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Methodologies

Coordinating Lead Authors
Jochen Harnisch (Germany), José Roberto Moreira (Brazil)

Lead Authors
Paul Atkins (United Kingdom), Daniel Colbourne (United Kingdom), Martin Dieryckx (Belgium), H.S. Kaprwan (India), Fred Keller (USA), Archie McCulloch (United Kingdom), Stephan Sicars (Germany), Bishnu Tulsie (St. Lucia), Jinhuang Wu (China)

Contributing Authors
Paul Ashford (United Kingdom), Kirsten Halsnæs (Denmark), Atsushi Inaba (Japan)

Review Editors
Pauline Midgley (United Kingdom), Mahi Sideridou (Greece)

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EXECUTIVE SUMMARY

The phase out of CFCs and HCFCs under the Montreal Protocol requires the selection of replacement technologies, and in many cases are these alternative fluids. These technologies have differing impacts on global climate change, health, safety and other environmental endpoints, and different private and social costs. Analyses that focus on one or more of these types of impacts can help decision-makers to make choices about competing replacement technologies. However the outcomes of such analyses are influenced by many factors not intrinsic to the technologies. Examples of these are the analytical approach (e.g., top-down compared with bottom-up), the degree of product or process optimization, service and disposal practices, regional circumstances and a wealth of other inputs and assumptions. Therefore in order to make informed choices, decision-makers need to be aware of the sensitivities, uncertainties and limitations inherent in each type of analysis, and must be able to evaluate whether the approach and assumptions used in an analysis are reasonable for the regions and time periods in which the competing technologies are to be applied.

The purpose of this chapter is to provide an overview of the different types of analyses as well as concise guidance on how to evaluate and apply these. For each type of analysis, the most important analytical approaches and variables are discussed, along with the associated sensitivities, uncertainties and limitations. The requirements and limitations of each method are explained. This provides a point of reference for the selection of assessment methods in the technical chapters of this report and gives a framework which helps to harmonize the reporting of results. Further the chapter provides an introduction to the technical chapters and to their subsequent application, non-application and specific-default macrodata. A description of the key methods used in these chapters is also given.

An overview is given of the key approaches used to compare the lifetime, and the direct and indirect emissions of different types of systems. These range from the modelling of partial or complete systems to measured values of individual systems or of representative equipment populations. There can be significant differences between the results from different approaches and therefore relevant policy comparisons can only be made if there is maximum transparency and a harmonization of assumptions. Reference values for emissions from energy consumption in the production of fluids and products are given along with values for CO_2 emissions from electricity generation for the national electricity grids. These values differ significantly over time and between regions, suggesting that great care should be taken if results of system comparisons based on total equivalent warming impact (TEWI) or Life Cycle Assessment (LCA) are transferred to related applications or other regions.

In any economic analysis, the cost of mitigation is calculated as the difference in costs (defined in monetary units) between a reference situation and a new one characterized by lower emissions. Both situations should, as far as possible, be defined such that the assessment can include all major economic and social impacts of the policies and the resulting impact on greenhouse-gas emissions. At the project level, the simplest cost assessment using cost-benefit analysis considers that a new technology requires capital investment to cover costs accounted in the project. Major categories of costs accounted in a project are labour, land, material, energy, investments, environmental services and foreign exchange. These costs are known as the direct engineering and financial costs. A more complete cost evaluation requires the inclusion of externalities, the costs not paid directly by the private commercial entity developing the project. External costs are paid by society and where available, these should be considered for wider policy assessments. In principle, the total cost to society (*social cost*) consists of both the *external cost* and the *private cost*. For the assessment of engineering-type measures relevant to this report, the focus is best placed on private costs, expressed in terms of their net present value (NPV) or as levelized costs to account for the time distribution of costs and investments during the project lifetime.

Health and safety issues are an integral aspect of decisions concerning the choice of fluids. These decisions can have far-reaching consequences for the workforce, the population, industry, the environment and the economy. The prevention of negative health and safety impacts requires methodologies such as risk assessment, risk management, and policy and regulatory controls. Health and safety issues are considered under the following criteria: Flammability, acute toxicity, chronic toxicity, carcinogenicity, acute ecotoxicity, chronic ecotoxicity, and persistence. Information on the substances covered by this report was drawn from several sources. The technical chapters provide detailed information on the substances and the products these are used in is provided in the subsequent technical chapters. The information is divided into general characteristics of a group of fluids followed by typical characteristics of certain fluids within the group. There are significant differences between the various fluid groups, and in some cases within the fluid groups, with respect to flammability, acute toxicity, ecotoxicity and persistence. The design of systems and processes should reflect the specific weaknesses of the fluids used.

A fairly wide range of assessment methods is described so that the impacts of different technologies on the environment and climate can be compared and understood. One significant problem identified is that methodologies like LCA and TEWI are installation-specific and therefore do not provide meaningful results for entire sectors. It is also demonstrated that the available assessment methodologies are not generic but have been developed for a specific purpose. Each of the methodologies can play a role in technology choices if used appropriately.

