of refrigerating equipment are mainly **the emissions due to refrigerant handling.**

One will find refrigerant handling in more than just the manufacturing process of the equipment. There needs to be included:

- splitting the bulk refrigerant in large containers into smaller volumes of refrigerant,
- losses related to connecting the smaller refrigerant volumes to the equipment, and
- **capacity "heels".**

The capacity "heels" represent the main loss during refrigerant handling. The “heels’ consist in fact by of the vapor inside the container, which cannot be extracted due to the pressure equilibrium between the vapor (the vapor heel) and the liquid phase remaining in the refrigerant volume (the liquid heel). Based on the recovery policy and the experience of the main refrigerant distributor in France, it can be derived that those “heels” represent between **2 and 10 % of the total amount of refrigerant sales.** This includes the charge of new equipment and the recharge of all the existing fleets of refrigerating equipment.

Note: the English word **fleet** covers the total number of equipment, e.g., for mobile air conditioning in cars, for refrigerating trucks, for reefers and refrigerating containers. It seems to be much more difficult to use the word fleet for domestic refrigerators, for refrigerating equipment in industrial processes and for stationary air conditioning systems. It is therefore proposed to use the French word "parc", which is easily understood in English and the following definition then applies: **"parc" is the total number of pieces of equipment in a category or sub-domain independent of their vintage.**

One of the improvements applied to the 1996 Tier 2 method of the IPCC Guidelines is the inclusion of the emissions from the container heels in the total sales of refrigerant.
Note: this improvement has been included in the 2006 IPCC Guidelines.

♦ **Emissions during the lifetime of the equipment**

Leaks during the lifetime of equipment depend on the type of application, e.g., domestic refrigerators show very low emission rates during their lifetime. On the contrary, many commercial, centralized refrigeration equipment and refrigerated transport systems are highly emissive. **Emission previsions need to be based on feedback via field data,** and field data from each country will substantially improve a number of global assumptions made in this study. In large commercial facilities or in industrial processes, the most precise approach for the determination of emissions is the collection of receipts and/or invoices for refrigerant delivered for system maintenance and for recharges.

In order to yield accurate results, the mobile air conditioning systems require very sophisticated methods. It is very common to form groups of vehicles of different vintages where the remaining refrigerant is carefully recovered from the system and subsequently measured by accurate weighing. By determining the difference between the initial refrigerant charge and the recovered charge, average levels of refrigerant emissions can be established.

♦ **Emissions from equipment at end of life**

Emissions from equipment at end of life depend on one hand on the regulatory policies in different countries, on the other hand on the recovery efficiency. For the inventory determination method, it is essential to have correct information regarding the lifetime of equipment, and annual market data for a number of years in the past, equal to the lifetime of the product. This point is crucial for almost every type of application due to:

- The rapid change in the application of refrigerant types, which changes are related to changing Montreal Protocol control schedules, and particularly to more stringent regional or national regulations,
- The rapid market growth of certain types of equipment, e.g. mobile air conditioning systems during recent years in Europe, or the rapid annual growth in China,
- The change in how recycling policies at the end of life of the equipment are regulated.

Taking into account
(1) the large numbers of equipment,
(2) the large variation in equipment type,
(3) the refrigerant charge amounts, and
(4) the different refrigerant types and their GWPs,
a large database has to be constructed, on an application by application basis. For each application, **the "parc" has to be derived for all the years covering the lifetime of this type of equipment**. Moreover, as the determination of inventories is performed on an annual basis, the updating of the database is a necessary factor to take into account.

1.2 Refrigerants and regulations

The use of CFCs, HCFCs or HFCs and other refrigerants is related to control schedules, which have been continuously adjusted since the Montreal Protocol has been ratified. For the developed countries (the non-Article 5(1) countries as defined in the Montreal Protocol), the phase-out of CFCs and HCFCs will be earlier than in the developing countries (the Article 5(1) countries). Moreover, where it concerns non-Article 5(1) countries, the European Union has accepted a much tighter control schedule for phasing out (CFCs in the past and) HCFCs.

The rapid CFC phase out in Europe and also the interdiction of use of CFCs for servicing have led to a significant uptake of intermediate blends (HCFC-based blends) for the retrofit of a number of refrigerating systems using CFCs. The retrofit allows to keep the residual value of equipment until its usual end of life. It is likely that the same behavior of equipment owners will be followed for the progressive phase out of HCFCs, which will be replaced by intermediate blends of HFCs. Based on these facts, RIEP includes retrofit options where the refrigerant can be changed during the equipment lifetime.

♦ Non-Article 5(1) countries

The CFC phase-out schedule as valid for the non-Article 5(1) countries is presented in Figure 1.2. Via the EU regulation 3093/94 CFCs were phased out one year before the phase-out defined in the Montreal Protocol, i.e. on 31 December 1994.

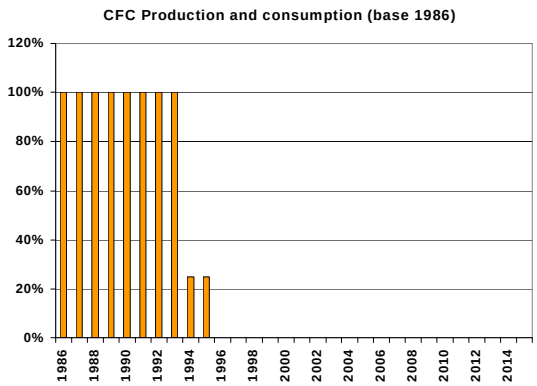

Figure 1.2 – CFCs phase out in non Article 5(1) countries.

