RIEP METHODOLOGY

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June 2013

This document is a compiled excerpt from Chapter 1 of S. Saba Thesis: "Global inventories and direct emission estimations of greenhouse gases of the refrigeration systems", December 2009

The Centre for Energy efficiency of Systems (CES) developed a global database for the refrigeration and air-conditioning application, containing the required activity data and emission factors for the establishment of inventories of refrigerant for countries and regions of United Nations. A calculation model called RIEP, Refrigerant Inventories and Emission Previsions, was developed at the CES based on the "bottom-up" approach as defined in the [IPC00] to assess direct emissions coming from refrigeration and air conditioning applications at a national or regional level.. The work done by the CES during eight years was taken into account for the update of the Tier 2 method as described in the IPCC 2006 Guidelines [CLO05], [ASH04]. The covered sub-applications are those listed below as defined by the IPCC 2006 Guidelines, and the disaggregation leads to the definition of more sub-groups:

- Domestic refrigeration (i.e. household)
- Commercial refrigeration (centralized systems, condensing groups, and standalone equipment)
- Industrial and food processes
- Transport refrigeration
- Stationary air conditioning
- Mobile air conditioning

Tier 2 method - Emission factor approach

The advanced method, Tier 2, as defined by the IPCC 1996 and 2000 guidelines calculates the actual emissions for each individual chemical in a given year on an application basis. It takes into consideration that there might be a considerable delay between the time when the fluid is produced and charged in the equipment, and the time when it is released into the atmosphere.

First, it estimates the consumption of each individual chemical, at an application basis level, in order to establish the global volume from which the emissions originate; it should be noted that an application might use several chemicals. Then, it calculates emissions on the basis of the evaluated consumption and the emission characteristics.

This advanced method might be implemented in two different ways: the “bottom-up” approach (application based) or the “top-down” approach (consumption derived).

In a “bottom-up” approach, the consumption of a certain fluid is evaluated based on the number of equipment, in which the fluid is charged, e.g. refrigerators, stationary air-conditioning equipment, and so on. It requires establishing an inventory of the number of products charged with related chemicals and the knowledge of their average lifetime, the emission rates, recycling, disposal, and other parameters. Annual emissions are then estimated as functions of these parameters during the equipment lifetime.

A “top-down” approach estimates emissions for a given year on the basis of the consumption of chemicals: it disaggregates chemical consumption data into sectors using distribution factors and then applies time-dependent emission factors. The access to such data might be very difficult due to confidentiality issues. Although in some cases producers might report to their government the quantity of a certain fluid sold into a specific sector; in other cases where the chemical is sold by many distributors before reaching its application, it might be difficult to gather the corresponding needed data [IPC00]. In such cases, estimating distribution factors is based on expert judgments.

In the mass-balance approach of the IPCC 2006 Guidelines, emissions are calculated as defined in Equation (1.1).

$$\begin{aligned} Emissions = {} & Annual\ sales\ of\ new\ chemical - Total\ charge\ of\ new\ equipment \\ & + Original\ total\ charge\ of\ retiring\ equipment \\ & - Amount\ of\ intentional\ destruction \end{aligned} \tag{1.1}$$

In the emission-factor approach, i.e. the approach used in RIEP, emissions are calculated based on emission factors applied to estimated banks, productions and annual charges of refrigerants.

Refrigerant emissions from refrigeration and air conditioning systems occur at four main levels: emissions during charging process, emissions from the existing bank, emissions at the equipment disposal, and emissions from containers.

Total emissions of a given refrigerant in year t $E_{total,\ t}$ are given by Equation (1.2) :

$$E_{total,t} = E_{containers,t} + E_{charge,t} + E_{lifetime,t} + E_{end-of-life,t} \tag{1.2}$$

Where,

$E_{containers,t}$	: Emissions related to the management of refrigerant containers
$E_{charge,t}$	: Emissions occurring during the charging process of the new equipment
$E_{lifetime,t}$	: Emissions occurring during the equipment lifetime
$E_{end-of-life,t}$	: Emissions occurring at equipment disposal

Emissions related to the management of refrigerant containers

Emissions at the fluid manufacturing stage occur from the feedstock materials in chemical processing plants. The good design and the plant operation lead to relatively low emissions [IPC05], which are not counted within the here mentioned methods.