The use of fluorocarbons is specific to certain technical sectors. In these sectors, technology selection and product development are influenced by the customers and a number of other factors, such as the enforcement of legislation, of a local, national or regional nature. An overview of the regional factors that should be reflected in the inputs for analyses is given. These factors include climate, labour costs, the availability of capital, skilled labour and spare parts, the replacement rates of systems, and disposal pathways. In this section a regional partitioning of developed and developing countries is used according to the Montreal Protocol.

For applications involving banked amounts of fluids, an overview is given of the available approaches and associated uncertainties for the modelling of process emissions compared to emissions in the usage phase and upon disposal. For both areas, the future usage pattern and emissions can be estimated using bottom-up and top-down approaches. The former ideally involves the modelling of the emissions of individual substances or substance classes from populations of equipment. The properties of these pieces of equipment will often be modelled differently for different years and in different regions so as to reflect anticipated technological changes. In contrast to these technology-rich approaches, top-down models rely on historically established relations between sales into certain sectors and economic growth. This approach is typically weakest in capturing long-term technological changes but is good for the appropriate capture of mid- to long-term growth and wealth effects. However for technologies involving the use of fluorinated greenhouse gases, uncertainties associated with both bottom-up and top-down models become so significant that projections beyond the year 2020 are unreliable.

In the past, too little attention was paid to ensuring the comparability and transferability of results from different technology assessments. The treatment of uncertainties is often incomplete and therefore the resulting recommendations are often not robust enough to be transferred across a sector. To address these concerns, analysts and decision-makers should ensure, wherever possible, that the assumptions and methods used to compare competing technologies are consistent and that uncertainties and sensitivities are identified and quantified. The development of simple and pragmatic standard methodologies and the respective quality criteria should be continued. It is recommended that future efforts should focus on increasing the involvement of relevant stakeholders and introducing additional measures to increase transparency for outside users, for example by providing more extensive documentation. For certain regions and policy questions the amount of resources needed for some of the assessment methods is prohibitive. There is a need for simple and pragmatic assessment methods that can also be used in regions with very limited resources.

3.1 Introduction

This chapter provides public and corporate decision-makers with an overview of assessment methodologies that can be used to support informed decisions on technologies to replace the use of ozone-depleting substances (ODSs). Such decisions are taken in the context of the phase out of ozone-depleting substances under the Montreal Protocol, and national and international policies aimed at reducing emissions of anthropogenic greenhouse gases. The latter include not only direct emissions of fluids during production, use and disposal but also energy-related emissions over the lifetime of products and equipment. Decisions on technology choices and the definition of appropriate practices will often take place at the level of individual projects but could also be important in designing policies. This chapter has therefore been designed as a toolbox for decision-makers. The intention is to give an overview of the most common assessment methodologies for evaluating competing technologies, including a description of how these are applied and their practical limitations. It also provides information used by several subsequent chapters in this report.

Fluorinated substances such as hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) are being widely used or are being considered for future use as refrigerants, blowing agents in foam production, propellants for aerosol applications, solvents, surfactants, fire-fighting agents and anaesthetics. These substances are used in many technical applications over a wide range of conditions. They are replacing the use of CFCs and HCFCs, which were and are being banned due to their significant impact as ODSs. In quantitative terms, stationary refrigeration and air conditioning, mobile air conditioning and foam blowing dominate usage and emissions in most countries.

As these substances are potent greenhouse gases, considerable efforts are underway to reduce the emissions of these from products or processes to well below the levels that can be obtained on the basis of current technical and economic drivers. The principal available emission reduction options – over the lifetime of the product equipment – for the aforementioned applications fall into five main groups:

a) Improved containment of fluorinated gases during the life cycle of a product or system (manufacture, use and decommissioning/disposal);
b) Use of technologies with a lower fluid charge;
c) Use of alternative fluids with a zero/low global-warming potential (GWP);
d) Use of not-in-kind (NIK) technologies;
e) Process modifications to avoid byproduct formation or emission.

The benefits of reducing emissions of fluorinated gases clearly need to be offset against potential changes in terms of energy efficiency, safety and costs or the impact on environmental categories such as air quality and the continuation of damage to the ozone layer (see Figure 3.1). The specific details of a sector – or even the application concerned – need to be taken into account when making decisions about technological options.

As a result of international concerted action, many of the sectors and applications covered in this report have undergone a rapid transition away from the use of ODSs. This mandated transition has also led to a significant increase in knowledge about technological alternatives to the use of ODSs and has resulted in increased innovation. This high rate of innovation has made it more difficult to appropriately characterize technology options and then to assess them in terms of their performance or costs. Therefore it is now more important than ever to apply consistent methodologies, as outlined in this chapter, for the purpose of producing valid comparisons upon which robust technology choices can be based.