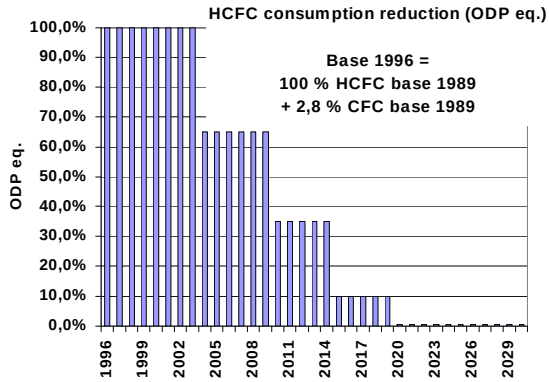

Figure 1.3 – HCFCs phase out in non Article 5(1) countries (except EU).

As indicated in Figure 1.3, the HCFC consumption base levels refer to the 1989 HCFC consumption plus 2.8% 1989 CFC consumption, ODP-weighted. On the basis of a certain ODP

for HCFC-22 and CFCs (0.055 and 1.0 respectively), the factor of 2.8% means that if all CFCs would be replaced by HCFC-22, about 55% of the CFC consumption in tonnes would be replaced by HCFC-22.

Figure 1.3 clearly shows that, even for non-Article 5(1) countries, brand-new equipment can be manufactured, charged with HCFC-22 and sold until 31 December 2009. Typically, the U.S. and many developed countries continue to use HCFC-22 for air-conditioning equipment.

As indicated in Figure 1.4, the EU regulation has changed the baseline level for the HCFC consumption by reducing the additional quantities of ODP weighted CFCs by nearly 30% (from 2.8 to 2.0%). Moreover, the time of the HCFC phase-out is been brought forward by about 7 years.

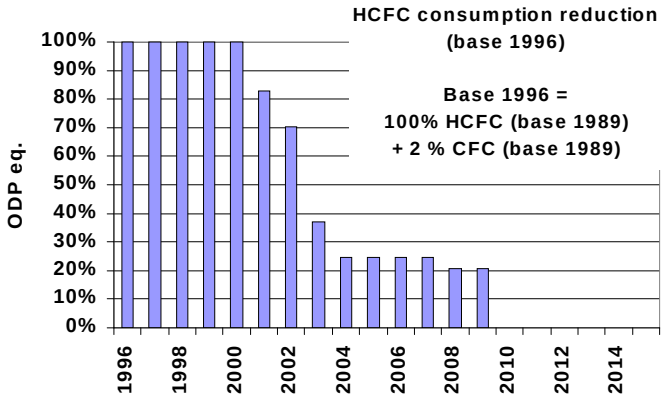

Figure 1.4 - European Union - (European regulation 2037/2000).

- **Article 5(1) Countries**

The CFC consumption and production (see Figure 1.5) for Article 5(1) countries has a delay compared to non-Article 5(1) countries of actually 14 years (1996 compared to 2010). There is an additional possibility of production and consumption of 10% compared to the 1996 level for Basic Domestic Needs of the developing countries where production can take place in the developed countries.

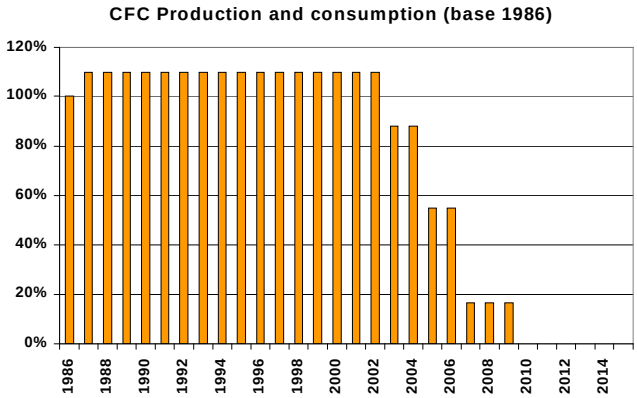

Figure 1.5 - CFC phase-out for Article 5 Countries.

For the HCFC phase-out the Montreal Protocol schedules are a bit more complicated. Where it concerns the freeze in consumption, Article 5(1) countries have a delay of about 15 years (freeze by 2016). Where it concerns the phase-out it actually is a 10-year delay period (phase-out in 2040 versus 2030) for the developing compared to the developed countries.

All these different constraints based upon global control schedules and more stringent regional and national regulations imply different refrigerant choices in countries and country groups. The refrigerant choices need to be taken into account on an application by application basis. In this project additional data have been used that have been derived from country reports as well as data that were available in publications.

1.3 Refrigerant GWPs from the Second and the Third Assessment Report of the IPCC

Table 1.1 lists the main refrigerant types in use: CFCs, HCFCs, HFCs, ammonia, and different blends, many of them being intermediate blends used for retrofit of CFC equipment. Table 1.1 has been updated taking into account all new blends as declared to ASHRAE 34. The most used of those blends are R-401A, R-409A, and R-413A for the replacement of CFC-12, R-402A and B, and R-408A for the replacement of R-502. The use of those blends can be verified at the global level by the declarations of sales by AFEAS of HCFC-124 and HCFC-142b, which are specific components of those intermediate blends. The list is nearly exhaustive, and takes into account more than 99% of all refrigerant types used. **The GWP values as given in the Second Assessment Report of the IPCC (SAR)** are used for the calculations of the equivalent CO_2 emissions of refrigerants.

Table 1.1 – GWP, physical of refrigerants [TOC03, IPCC06].