Once manufactured, fluids are loaded in large containers, or in individual cylinders. They are therefore delivered to product manufacturers in bulk quantities or into smaller containers. Emissions can occur at this level of fluid handling: splitting the bulk refrigerant in large containers into smaller volumes of refrigerant. Capacity heels are also considered as a main loss during the refrigerant handling. The “heels” consist of both the liquid and vapor inside the container, which cannot be extracted due to the pressure equilibrium between the vapor (the vapor heel) and the liquid phases remaining in the refrigerant volume (the liquid heel).

Emissions related to the management of the containers (used for charging of new equipment or servicing of existing ones) are considered between 2 and 10% of the total refrigerant market [IPC06].

$$E_{containers,t} = RM_t * \frac{c}{100} \tag{1.3}$$

Where,

RM_t The refrigerant market for new equipment and servicing in year t
c The emission factor of the management of refrigerant containers expressed in percentage

Emissions occurring during the charging of new equipment

At this stage, emissions occur when the refrigerant containers are connected to or disconnected from the equipment being charged. These emissions are usually higher for field-assembled and field-charged equipment than for the factory-produced ones. For example, these emissions include those taking place when hoses and valves are being connected or disconnected [CLO05].

All the systems that are charged in a country in a given year t, including those that are exported are taken into account for the calculation of $E_{charge,t}$ as shown in Equation (1.4). Systems being imported are not considered [CLO05].

$$E_{charge,t} = M_t * \frac{k}{100} \tag{1.4}$$

Where,

M_t The amount of refrigerant charged into new equipment in year t
k The emission factor occurring during assembly, expressed in percentage; it ranges between 2 and 5%.

Emissions occurring during the equipment lifetime

The largest emissions for most applications take place particularly during the in-use stage and depend on the type of the application. For example, domestic refrigerators show very low emission rates during their lifetime, due to their hermetically sealed technology, whereas for centralized systems in the commercial refrigeration application these rates tend to be very much higher. These emissions generally originate from system component leakage, such as fittings, joints, and seals, but also from ruptures of the pipes and from the refrigerant handling during the servicing operations. These rates vary among applications and countries depending on the system technology, the operating conditions, and the servicing quality. The good understanding of these factors allows focusing on the emission sources and thus preparing the stakeholders for the establishment of policies helping reduce the emission level. These emissions are calculated as shown in Equation (1.5). They include those occurring during servicing.

$$E_{lifetime,t} = B_t * \frac{x}{100} \tag{1.5}$$

Where,

B_t The bank of refrigerant contained in existing equipment in year t
X The emission factor of annual leakage from the bank occurring in year t, given in percentage

Emissions occurring at disposal of equipment

Emissions from equipment at end of life depend on regulations in a country affecting the recovery efficiency at disposal. The parameters used for the calculation of these emissions as shown in Equation (1.6).

$$E_{end-of-life,t} = M_{t-d} * \frac{p}{100} * (1 - \frac{\eta_{end-of-life,t}}{100}) \quad (1.6)$$

Where,

M_{t-d}	The amount of refrigerant charged into new equipment in year t-d, reaching the end of life at age d
p	The remaining charge in the equipment being disposed of expressed in percentage of the initial charge
$\eta_{end-of-life,t}$	The recovery efficiency at end of life expressed in percentage of the remaining charge in the system

At the equipment end of life, many scenarios for fluid handling are available:

- The fluid is not recovered ($\eta_{end-of-life,t} = 0$), thus the remaining refrigerant quantity in the equipment constitutes the end of life emissions
- The fluid is recovered; after this, it can be considered as waste, therefore either destructed or emitted or disposed of. If it is not the case, the recovered fluid can be reclaimed or recycled without reclaim.

Particularities of the RIEP calculation method

A series of improvements of the RIEP calculation method is related to the work performed during this thesis. Those refinements are important in order to figure out more precisely activity data, such as equipment lifetime and emission factors.

Emission factors

Equations used for the emission-factor approach of the Tier 2 method are the basis of the general calculation method implemented in RIEP. Still, some particularities might appear for each sub-application requiring specific input parameters and therefore some modifications to the main calculation algorithm, depending on the availability of the activity data and emission factors.