The subsequent sections of this chapter cover the following aspects of technology assessment relevant to the sectors using fluorinated gases: Key performance characteristics such as direct and indirect emissions (3.2), categories of costs (3.3), consideration of health and safety issues (3.4), assessment of climate and environmental impacts (3.5), regional dimensions of technology choices (3.6), basics of emission projections (3.7) and future methodological developments (3.8).

3.2 Direct and indirect emissions

This section considers aspects related to emissions from products and equipment using HFCs or PFCs. Direct and indirect emissions need to be identified to account for the full inventory of such emissions. Indirect emissions are usually associated with the amount of energy consumed for the operation of equipment loaded with the fluid. Table 3.1 gives an overview of the relative contribution of direct HFC emissions to the total greenhouse-gas emissions associated with systems, for example, a domestic refrigerator, a refrigerated truck, a supermarket cooling system or the energy losses through an insulated area of building surface. The table shows that for several important technical systems (e.g. mobile air conditioners or supermarket refrigeration) direct and indirect emissions are of the same order of magnitude but that for several other applications, energy-related indirect emissions outweigh direct emissions by one or two orders of magnitude. The methodologies stated in Table 3.1 are described in greater detail in Section 3.5. Specific values are highly dependent on emission factors, end-of-life treatment of equipment, the GWP of the fluids used and the carbon intensity of the energy supply system.

3.2.1 Direct emissions

Emissions are possible throughout the lifetime of the fluid, from the initiation of fluid manufacture through use within the intended equipment, to its destruction. The following paragraphs describe key stages within the lifetime of the fluid where direct emissions occur. The identification of emissions from these various stages is necessary for both the environmental impact and safety assessments of applications that use any type of fluid.

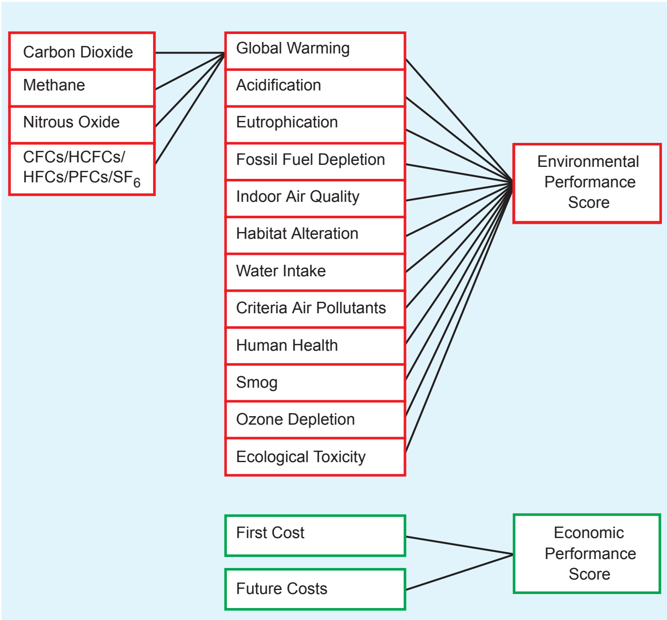

Figure 3.1. Example of impacts to be accounted when taking decisions about the introduction of new technologies or products (Lippiatt, 2002 adapted by authors).

3.2.1.1 *Emissions by fluid life stage*

Fluid manufacture [1]

The manufacture of fluids requires feedstock materials, which are sourced, produced and used worldwide. Emissions from these feedstock materials, their intermediates and the end substance can occur in chemical processing plants. For the production of many HFCs, these direct emissions can be significant in terms of CO_2 equivalent (on a GWP(100) basis – see Section 3.5.1). For example, the substances emitted during the production of HFC-227ea were estimated to amount to 120 kg CO_2-eq kg^{-1} of material manufactured (Banks *et al*., 1998), whereas for HFC-134a this figure was relatively low with estimates ranging from 2–40 kg CO_2-eq kg^{-1}. (McCulloch and Lindley, 2003 and Banks and Sharratt, 1996, respectively). These values are strongly dependent on the fluid manufacturing process and the integrity of the chemical plant. The good design and operation of the plant can lead to lower emissions. It should be noted that some of the intermediate substances might be ODSs (although these are converted into the end product without being emitted). For example CFC-114a, HCFC-133 and HFCF-124 are used in particular routes for the manufacture of HFC-134a (Frischknecht, 1999). The emissions of GHGs are significantly less for alternative fluids. HC-290, HC-600a and HC-1270 are generally extracted from natural gas mixtures and leakage from the process plant will generally comprise a variety of hydrocarbons. Gover *et al*. (1996) estimate 0.14 kg CO_2, 0.5 g HC and 0.7 g methane emissions per kg of propane/butane, which equates to 0.2 kg CO_2-eq kg^{-1}, and data from Frischknecht (1999) are lower than this. Ammonia is normally produced from natural gas and emissions of GHGs will only comprise methane and CO_2. Frischknecht (1999) estimates between 1.5 and 2.3 kg CO_2 kg^{-1} ammonia produced, consistent with the value in Campbell and McCulloch (1998). CO_2 is a slightly different case, as commodity CO_2 is generally a recovered byproduct from numerous other chemical manufacturing processes and it is therefore difficult to specifically attribute emissions to CO_2. Frischknecht (1999) reports emissions of CO_2 and methane, equivalent to 0.2 kg CO_2 kg^{-1} CO_2 produced.