Refrigerant		Physical data				GWP		
Number	Chemical formula or blend composition – common name	Molecular mass	NPB (°C)	TC (°C)	Pc (Mpa)	GWP 2nd AR 1996	GWP 3rd AR 2001	% 2nd /3rd
11	CCl3F	137.37	23.7	198.0	4.41	3 800	4 600.0	21
12	CCl2F2	120.91	-29.8	112.0	4.14	8 100	10 600.0	31
22	CHClF2	86.47	-40.8	96.2	4.99	1 500	1 700.0	13
32	CH2F2-methylene fluoride	52.02	-51.7	78.1	5.78	650	550.0	-15
115	CF3CClF2	154.47	-38.9	80.0	3.12	9 300	7 200.0	-23
116	CF3CF3-perfluoroethane	138.01	-78.2	19.9	3.04	9 200	9 200.0	0
123	CHCl2CF3	152.93	27.8	183.8	3.66	90	120.0	33
124	CHClFCF3	136.48	-12.0	122.3	3.62	470	620.0	32
125	CHF2CF3	120.02	-48.1	66.2	3.63	2 800	3 400.0	21
134 a	CH2FCF3	102.03	-26.1	101.1	4.06	1 300	1 300.0	0
143 a	CH3CF3	84.04	-47.2	72.9	3.78	3 800	4 300.0	13
152 a	CH3CHF2	66.05	-24.0	113.3	4.52	140	120.0	-14
245 fa	CHF2CH2CF3	134.05	15.1	154.1	4.43	820	950.0	16
290	CH3CH2CH3 - propane	44.10	-42.1	96.7	4.25	20	20.0	0
401 A	R-22/152a/124(53/13/34)-MP39	94.44	-34.4	105.3	4.61	973	1 127.4	16
401 B	R-22/152a/124(61/11/28)-MP66	92.84	-35.7	103.5	4.68	1 062	1 223.8	15
402A	R-125/290/22(60/2/38)-HP80	101.55	-49.2	76.0	4.23	2 250	2 686.4	19
402B	R-125/290/22(38/2/60)-HP81	94.71	-47.2	83.0	4.53	1 796	2 108.4	17
403A	R-290/22/218(5/75/20)	92	-47.8	87	4.7		3 000	
403B	R-290/22/218(5/56/39)	103.2	-49.2	79.7	4.32		4 300	
404A	R-125/143a/134a(44/52/4)	97.60	-46.6	72.1	3.74	3 260	3 784.0	16
405A	R-22/152a/142b/C318(45/7/5.5/42.5)	111.9	-32.6	106.1	4.29		5 200	
406A	R-22/600a/142b(55/4/41)	89.9	-32.5	116.8	4.96		1 900	
407A	R32/125/134a(20/40/40)	90.1	-45	82.3	4.52		2 000	
407B	R32/125/134a(10/70/20)	102.9	-46.5	75	4.13		2 700	
407C	R-32/125/134a(23/25/52)	86.20	-43.8	87.3	4.63	1 526	1 652.5	8
407D	R-32/125/134a(15/15/70)	91	-39.2	91.4	4.47		1 500	
407E	R-32/125/134a(25/15/60)	83.8	-42.7	88.5	4.7		1 400	
408A	R-125/143a/22(7/46/47)-FX-10	87.01	-45.5	83.3	4.42	2 649	3 015.0	14
409A	R-22/124/142b(60/25/15)-FX-56	97.43	-35.4	106.9	4.69	1 288	1 535.0	19

Refrigerant		Physical data				GWP		
Number	Chemical formula or blend composition – common name	Molecular mass	NPB (°C)	TC (°C)	Pc (Mpa)	GWP 2nd AR	GWP 3rd AR	%
						1996	2001	2nd /3rd
410A	R-32/125(50/50)-Suva9100;AZ-20	72.58	-51.6	72.5	4.95	1 730	1 975.0	14
411A	R-1270/22/152a(1.5/87.5/11)	82.4	-39.5	99.1	4.95		1 500	
412A	R-22/218/142b(70/5/25)	92.2	-38	107.2	4.9		2 200	
413A	R-218/134a/600a(9/88/3)	104	-30.6	98.5	4.07		1 900	
414A	R-22/124/600a/142b(51/28.5/4/16.5)	96.9	-32.9	112.7	4.68		1 400	
415A	R-22/152a(82/18)	81.9	-37.2	102	4.96		1 400	
416A	R-134a/124/600(59/39.5/1.5)	111.9	-24	107	3.98		1 000	
417A	R-125/134a/600(46.6/50/3.4)	106.7	-39.1	87	4.04		2 200	
418A	R-290/22/152a(1.5/96/2.5)	84.6	-41.6	96.2	4.98		1 600	
419A	R-125/134a/E170-77/19/4)	109.3	-43.8	79.2	4		7 900	
420A	R-134a/142b(80.6/19.4)	101.7	-24.2	107.2	4.11		1 500	
421A	R-125/134a(58/42)	111.7	-35.5	82.4	3.88		2 520	
422A	R-125/134a/600a(85.1/11.5/3.4)	113.5	-43.2	75.4	3.92		3 040	
500	R-12/152a(73.8/26.2)	99.30	-33.6	102.1	4.17	6 014	7 854.2	31
502	R-22/115(48.8/51.2)	111.63	-45.3	80.7	4.02	5 494	4 516.0	-18
503	R-23/13(40.1/59.9)	87.25	-87.5	18.4	4.27	11 700	13 198	13
504	R-32/115(48.2/51.8)	79.25	-57.7	62.1	4.44	5 131	3 994.7	-22
505	R-12/31(78.0/22.0)	103.48	-30.0	117.8	4.73	6 318	8 268.0	31
506	R-31/114(55.1/44.9)	93.69	-12.3	142.2	5.16	4 131	4 400.0	7
507A	R-125/143a(50/50)-AZ-50	98.86	-47.1	70.9	3.79	3 300	3 850.0	17
600a	CH(CH3)2-CH3 - isobutane	58.12	-11.6	134.7	3.64	20	20.0	0
717	NH3 - ammonia	17.03	-33.3	132.3	11.33	< 1	< 1	
744	CO2	44	-78.4	31	7.38		1	

NBP = normal boiling point; Tc = critical temperature; Pc = critical pressure; GWP = global warming potential (for 100 yr integration).