For example, for the commercial refrigeration sector, and more specifically for centralized systems, the emission factors are established based on purchase invoices of refrigerant. The amount of refrigerant purchased includes the refrigerant used to replace losses from leakages and losses during the system servicing, and therefore both types of emissions are considered within this factor, which is then applied to the bank of refrigerant.

The mobile air-conditioning (MAC) systems are not represented the same way. The information sources for the emission factors for this sector are scarce; some studies provide numbers on the initial leak flow rate (LFR) and others give numbers on the LFR of a fleet of vehicles from different vintages. The calculation method implemented in RIEP considers an overall emission factor including “regular” and “irregular” emissions resulting from road accidents and accidents taking place in garages.

Regular leaks are those related to joints, seals, and every location where one can find clearances between metallic parts with an elastomer seal. Those regular leaks increase along the time due to wear and vibrations, so the emission factor increases along the vehicle lifetime. A degradation factor has to be taken into account rather than an average value.

The regular leaks are known from test on new systems, their values are low and do not explain the refrigerant sales dedicated to servicing of the mobile air-conditioning sector. Using an initial LFR increasing with time instead of an average value implies a different schedule for the maintenance operations. For example, in the first case a vehicle undergoes maintenance at age 6, then at age 8, while for the second case, the servicing operations occur on a regular basis, i.e. every 4 years, which definitely impacts the results of emissions and the refrigerant demand.

Recent studies done at the CES ([SOU08], [CLO07]) were taken into account within the scope of this thesis. As a result, the initial LFR values considered in the RIEP database have been updated and the emission factors have been separated in two parts:

- the first one, relative to the initial LFR given per vintage and being worsened with time, and
- the second one, relative to the irregular emissions and applied to the fleet of vehicles.

A specific algorithm is implemented for the servicing operation within this sub-category allowing the calculations of emissions occurring during maintenance $E_{servicing,t}$ and the amount of refrigerant required during this operation.

Change of refrigerant by retrofit

The RIEP model also distinguishes the retrofit operation, and emissions $E_{retrofit,t}$ occurring during this process are calculated apart.

The retrofit or drop-in operations consist in replacing one refrigerant by another one. Such operations include the following actions: the old refrigerant recovery from the refrigeration system, the system evacuation, and the recharge of the system with the new refrigerant. For recovery, the behaviour of the operator is quite similar to the one held at equipment disposal, so a recovery efficiency has to be defined. The amount of refrigerant being replaced is calculated based on the retrofit schedule of the remaining bank of this refrigerant; for every year a percentage of the bank of this refrigerant is to be replaced. In the current version of RIEP, this percentage is applied equally to all vintages of equipment of the corresponding installed base. Further researches could be done in order to apply different percentages as a function of the vintage, taking into account for example the fact that equipment are not retrofitted one or two years before their end-of-life.

Retirement curve instead of average lifetime

Another modification applied to the RIEP model within the scope of this thesis is the consideration of a retirement curve to account for the equipment being disposed of instead of the mean lifetime used so far. For MAC systems, the equipment experiments usually a shorter lifetime than the vehicle one. This lower value is usually typical for European countries, where beyond a certain age of the vehicle, the maintenance cost of the MAC system is found to be too high, hence stopping the use of the MAC system as of this age. In the U.S., the availability of refrigerant small cans for the recharge of MAC systems by do-it-yourselfers induces a longer lifetime for old MAC systems and a higher emission rate.

The modified equations taking into account the retirement curve are presented now. Equations related to the mean lifetime are taken from [CL005], [ASH04]. Hereafter, equations are given for the mean lifetime and retirement curves:

$$B_t = \sum_{v=t-ml+1}^{t} M_v \qquad (1.7)$$

$$B_t = \sum_{v=t-Ml+1}^{t} M_v * r_{v,t} \qquad (1.8)$$

Where,

B_t	The refrigerant bank at year « t » expressed in kilograms
M_v	The amount of refrigerant charged into new equipment for vintage v (per application category) expressed in kilograms and calculated by multiplying the national sales of equipment of the vintage by the average equipment charge
ml	The mean lifetime of the system
Ml	The maximum lifetime of the system when using a retirement function
$r_{v,t}$	The remaining installed base of equipment of vintage v at year t expressed as a fraction of the initial number

It can be seen then that the calculation of the bank requires the knowledge of the mean lifetime for Equation (1.12) or the establishment of a retirement curve for Equation (1.13). The national sales of equipment as well as its average charge should also be known. The access to this activity data might be difficult, especially for the years before the Montreal Protocol.