Distribution of fluids

Once manufactured, fluids can be shipped nationally or internationally, often as bulk shipment or in individual cylinders. Typically, national or regionally organized distribution chains deliver bulk quantities to product manufacturers or transfer the substances into smaller containers for use by manufacturers and service companies, in the case of refrigerants and solvents. The distribution chain stops when the substance enters into the management or control of the 'user', such as a manufacturer or a service company. Losses normally occur during the transfer of fluids, connection and disconnection of hoses, and leakage from containers and pressure relief devices. These losses tend to be relatively small in relation to the large quantities of materials handled (Banks *et al*., 1998), as transfer operations take place under carefully-controlled conditions and are subject to international regulations for the prevention of releases (e.g. UN, 2002; IMO, 2000).

Manufacture and distribution of products

HFCs and alternative fluids are generally used in the manufacture of refrigeration systems, foams, aerosols and fire protection equipment, whereas solvent applications (e.g. cleaning) tend to apply fluids directly on-site during the in-use stage. The manufacture of refrigeration products requires transfer of the fluid. Losses normally occur due to the connection and disconnection of hoses and valves. Emissions also originate from storage vessels and the associated piping, but these are less frequent.

Some sources of emissions are specific to certain applications and products. For example, refrigerants are often used to rinse out air, moisture and other contaminants from refrigeration equipment to ensure internal cleanliness prior to charging. Moreover, the refrigerant may also be employed as a tracer for the detection of leaks. Equipment leaks may be found after charging of the refrigerant, in which case further emissions will occur during the recovery and evacuation process prior to repairing the leaks. During the manufacture of foams, fluids are used as blowing agents. The blowing-agent emissions during the preparation of foam formulations, when the blowing agent is mixed with other raw materials such as polyols, are low due to the use of closed systems. Depending on the type of foam

[1] Only direct emissions from the production process are considered here and not indirect emissions from electrical energy requirements.

Table 3.1. Percentage contribution of direct (HFC) emissions to total lifetime greenhouse-gas emissions in various applications (emissions associated to functional unit) – selected indicative examples.

Application	Method applied	HFC emissions as percentage of lifetime systemgreenhouse-gas emissions (using GWP-100)	Characterization of system and key assumptions	Publication
Mobile Air Conditioning	TEWI	**40–60%** – Current systems (gasoline engine) **50–70%** – Current systems (diesel engine)	Passenger vehicle; HFC-134a Sevilla (Spain)	Barrault *et al*. (2003)
Commercial Refrigeration	LCCP	**20–50%** – for a wide range of sensitivity tests on leakage rate, energy efficiency and energy supply	Direct Expansion Refrigeration Unit; Supermarket (1000m^2); HFC-404A; Germany	Harnisch *et al*. (2003)
Domestic Refrigeration	TEWI	**2–3%** – No recovery at end-of-life	European standard domestic refrigerator; HFC-134a; World average electricity mix	Chapter 4 of this report
Insulation Foam of Domestic Refrigerators	LCCP	**6%** – with 90% blowing agent recovered at disposal **17%** – with 50% blowing agent recovered at disposal	HFC-245 fa; Europe	Johnson (2004)
PU Insulation Foam in Refrigerated Truck	LCCP	**2%** – with full recovery of HFC at disposal **13%** – without recovery of HFC at disposal	Refrigerated Diesel truck; Germany	Harnisch *et al*. (2003)
PU Spray Foam Industrial Flat Warm Roof	LCA	**13%** – with full recovery of HFC at disposal **20%** – without recovery of HFC at disposal	4 cm thickness; HFC-365 mfc; Germany	Solvay (2000)
PU Boardstock in Private Building Cavity Wall	LCA	**4%** – with full recovery of HFC at disposal **17%** – without recovery of HFC at disposal	5 cm thickness; HFC-365 mfc; Germany	Solvay (2000)
PU Boardstock in Private Building Pitched Warm Roof	LCA	**10%** – with full recovery of HFC at disposal **33%** – without recovery of HFC at disposal	10 cm thickness; HFC-365 mfc; Germany	Solvay (2000)

and process, either a small fraction (rigid closed cell foam) or the entire blowing agent (flexible open cell foam) is emitted during the manufacturing process. The foaming usually takes place under ambient atmospheric conditions. The blowing agent emitted from the foaming process mixes with the air and is then vented or incinerated. Aerosols are generally charged in factory premises and, as for refrigerating systems, the disconnection of charging heads results in small releases. Cleaning machinery is occasionally filled with solvent, although emissions tend to be minimal at this stage because fluids with a low vapour pressure are generally used.