The GWP calculation for blends is based on the GWP values of the pure refrigerants, and their mass concentration in the blend. It has been preferred to not round the GWP numbers for blends so that their origin can still be traced. For propane and isobutane no official GWP values have been presented in the IPCC Third Assessment Report, and the rounded value of methane (23) has been taken for all HCs.

1.4 Consistency and improvement of data quality

Using the Tier 2 method, the consistency in the emission forecast cannot be directly verified. **The first essential cross check can be done via deriving the annual market of the different refrigerant types** based on the initial charge of brand-new equipment (on an application by application basis) and on the recharge at servicing of the different "parcs" of equipment. By merging those two data series, it should be possible to derive the size of the market for every refrigerant type **and to compare those data to the official data submitted by manufacturers and distributors.**

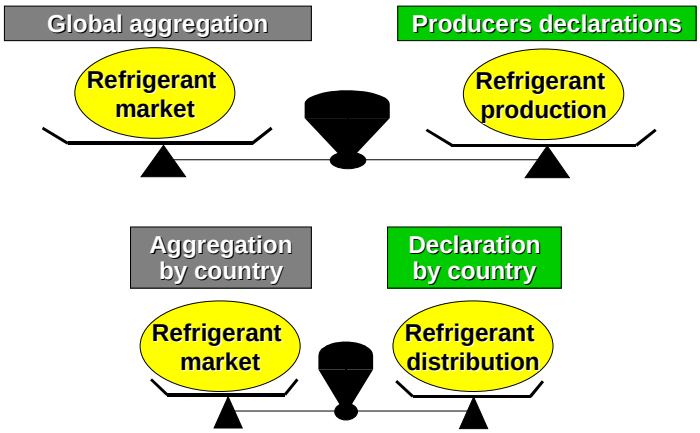

Figure 1.6 – Cross check of the annual refrigerant market derived from the initial charges and the recharges with the declarations made by refrigerant producers.

The cross-checks can be performed both on a country by country basis and globally (see Figure 1.6).

If the refrigerant inventories and the related emissions are adequately determined, the difference between the figures submitted and the calculated refrigerant sales will be small. If not, additional analyses are required.

♦ **Consistency for refrigerating equipment at the global level**

To reach a high accuracy in the sizes of the refrigerant inventories, the first step required is to gather reliable data for the equipment numbers. Fortunately, annual statistical data are available for nearly all mass-produced equipment. Some data have been published by manufacturer associations, and some (marketing studies) can be purchased from specialized companies. The data on annual equipment sales allow deriving figures on production and sale at the national level for nearly all the OECD countries, and also at the global level, when they are based on production data (see Figure 1.7).

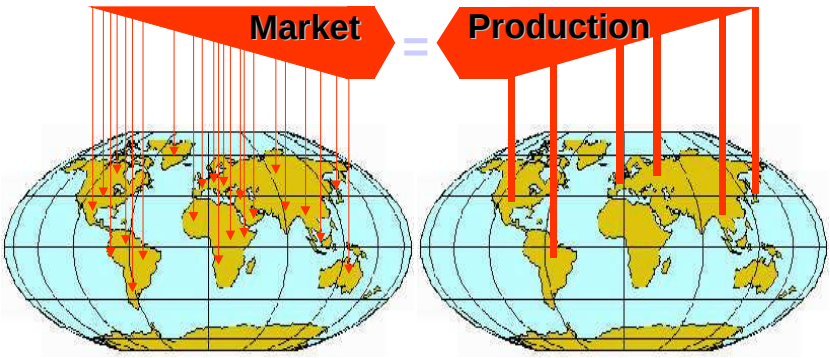

Figure 1.7 – Cross check between markets and production quantities.

At the global level, for a given year one can postulate "Production = Sales" (except for the small amount of equipment produced but not yet sold). For domestic refrigerators, stationary air conditioning systems, chillers, cars, trucks, buses, reefers… annual numbers of production and sales are available. Application of these numbers avoids double counting, which would happen easily when national inventories are merged, particularly if methods of determination are different.

♦ **Inventories of all refrigerant types and the method of aggregation**

The schedule for phasing out CFCs and HCFCs depends for the larger part on country regulations (see section 1.2). Even if only HFC inventory reporting is required under the UN Framework Convention on Climate Change (UNFCCC), it is required to have information on the emission predictions and on the changes in refrigerant use. Only in this way the size of the "banks" of all types of refrigerants charged in the different types of equipment can be determined. The --changing-- trends in the selection of the refrigerant need to include the quantities of hydrocarbons (HCs) and ammonia, which are both being used as HFC replacement options in the European Union.

As shown in Figure 1.8 the bottom-up approach used defines:

- the annual sales of brand-new equipment and the amount of refrigerants charged in this equipment,
- the determination (dependent on their lifetime) of all the fleets or parcs, which yields a cumulative value for the refrigerant bank for the specific application,
- the determination of the refrigerant market for servicing (dependent on the leak factor), and thereafter all the different domains are aggregated
- refrigerant by refrigerant,
- country by country,

by country groups and globally.