Equations for $E_{containers,t}$ and $E_{charge,t}$ remain unchanged as given in (1.3) and (1.4) when the retirement curve is used.

When emission factors are applied directly to the bank, like for the centralized systems in the commercial refrigeration sector, Equation (1.5) is used to calculate emissions during the lifetime, taking indirectly (within the bank) into account the retirement curve for the bank calculation.

For MAC systems the algorithm given by Figure 1.1 is used to represent the servicing operation and to calculate regular and irregular emissions. Equations (1.9), (1.10) (in the case of the mean lifetime), (1.11) and (1.12) (in the case of the retirement curve) are used:

$$E_{regular,t} = \sum_{v=t-ml+1^*}^{t} (N_v * LFR_{v,t}) \qquad (1.9)$$

** If the system is not empty*

$$E_{irregular,t} = \left(\sum_{v=t-ml+1^*}^{t} N_v \right) * EF_{irr,t} \qquad (1.10)$$

** If the system is not empty*

$$E_{regular,t} = \sum_{v=t-Ml+1^*}^{t} (N_v * r_{v,t} * LFR_{v,t}) \qquad (1.11)$$

** If the system is not empty*

$$E_{irregular,t} = \left(\sum_{v=t-Ml+1^*}^{t} (N_v * r_{v,t}) \right) * EF_{irr,t} \qquad (1.12)$$

** If the system is not empty*

Where,

N_v	The number of equipment of vintage v
LFR_v	The value of the LFR of vintage v at year t expressed in g/year
$EF_{irr,t}$	The emission factor for irregular emissions at year t expressed in g/year
$r_{v,t}$	The remaining installed base of equipment of vintage v at year t expressed as a fraction of the initial number

Servicing emissions are given by equations (1.13) and (1.14):

$$E_{servicing,t} = \left(\sum_{v=t-ml+1^*}^{t} (M_v * \frac{s_{v,t}}{100}) \right) * (1 - n_{serv,t}) \qquad (1.13)$$

** If the vintage requires servicing*

$$E_{servicing,t} = \left(\sum_{v=t-Ml+1^*}^{t} (M_v * r_{v,t} * \frac{s_{v,t}}{100}) \right) * (1 - n_{serv,t}) \qquad (1.14)$$

** If the vintage requires servicing*

Where,

$s_{v,t}$ The residual charge of vintage v in year t expressed in percentage

$\eta_{serv,t}$ The recovery efficiency at servicing expressed as a fraction of the amount contained in the equipment being recharged

The algorithm presented in Figure 1.1 describes how the emissions during servicing operation are taken into account in the calculation method for MAC systems. This algorithm is applied to every vintage of vehicles. The criterion for recharge is a threshold for the charge emitted before servicing, above which the vehicle should undergo maintenance. For the calculation, it is represented by the percentage of charge emitted before servicing.

For every year j, the refrigerant loss is calculated following Equations (1.9) and (1.11). The loss is compared to the threshold of the residual refrigerant charge, which requires the AC system maintenance due to the lack of cooling capacity. If the loss is larger than this quantity, and the MAC system did not reach its end-of-life, the system undergoes maintenance and the amount of refrigerant required for the servicing operation and emissions occurring during this operation are calculated for this year of recharge. After this intervention, the system is fully charged again.

However, if the loss is lower than the threshold leading to maintenance, no maintenance occurs at this year of calculation which is then incremented. Losses calculated for the following year are then added to those previously calculated, and the threshold for maintenance is then verified. If the condition for maintenance is verified, the maintenance operation takes place as described previously; otherwise, the year of calculation is incremented again until the MAC system reaches its end-of-life.

As a result of this calculation algorithm, the $s_{v,t}$ parameter used in Equations (1.13) and (1.14) is calculated dynamically each year the system undergoes maintenance. The same thing applies to the end-of-life emissions that are then calculated dynamically for this sector.