Use

The in-use stage of the product lifetime tends to result in the greatest emissions for most applications, particularly for refrigeration, aerosols, solvents and fire protection systems. For refrigeration and air-conditioning systems, for example, in-use emissions can vary widely depending on the service and disposal practices as well as other operational and environmental factors not intrinsic to the technology. Emissions from domestic, commercial and industrial refrigerating equipment generally originate from failures in system components or from the handling of refrigerant during servicing, with the size and frequency of leaks depending upon several factors. External factors include usage patterns, frequency of equipment relocation, weathering and aggressive environments, repair quality and frequency of preventative maintenance. Rapid fluctuations of temperature or pressure and excessive vibration of piping, joints and so forth, due to fan motors and compressors or other external sources are major causes of in-use leakage. Other integral aspects are associated with the design and construction of the equipment. The design quality of the equipment and the use of suitable components have a significant impact on leakage rates. Control systems are also responsible for emissions, such as pressure-relief devices. Most industry guidance on emissions focuses on leak prevention for the in-use stage (e.g., see Institute of Refrigeration, 1995; Butler, 1994; ETSU, 1997). The multiple factors contributing to emissions of refrigerant often lead to a fairly broad distribution of net leakage rates for individual pieces of equipment. Figure 3.2 shows an example

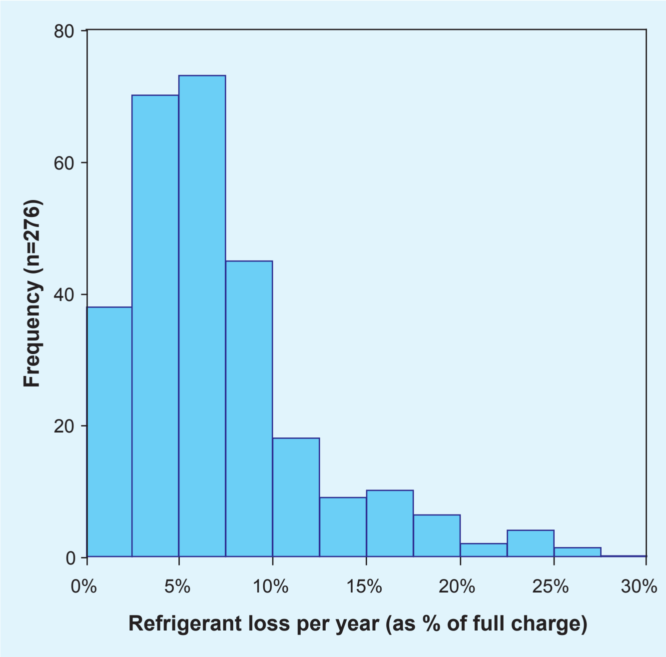

Figure 3.2. Distribution of annual leakage rates of mobile air conditioning systems in a fleet of 276 European passenger vehicles (after Schwarz & Harnisch, 2003.

from a survey carried out on mobile air-conditioning systems in Europe (Schwarz and Harnisch, 2003). A similar distribution is seen with supermarket systems (Radford, 1998). It is clear that the mean leakage rate for an equipment population can result from a broad distribution that includes many very tight, a large number of fairly tight and a small number of very leaky systems.

Decision-makers should realise that, in general, a leakage rate is not necessarily intrinsic to a certain technology but can also strongly depend on a number of environmental and operational factors. If properly understood, these factors can be systematically influenced to reduce emission levels. Whilst the quality of maintenance and repairs to equipment influence the leakage during operation, the actual handling of refrigerant may also lead to significant emissions, for example the removal of fluid from a system and the subsequent recharge. The degree of leakage is strongly dependent on the behaviour of the personnel and the tools they use, and will range from the minimum (that associated with residual gas within hoses and the system) up to quantities exceeding the system charge. Despite the legislation against venting in a number of countries, practices frequently prevail in which the whole system is vented, leak-tested with the fluid (possibly several times until all leaks are repaired) and flushed with the fluid before final recharging. Poorly connected hoses and fittings, and poor-quality recovery equipment can significantly contribute to high emissions.