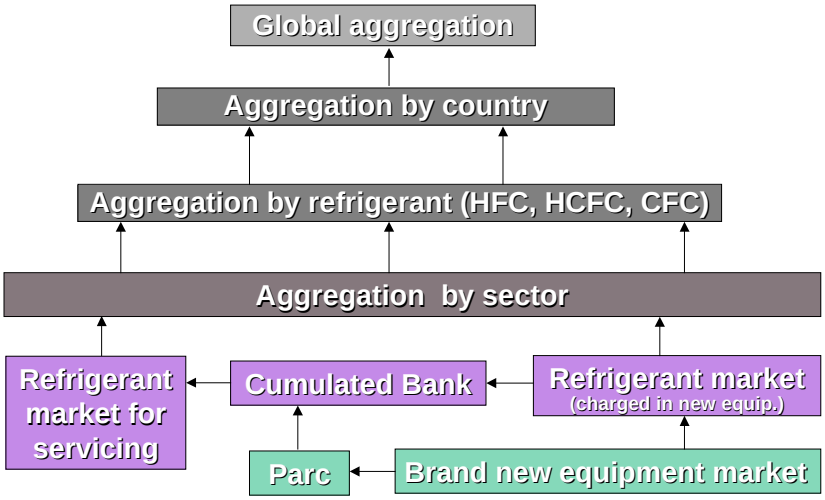

Figure 1.8 – Determination of the refrigerant markets.

This method of cross-check has been adopted in the quality assurance process of the updated version of the IPCC Guidelines 2006.

1.5 Tools for refrigerant inventories and emission previsions

To determine the annual emission forecasts for all categories of refrigerating equipment, it is necessary to create the tools that allow cumulative improvements in the data quality. The large number of data to be handled necessitates:

- to program in a database language
- to perform calculations based on reality data
- to create user friendly interfaces

- to transfer the results to tables written in spreadsheet language, which tables are based on the prescribed Common Reporting Format (CRF) of the IPCC for HFCs.

For the first year, such a database needs to “create” the "parcs" of all the different categories and sub-categories of refrigerating equipment. For the years thereafter the updating process requires less efforts and basically consists of the following input data:

- the annual equipment market for each category in the reference year
- the type of refrigerant used in brand-new equipment, and possibly also information on conversion from CFCs or HCFCs to HFCs or other refrigerants
- the emission factors.

All those elements allow to perform:

- calculations of emissions from all existing parcs of equipment,
- calculations of emissions from all types of decommissioned equipment
- a calculation of the amount of refrigerants which are recovered or reclaimed
- a calculation of the refrigerant banks per category of equipment
- a calculation of the annual refrigerant market sales, per refrigerant type.

As soon as better data become available, the database can be updated in a transparent manner. National, regional or global data reviews are necessary in order to control the quality of the inventory determinations.

A database enables the development of data acquisition in a single way: **improvement**, because it creates storage of data on the refrigerants in use inside the parcs of equipment that have been calculated.

1.5.1 Refrigeration equipment and refrigerant bank database

RIEP is connected to another database, CDB (Country Data Base), which has been developed as the source for economic, demographic, and technical data for both countries and country groups (see Annex 1).

RIEP is written in the ACCESS language, and deals with the separate countries, for any given year. Based on inputs from the user interface, RIEP can calculate the emissions during the equipment lifetime (see Figure 1.9). For these calculations, data have to be used for each year of the lifetime of a given equipment type or category.

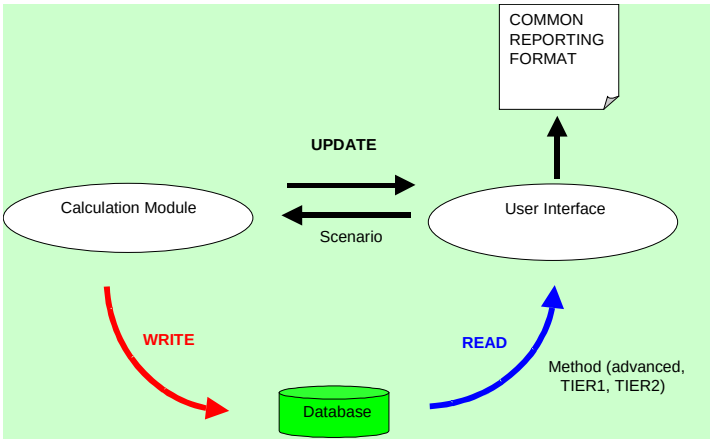

Figure 1.9 – Scheme of the application of the RIEP program.

1.5.2 Country Data Base

As indicated in Figure 1.10, if one selects a certain year and either the national or the regional level, the CDB can produce data on:

- demography,
- energy production and consumption,
- agriculture, and
- economy, including commerce.

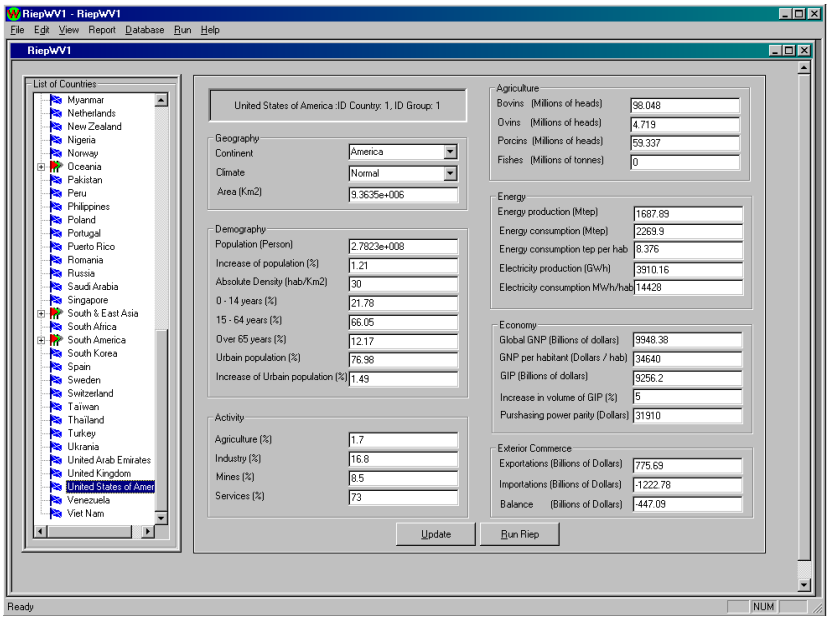

Figure 1.10 – Example of a screen of the United States of America CDB.