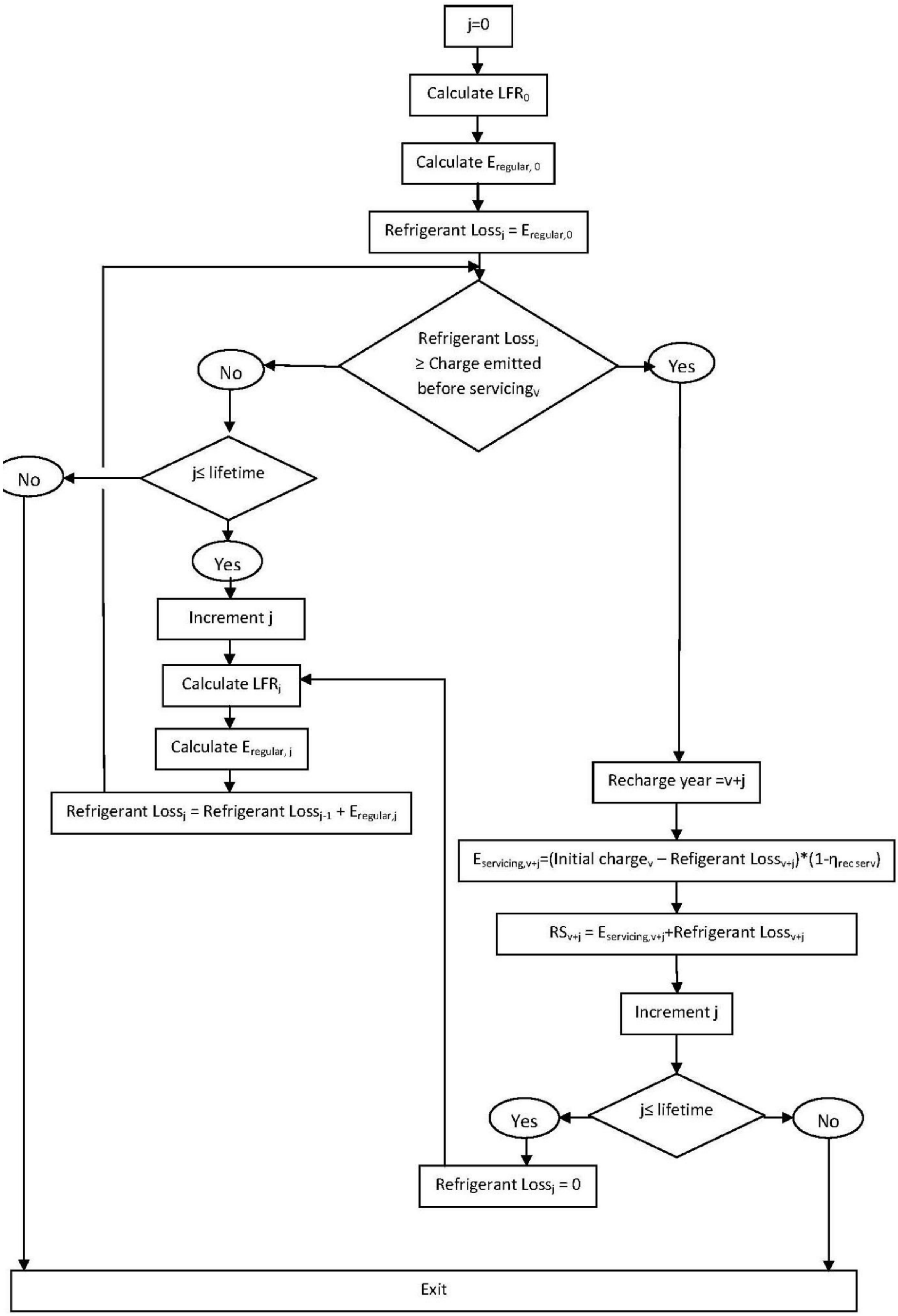

Figure 1.1 Refrigerant servicing demand and emissions for MAC systems

The retrofit emissions $E_{retrofit,t}$ are calculated using Equation (1.15):

$$E_{retrofit,t} = M_{refrigerant-out,t} * (1 - n_{end-of-life,t}) \quad (1.15)$$

Where,

$M_{refrigerant\text{-}out,t}$: The refrigerant being replaced at year t
$\eta_{end\text{-}of\text{-}life,t}$: The recovery efficiency at end of life in year t expressed as a fraction of the remaining amount of refrigerant being recovered