The majority of emissions from aerosols, fire protection systems and solvents also occur during the in-use stage, although these are intentional since a release is part of the functionality of the equipment. Emissions from aerosols are simply a function of the amount of propellant used. Fire protection systems produce emissions upon demand, as is the intention, although undesired emissions occur from false alarms or faulty signals, or from mandatory system qualification tests that require full system discharge. Sometimes training also involves the operation of the fire protection system. Within the use phase of certain applications, such as fire protection systems, equipment servicing and maintenance may require the removal of fluid from a system and subsequent recharge, and emissions associated with this. Fire protection systems also exhibit slow passive emissions throughout the in-use stage, particularly in the case of high-pressure cylinder systems. Similarly systems that are being maintained can produce significant emissions if the system is accidentally initiated, or when servicing of the systems requires checking and confirmation of operation. Processes that use solvents generally lead to emissions as a result of residual fluid evaporation of treated items, and to a lesser extent whenever equipment is opened as part of its use.

Annual emissions from foams are generally minor during the in-use stage. The blowing agent in closed cell foams is released over time and typically only part of the blowing agent/insulant will be released during the useful life of the product. Caleb (2000) has calculated emission factors for different rigid foams based on a survey and the collection of data from emission factors reported in the literature. Lee and Mutton (2004) recently did the same for extruded polystyrene or XPS foam.

Decommissioning

Fluids may be vented or recovered during the decommissioning of refrigeration equipment, unexpelled fire protection systems and equipment using solvents. Over the past decade the price of recovery equipment has fallen significantly and the sales of such equipment have expanded, indicating that recovery has become much more widespread than was the case during the 1980s and first half of the 1990s. Blowing agents from foams and propellant from aerosols can also be recovered at end-of-life, but current methods have a low effectiveness. Emission levels of refrigeration and air-conditioning systems, and of foam applications are very sensitive to disposal practices.

For refrigerants, fluids from fire protection systems and solvents, the sources of emissions associated with removal at end-of-life are the same as those associated with normal handling, as discussed previously for the servicing aspect during the in-use stage. Fluids used to be vented when equipment was decommissioned but where legislation has been introduced, the expected practice is to recover the fluid. If the fluid is recovered, it may be re-used (in its recovered form), recycled (using on-site machinery) or taken back to the supplier or recycling centre for cleaning (and re-use) or disposal. Uncontaminated fluids can normally be reused and whether a fluid can be cleaned on-site or has to be returned to the supplier, depends on the type and degree of contamination and the process needed to return it to the purity of virgin fluid. However, in many situations, the resources required to clean up contaminated refrigerant rarely outweigh the risks and benefits to the service company. Therefore in most countries recovery rates have remained low if the chemical to be recovered is relatively inexpensive. Some suppliers or governments (e.g. Australia) have introduced cash incentives for the return of 'minimally-contaminated' refrigerant, but the success rate of such schemes is still unknown.

In the case of rigid insulating foams, the majority of blowing agents remain in the foam until end-of-life. Some rigid insulating foams such as 'board stock' and 'sandwich panels' can be recovered or re-used if they are not adhered to substrates or can be easily separated from these. A similar approach can be used with aerosol cans that contain residual propellant, although this procedure is not normally used.

Disposal

Following the recovery, and potentially recycling and reclamation, of refrigeration equipment, fluids meant for disposal are stored ready for destruction. The handling and storage of refrigerants and fire protection system fluids, solvents and recovered aerosol propellants prior to destruction can lead to emissions in the same way as in the distribution of fluids stage.

In the case of rigid insulating foams, the disposal is complicated because the foams are only a small part of overall systems such as a refrigerator or a building. Refrigerator foams can be shredded and incinerated to destroy all blowing agents. Alternatively they can be sent to landfills, where the blowing agents will slowly be emitted and/or decompose (Kjeldsen and Scheutz, 2003).

In general, destruction by incineration produces a small amount of emissions (of the original material). Destruction (or destruction and recovery) efficiencies are typically between 99% and 99.99%, resulting in 0.1–10 g released per kg of material (UNEP-TEAP, 2002). Gases such as CO_2, resulting from the combustion of fuel and fluid, are also emitted.

3.2.1.2 Types of emission

Table 3.2 identifies the types of emission common to the various applications in the subsequent technical chapters. These can be categorized into four general groups. Mitigation of emissions for each category requires attention for a particular process within the life of the equipment: Material selection (passive), mechanical design/construction (rupture), technician training (handling) and usage patterns (intentional/functional).

Passive

Passive emissions are generally small, 'seeping' leaks that occur constantly and are normally the result of permeation through construction materials and metal fatigue. This applies in particular to refrigerants, fire protection system fluids and aerosols when materials gasket, plastics and elastomers for seals and hosing are used. Emissions are minimized by selecting the correct materials for the fluids used. In making this choice, the influence of other fluids within the mixture such as refrigeration oils and aerosol fragrances, which can affect permeability, should also be considered. In rigid insulating foams, the passive emission of blowing agents occurs through diffusion. The diffusion coefficients of HFCs through the rigid insulating foams vary considerably, dependent on the type of blowing agent. The use of non-permeable facer materials such as aluminium foils and metal skins can significantly reduce the diffusion of blowing agents. Passive emissions typically occur throughout all stages of the fluid and foam life, but as they are relatively constant, they predominate during the in-use stage.