The Country Data Base (CDB), which has been constructed for the determination of global inventories covers 62 countries and 8 regions, which each contains a portion of the remaining 110 countries (see annex 1).

For countries where only few specific equipment data is available, some of the general data mentioned above can be used to create ratios between refrigerating equipment, national economy and population. From the CDB, it is possible to run the RIEP program. The CDB is also written in Access and interfaces are handled in the C^{++} language.

India and Brazil are analyzed per se because of their economic growth. Moreover taking into account the integration of the 10 new European countries, Europe is followed as Europe 25. Russia is also followed per se, Oceania has been merged with other Asia and Australia is followed per se. The database has been used for the Supplementary Report [UNE05] and specific groupings have been done for non Article 5(1) countries and Article 5(1) countries.

1.6 Review process

The results of the previous report [INV03] have been thoroughly used in the IPCC TEAP report [IPC05] and in the Supplement to the IPCC/TEAP report [UNE05]. Data have been analyzed by a number of experts, among them L. Kuijpers, A. MacCulloch, M. Mc Farland, S. Solomon, F. Keller, N. Campbell, and many others. Their comments have been fruitful and the main changes or improvements have been as follows:

- The sharing between CFC-11 and CFC-12 for chillers in many countries was not well set in the previous version with a too high share of CFC-12; in fact the "US model" where CFC-11 was predominant had a strong influence in all Asian countries.
- R-502, which was significantly used in commercial refrigeration in Europe was much less used in the U.S. So HCFC-22 was underestimated in the U.S. inventory, and R-502 overestimated. Corrections have been done and as it is seen in Section 2 the correction has been effective due to the quite good match between AFEAS data on CFC-115 (CFC only used in R-502) and RIEP calculations.
- The phase in of HFCs in stationary air conditioning in the U.S. has been overestimated whereas HCFC-22 was nearly the only refrigerant in use until the end of 2005.

Independently of those modifications, the main other modifications based on new data are:

- the integration of retrofit blends for the replacement of CFCs,
- a new method of calculation for the number of refrigerate trucks based on the evolution of food products followed by the FAO database,
- modification of the emission model for mobile air conditioning systems, which is no longer taking into account a percentage, but the value expressed in g/yr because it has been demonstrated that emissions are not directly related to the refrigerant charge.

One of the best review process if that the document is used by international experts and that the emissions as presented are compared to atmospheric concentration. This work has begun with the two papers published in the International Journal of Refrigeration with P. Ashford, A. Mc Culloch and L. Kuijpers [ASH04a, ASH04b, ASH04c]. Other review papers are under preparation in order to develop the correlation between atmospheric concentration and emissions of refrigerants.

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[UNE05] UNEP, 2005: Supplement to the IPCC/TEAP Report, November 2005.

[UNE03] 2002 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Option Committee (RTOC). 2002 Assessment. March 2003. ISBN 92-807-2288-3.

Annex 1 to Chapter 1

Equations used for the Calculation Method

The calculation method complements the Tier 2 method as recommended by the IPCC, by cross checking:

- the sum of refrigerant quantities charged in brand-new equipment and those recharged for servicing purposes in all the different refrigerating systems, with
- the annual national market sales of refrigerants as declared by the refrigerant manufacturers and distributors.

The method includes the following calculations:

- the refrigerant « bank » at year ***t*** charged into the parc of systems of each of the six system categories (taking into account the refrigerant changes as a result of regulations which could apply),
- the emissions of each system category, based on the understanding where the emissions occur (at system charge, during operation, during servicing and at the system's disposal).

The six categories of systems have been selected following the division used by the UNEP[1] Refrigeration Technical Options Committee [UNEP03]. The refrigerating chain includes:

- domestic refrigeration
- commercial refrigeration
- refrigerated transports
- refrigerated warehouses, food storage and industrial processes.

Air conditioning includes two sub-groups:

- air to air systems and water chillers
- mobile air conditioning.

All these categories must again be split in sub-groups.

Calculation method (Tier 2a) (extract from the draft of the IPCC Guideline 2006 Draft)

Note: here only HFCs are addressed. In RIEP all types of refrigerants are taken in account.

Refrigerant emissions at a year **t** from the six categories of refrigeration and air conditioning systems, result from:

1 emissions related to the management of refrigerant containers: $E_{containers,t}$
2 emissions related to the refrigerant charge :connection and disconnection of the refrigerant container and the equipment to be charged: $E_{charge,t}$
3 emissions from the six banks during operation (fugitive emissions and ruptures): $E_{operation,t}$
4 emissions during servicing: $E_{servicing,t}$
5 emissions at system disposal: $E_{disposal,t}$

All these quantities are expressed in kilograms and have to be calculated for each type of HFC used in the six different application categories.

$$E_{total,\ t} = E_{containers,t} + E_{charge,\ t} + E_{operation,\ t} + E_{servicing,\ t} + E_{disposal,\ t} \qquad \text{Equation 1}$$

[1] United Nations Environment Programme

Methods for estimating average emission rates for the above-mentioned domains need to be calculated on a refrigerant by refrigerant basis for all equipment whatever their vintage.