The total emissions during the lifetime are given by Equation (1.16):

$$E_{operation,t} = E_{regular,t} + E_{irregular,t} + E_{servicing,t} + E_{retrofit,t} \quad (1.16)$$

Emissions during servicing and retrofit given by Equations (1.18) to (1.21) occur during the refrigerant recovery. However, when the refrigerant is being re-introduced, emissions can take place. Those emissions do not figure in the equations provided by [CLO05] or the IPCC 2006 Guidelines, and can be written as follows:

$$E_{charge(servicing-retrofit),t} = (RS_t + RR_t) * \frac{k}{100} \quad (1.17)$$

Where,

RS_t Refrigerant demand for servicing at year t
RR_t Refrigerant demand for retrofit at year t
k The emission factor at the charging process expressed in percentage

The end-of-life emissions represented by Equation (1.6) are calculated using Equation (1.18) in the case of the retirement curve:

$$E_{end-of-life,t} = \sum_{v=t-Ml+1}^{t} (M_v * (r_{v,t-1} - r_{v,t}) * \frac{p}{100} * (1 - \eta_{end-of-life,t})) \quad (1.18)$$

Where,

$r_{v,t-1}$ The remaining installed base of equipment of vintage v at year t-1 expressed as a fraction of the initial number
$r_{v,t}$ The remaining installed base of equipment of vintage v at year t expressed as a fraction of the initial number

For MAC systems, the residual charge at end-of-life is calculated for every vintage; therefore the value of p in Equation (1.18) depends on the vintage and on the year of disposal.

Refrigerant container heels are taken into account in the calculations of the refrigerant demand as it will be described later (Equation (1.19)).

Verification

At the global level, emissions are calculated, and can be compared to those obtained from the atmospheric concentrations.

Besides, a comparison of the refrigerant demand, as calculated on the basis of the emission-factor approach of the Tier 2 method, with the one declared by the refrigerant distributors leads to verify that the refrigerant amount purchased in a given year is used for the new equipment charging and the replacement of what have been lost during that year.

Equation (1.19) allows the calculation of the refrigerant demand, which is then compared to the declared numbers.

$$R_t = (1 + \frac{c}{100} + \frac{k}{100}) * (RP_t + RS_t + RR_t) \tag{1.19}$$

Where,

R_t	The total refrigerant demand at year t, expressed in kilograms
RP_t	The total refrigerant demand for the new equipment being charged in the country, expressed in kilograms
RS_t	The refrigerant demand for servicing at year t, expressed in kilograms
RR_t	The refrigerant demand for retrofit at year t, expressed in kilograms
c	The emission factor of the refrigerant containers management expressed in percentage
k	The emission factor occurring during assembly expressed in percentage

The refrigerant demand for new equipment is given by Equation (1.20):

$$RP_t = \sum_{i=1}^{6} (S_{prod_{i,t}} * m_{i,t}) \tag{1.20}$$

Where,

$S_{prod,i,t}$	The national production of equipment for the application i at year t
$m_{i,t}$	The average charge of equipment for the application i at year t expressed in kilograms

The refrigerant demand for servicing is calculated using Equation (1.21) when the emission factor is applicable to the bank, and by Equation (1.22) in other cases.

$$RS_t = \sum_{i=1}^{6} E_{lifetime_{i,t}} \tag{1.21}$$

Where,

$E_{lifetime\ i,t}$	The total emissions as calculated by Equation **Erreur ! Source du renvoi introuvable.** when the emission factor is applicable to the bank of application i

$$RS_t = \sum_{i=1}^{6} \left[\left(\left(\sum_{v} E_{regular_{i,t\_vingtage^*}} \right) + \left(1 - n_{serv_{i,t}}\right) * RemainingCharge \right) + E_{irregular_{i,t}} \right] \tag{1.22}$$

** If the vintage requires servicing*

Where,

$E_{regular\ i,t\_vintage}$	Losses of vintage v since its last recharge until year t, if the vintage requires recharging, and for the application i
$\eta_{serv\ i,t}$	The recovery efficiency at servicing at year t for application i
RemaningCharge	The remaining charge in the equipment, being recovered at the moment of servicing
$E_{irregular,t,i}$	The irregular emissions at year t for application i

The refrigerant demand for retrofit RR_t corresponds to the amount of refrigerant being introduced into the system during the retrofit operation.

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