Table 3.2. Sources of emissions by type and application.

Application	Production				Use				Decommissioning				Disposal			
	Passive	Rupture	Handling	International	Passive	Rupture	Handling	International	Passive	Rupture	Handling	International	Passive	Rupture	Handling	International
Refrigeration		✓	✓	✓	✓	✓	✓	✓			✓	✓			✓	✓
Air conditioning		✓	✓	✓	✓	✓	✓	✓			✓	✓			✓	✓
Mobile air conditioning		✓	✓	✓	✓	✓	✓	✓			✓	✓			✓	✓
Foams			✓	✓	✓				✓		✓				✓	✓
Aerosols			✓	✓	✓	✓		✓			✓	✓		✓	✓	✓
Fire protection			✓	✓	✓	✓	✓	✓			✓	✓			✓	✓
Solvents			✓	✓	✓	✓		✓			✓	✓		✓	✓	✓

Note: Fluid manufacture and distribution are excluded from this table since they do not pertain to any one specific application.

Rupture
Ruptures are accidental breaks in pressure systems, such as fractures in pipework, vessels and components. These are normally associated with fluids under high pressure and therefore tend to occur throughout most stages of the fluid life. Ruptures can result from external forces applied to components, inherent material weaknesses, the influence of pressure and temperature changes, vibration, the ageing of materials and corrosion. Large ruptures are generally the most notable type of leaks and tend to cause rapid and often complete release of the fluid. Rupture leaks or emissions do not apply to foam because the pressure differential within and outside the foams is very small. Ruptures can be minimized by appropriately designing piping and components to account for anticipated stresses, protecting against external impact and avoiding a chemically aggressive environment.

Handling
Handling emissions are unintentional releases that occur with human intervention, for example, where a fluid is being transferred into or out of equipment and complete recovery is impractical. Residual amounts of fluid occur in transfer hoses, within components and systems following recovery, and absorbed in certain materials such as oil. The fluid will subsequently migrate to the atmosphere when hoses are disconnected or systems are opened following recovery. Such releases occur throughout the life of the fluid regardless of the application, but a lack of training and insufficient awareness of the environmental impact of fluids means that personnel are less likely to mitigate emissions when handling them.

Intentional/Functional
Intentional releases are determined by human activity and may be unnecessary or required because of the function of the application (e.g. aerosols, fire protection). Unnecessary intentional releases occur where the operator chooses to directly release the fluid to the atmosphere. Examples include venting where the fluid is not recovered following removal from an application, the fluid being released directly through opening valves or cutting into pipe work, or the operator employing the fluid for ulterior uses such as blowing dust from pipes, and so forth.

Functional emissions occur specifically with fire protection, aerosols and some solvent uses. In situations where the fluid is within storage facilities, or within pressure systems during the in-use stage, intentional releases can occur in response to uncontrolled circumstances, for example, when pressure relief devices vent in the event of fire. Similarly, fire protection systems may release fluid in response to false signals from heat, smoke or light detectors, thus discharging the whole system.

3.2.1.3 Measurement and estimation of emissions
Quantifying emissions from a specific application is useful for several purposes, including the retrospective environmental impact assessment or the evaluation of operating costs. Unfortunately for most applications it is difficult to measure the field leakage and even where this is possible, the measurement is imprecise. Laboratory studies are largely impractical for most applications, for example large supermarket refrigeration systems that are built and maintained by a number of different companies. However, emissions from foams are usually less sensitive to external conditions and so laboratory measurements are normally highly appropriate. Releases during fluid manufacture, fluid distribution and the manufacture/distribution of equipment would normally be measured by monitoring the mass flow of material into and out of facilities. The same applies at end-of-life, when recovered fluid is returned to suppliers and delivered to recycling or incineration facilities.

Since releases at the in-use stage tend to predominate, these are more frequently monitored. The problem with existing methods such as gas detection is that they do not measure the mass of fluid released; concentrations of leaked gas detected indicate the presence of a leak, but do not permit this to be quantified (Van Gerwen and Van der Wekken, 1995). Recent developments in leak detection for refrigerating systems include intrinsic detectors, where a reduction in refrigerant inventory is measured within the system (as opposed to measuring the presence of refrigerant outside it) (Peall, 2003, www.nesta.org.uk/ourawaardees/profiles/3763/index.html). Such an approach is particularly useful for accurately measuring the loss of charge but does not provide information on losses from handling activities. The most accurate method is to record the mass usage of the substance. For refrigerating equipment, fire protection systems and solvent use, this involves tracking the quantities of chemicals that are acquired, distributed and used to fill a net increase in the total mass (charge) of the equipment. Quantities not accounted for are assumed to have been emitted. Entities that contract equipment maintenance to service companies can estimate their emissions by requesting the service company to track the quantities of refrigerant recovered from and added to systems.