Refrigerant management of containers

The emission related to the refrigerant container management comprises all the emissions related to the refrigerant transfers from bulk containers (typically 40 tonnes) down to small capacities where the mass varies from 0.5 kg (disposable cans) to 1 tonne (containers) and also from the remaining quantities --the so-called refrigerant "heels" (vapour and /or liquid)-- left in the various containers, which are recovered or emitted.

$E_{containers,t} = RM_t \bullet (c)$ Equation 2

where:

$E_{containers,t}$	=	emissions from all HFC containers in year t expressed in kilograms
RM_t	=	the HFC market for new equipment and servicing of all refrigeration application in year t expressed in kilograms
c	=	Emission factor of HFC container management of the current refrigerant market expressed in percentage

The emissions related to the complete refrigerant management of containers are estimated between 2 and 10 % of the refrigerant market.

Refrigerant charge emissions of new equipment

The emissions of refrigerant due to the charging process of new equipment are related to the process of connecting and disconnecting the refrigerant container to and from the equipment.

$E_{charge,t} = M_t \bullet (k)$ Equation 3

where:

$E_{charge,t}$	=	emissions during system manufacture/assembly in year t expressed in kilograms
M_t	=	The amount of HFC charged into new equipment in year t (per application category) expressed in kilograms
k	=	assembly losses of the HFC charged in new equipment (per application) expressed in percentage

Note: the emissions related to the process of connecting and disconnecting during servicing are covered in Equation 5 for servicing.

The amount charged (M_t) should include all systems which are charged in the country, including those which are produced for export. Systems that are imported pre-charged should not be considered.

Typical range for the emission factor k varies from 0.1 % to 2 %. The emissions during the charging process are very different for factory assembled systems and for field-erected systems where emissions can be up to 2 %.

Emissions during operation

Annual leakage from the refrigerant banks represent fugitive emissions, i.e. small leaks from fittings, joints, shaft seals, … but also ruptures of pipes or heat exchangers leading to partial or full release of refrigerant to the atmosphere. The following calculation formula applies:

$E_{operation,\ t} = B_t \bullet (x/100)$ Equation 4

where:

$E_{operation,\ t}$	=	amount of HFC emitted during system operation in year t expressed in kilograms
B_t	=	amount of HFC banked in existing systems (per application) in year t expressed in kilograms
x	=	annual leakage rate of HFC of each application bank during operation expressed in percentage

In calculating the refrigerant "bank" (B_t) all systems in operation in the country (produced domestically and imported) have to be considered on an application by application basis.

Emissions during servicing

Equation 5 takes into account the discontinuous process of servicing. Besides component failures, such as compressor burn-out, equipment is serviced mainly when the refrigerating capacity is too low due to loss of refrigerant from fugitive emissions. Depending on the application, servicing will be done every year or every three years, or sometimes not at all during the entire lifetime such as in domestic refrigeration applications. For some applications, leaks have to be fixed during servicing and refrigerant recovery may be necessary, so the recovery efficiency has to be taken into account when the refrigerant is recovered.

$$E_{servicing,\ t} = \sum_{a=1}^{\frac{d}{z}} M_{t-az} \bullet s \bullet (1-\eta_{rec})$$ Equation 5

where:

$E_{servicing,t}$	=	amount of HFC emitted during system servicing in year t expressed in kilograms
D	=	average equipment lifetime expressed in years
S	=	residual charge of HFC in equipment requiring recharge expressed in percentage
M_{t-az}	=	the amount of HFC charged into the equipment either at manufacturing or after each servicing per application domain expressed in kilograms
a	=	number of recharges during the equipment lifetime d expressed in round numbers (lies in the interval [0-d/z])
Z	=	$\frac{1-\frac{s}{100}}{\frac{x}{100}}$; number of years elapsed before equipment recharge expressed in round numbers
η_{rec}	=	recovery efficiency, which is the ratio of recovered HFC referred to the HFC contained into the system

The importance of Equation 5 lies in deriving the annual refrigerant quantities needed for servicing. Knowing the annual refrigerant needs for servicing per application allows the determination of the national refrigerant market by adding the refrigerant quantities charged in new equipment.

When technical data are not available, Equation 5 could be simplified drastically and replaced by Equation 6.

$E_{servicing,\ t} = B_t \bullet (j/100)$ Equation 6

where:

$E_{servicing,t}$	=	amount of HFC emitted during system servicing in year t expressed in kilograms
B_t	=	amount of HFC banked in existing systems (per application) in year t expressed in kilograms
J	=	annual leakage rate of HFC of each application bank during servicing expressed in percentage

Emissions at disposal

The amount of refrigerant released from scrapped systems depends on the amount of refrigerant left at the time of disposal, and the portion recovered. From a technical point of view, the major part of the remaining fluid can be recovered, but recovery at end of life depends on regulations, financial incentives, and environmental concerns.

To estimate emissions at system disposal, the following calculation formula is applicable:

$$E_{disposal,\ t} = M_{(t-d)} \bullet s_d \bullet (1-\eta_{rec}) \qquad \text{Equation 7}$$

where:

$E_{disposal,t}$	=	amount of HFC emitted at system disposal in year t expressed in kilograms
$M_{(t-d)}$	=	amount of HFC initially charged into new systems installed in year (t-d) expressed in kilograms
S	=	residual charge of HFC in equipment requiring recharge expressed in percentage.
D	=	average equipment lifetime expressed in years
η_{rec}	=	Recovery efficiency, which is the ratio of recovered HFC referred to the HFC contained into the system

In estimating the amount of refrigerant initially charged into the systems (M_{t-d}), all systems charged in the country (for the domestic market) and systems imported precharged should be taken into account.

Quality assurance/quality control

In order to conduct a quality control for Tier 2 method, it is possible to compare the annual national HFC refrigerant market as declared by the chemical manufacturers or the refrigerant distributors with the annual HFC refrigerant needs as derived by the Tier 2 method. The following formula leads to this verification.

$$R_t = \sum_{6} S_{prod} \times m_t + \left(\sum_{a=1}^{\frac{d}{z}} M_{t-az} \times \left((1-s) + s(1-\eta_{rec}) \right) \right) \qquad \text{Equation 8}$$

where:

R_t	=	HFC needs in year t expressed in kilograms
S_{prod}	=	national production of equipment using HFC refrigerant for the six application domains
S	=	residual charge of HFC in equipment requiring recharge expressed in percentage
M_t	=	elementary charge of HFC in each type of equipment expressed in kilograms
M_{t-az}	=	the amount of HFC charged into the equipment either at manufacturing or after each servicing expressed in kilograms
A	=	number of recharges during the equipment lifetime d expressed in round numbers (lies in the interval [0-d/z])
Z	=	$\frac{1-\frac{s}{100}}{\frac{x}{100}}$; number of years elapsed before equipment recharge expressed in round numbers
η_{rec}	=	recovery efficiency, which is the ratio of recovered HFC in relation to the HFC contained into the system

The first Σ corresponds to the refrigerant charge of new refrigerating and air conditioning system produced in the country at the current year t including exports.

The second Σ corresponds to the refrigerant charge used for servicing.

The term $s(1-\eta_{rec})$ represents the recovered refrigerant.

The annual refrigerant market as declared by chemical manufacturers or refrigerant distributors RD is calculated by Equation 9.

$$RD_t = R_{prod_t} - R_{exp_t} + R_{imp_t} + R_{recl_t} \qquad \text{Equation 9}$$

where

R_{prod_t}	=	quantities of HFC refrigerant production expressed in kilograms
R_{exp_t}	=	quantities of HFC refrigerant produced in the country and exported expressed in kilograms
R_{imp_t}	=	quantities of imported HFC refrigerant expressed in kilograms
R_{recl_t}		quantities of HFC refrigerant recovered and reprocessed for sale as new HFC refrigerant in kilograms

All quantities are calculated for the current year t.

Comparing R_t that is the HFC refrigerant needs as derived from the inventory method and RD_t the HFC refrigerant market as declared by refrigerant manufacturers and distributors gives a clear quality control of the inventory method, and also of the global emissions. R_t and RD_t are calculated for each HFC type.

Annex 2 to Chapter 1

List of Countries and country groups for refrigerant inventories

Calculations are performed independently for eighty entities: seventy countries and ten country groups.

Table A2.1 – List of countries and country groups where refrigerant inventories are performed

AFRICA*	Egypt	LITTLE EUROPEAN COUNTRIES*	Saudi Arabia
Algeria	Estonia	Luxembourg	Singapore
Argentine	Finland	Malaysia	Slovakia
Australia	France	Malta	Slovenia
Austria	Germany	Mexico	SOUTH & EAST ASIA*
BALKANS*	Greece	MIDDLE EAST*	South Africa
Bangladesh	Hong kong	Morroco	SOUTH AMERICA*
Belarus	Hungary	Myanmar	South Korea
Belgium	Iceland	Netherlands	Spain
Brazil	India	New Zealand	Sweden
Bulgaria	Indonesia	Nigeria	Switzerland
Canada	Iran	Norway	Taiwan
CENTRAL AMERICA & CARIBBEAN*	Ireland	PACIFIC ISLAND COUNTRIES*	Thailand
CENTRAL ASIA*	Israel	Pakistan	Turkey
Chile	Italy	Peru	Ukrania
China	Japan	Philippines	United Arab Emirates
Colombia	Kuwait	Poland	United Kingdom
Cyprus	Latvia	Portugal	USA
Czech Republic	Libya	Romania	Venezuela
Denmark	Lithuania	Russia	Viet Nam

Country groups are indicated by *, and calculations are performed for the integral values of these groups.

Table A2.2 details the composition of each country group.

Table A1.2.2 – Country groups

AFRICA	Angola, Benin, Botswana, Burkina, Burundi, Cameroon, Cape Verde, Central Africa, Chad, Comoros, Congo, Congo RD, Côte d'Ivoire, Djibouti, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea Bissau, Guinea Equatorial, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Rwanda, Sao Tome, Senegal, Seychelles, Sierra Leone, Somalia, Sudan, Swaziland, Tanzania, Togo, Tunisia, Uganda, Zambia, Zimbabwe
BALKANS	Albania, Bosnia, Croatia, Kosovo, Macedonia, Moldova, Serbia Montenegro
CENTRAL AMERICA & CARIBBEAN	Antigua, Aruba, Bahamas, Barbados, Belize, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Grenada, Guatemala, Haïti, Honduras, Jamaica, Nicaragua, Panama, St Vincent, Trinidad & Tobago
CENTRAL ASIA	Afghanistan, Armenia, Azerbaijan, Georgia, Kazakstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan
LITTLE EUROPEAN COUNTRIES	Andorra, Liechtenstein, Monaco, San Marino
MIDDLE EAST	Bahrain, Irak, Jordan, Lebanon, Oman, Palestine, Qatar, Syria, Yemen
PACIFIC ISLAND COUNTRIES	Fiji, Kiribati, Mariannes, Marshall Islands, Micronesia, Nauru, Niue, Palau, Papua New Guinea, Tonga, Vanuatu, West Samoa
SOUTH & EAST ASIA	Bhutan, Brunei, Cambodia, DP N Korea, Lao, Macao, Maldives, Mongolia, Nepal, Sri Lanka
SOUTH AMERICA	Bolivia, Ecuador, Guyana, Paraguay, Surinam, Uruguay