Different approaches can be used to prediction emissions associated with particular equipment or systems. The least accurate but most simplistic approach is to apply annual leak rates (% yr^{-1}) for the appropriate sector or equipment types to the mass of fluid used. However, these are generally approximated using bottom-up methods, combined with limited measured data and industry interviews (e.g. March, 1996). At best, leak rates may be found for equipment manufacture, aggregate in-use stage and end-of-life recovery. More detailed analyses may be conducted by calculating releases from each element throughout the equipment life. This also depends on good information about the flow of material throughout its life, data on component dimensions and knowledge about the behaviour of technician handling (US EPA, 1995). For example, Colbourne and Suen (1999) provide empirically-derived emission indexes for the leakage of different components and different servicing frequencies in order to estimate leakage for a whole system. With this more detailed approach, the actual design of systems and equipment can be more accurately assessed and ‘emission optimization’ can be applied to the design and operation.

Nevertheless, it is known that leakage rates are highly erratic and for two similar systems these may vary from 0% to over 100% yr^{-1}.

The emission of foam-blowing agents through diffusion can be derived from model calculations (Vo and Paquet, 2004; Albouy *et al*., 1998). Alternatively, the residual quantity of blowing agents can be determined analytically, although caution must be exercised when using these measurements to estimate in-use emissions. Although the emission of the blowing agent out of a well-defined foam system (e.g., a refrigerator or a piece of rigid foam) can be estimated, obtaining accurate emissions from the foam sector remains difficult due to the variety of foams, blowing-agent initial concentrations, diffusion rates of specific blowing agents, product thicknesses, densities, usage conditions and cell structures.

Direct measurement of greenhouse gas and other fluid emissions is only possible in a few cases and so the values described as 'real' data have to be calculated from secondary data. These calculations should conform to the standard methodologies already developed for emissions trading, which cover refrigeration and air-conditioning systems and chemical processes (DEFRA, 2003), and the standards and guidance for greenhouse-gas emissions inventories (IPCC, 1997; IPCC, 2000a).

The IPCC Good Practice Guidance on National Greenhouse Gas Inventories published in 2000 (IPCC, 2000a) includes three methods for estimating emissions of ODS substitutes. The tier 1 method that equates emissions to consumption (potential emissions), the tier 2a bottom-up method that applies country-specific emission factors to estimates of equipment stock at different life-cycle stages, and the tier 2b top-down method that uses a country-level, mass-balance approach. For sectors where the chemical is banked into equipment, the tier 1 method is significantly less accurate than the other two approaches. This is particularly the case where the equipment bank is being built up and this is precisely the current situation for air conditioning and refrigeration equipment during the transition from CFCs and HCFCs to HFCs. In this situation, most of the chemical consumed is used to fill new equipment volume (charge) rather than to replace emitted gas, and therefore the tier 1 method greatly overestimates emissions. To a lesser extent, the tier 2b country-level, mass-balance approach is also inaccurate during the period of bank building, but in this case, the error is an underestimate (see the discussion in Section 3.2.1.3 for an explanation of this underestimate). That is why the IPCC recommends supplementing the tier 2b approach with the tier 2a emission-factor based approach. The disadvantage of the tier 2a approach is that for the first few years of equipment life, the emission factors will necessarily be based on engineering estimates rather than empirical experience. However, when the first cohort of equipment is serviced, the emission factors can be corrected as necessary. Ultimately, when the HFC-using equipment starts to be retired, the tier 2b method can be used on its own with a high level of accuracy.

More detailed requirements for calculations are stated in IPCC (1997). IPCC (2000a) should be consulted for additional guidelines on emission estimation methods, particularly for the different sectors.

3.2.2 *Indirect emission*

This section examines aspects related to emissions arising from the energy consumption associated with the manufacturing of products and their components, the use of these products during their useful life and their disposal. The use phase is outlined for cooling applications, heat pumps and foams, as this phase usually dominates the energy consumption of these systems. More application-specific energy aspects are covered in the specific sections of Chapters 4 to 10 of this report.

3.2.2.1 Use phase

ODS substitutes are typically used in cooling applications and thermal insulation foams. For aerosols, solvents and fire protection, the energy consumption during the use phase is not relevant.

Cooling applications and heat pumps

The refrigeration, heat pump and air-conditioning sectors use different approaches to establish and compare energy efficiencies for various technologies:

- Modelled efficiencies based on modelled coefficients of performance (COP);
- Measured efficiencies of products in the research and development phase (established under standard test conditions)[2];
- Measured efficiencies of products in mass productions (established under standard test conditions);
- Measured consumption under representative real conditions.

The coefficient of performance (COP[3]) of a refrigerating plant, product or system is a key parameter for characterizing the energy efficiency of a process. It is the ratio of refrigerating capacity to the input power required to operate the compressor, pumps, fans and other ancillary components.

$$COP = Q_0 / P \qquad (3.1)$$

Where:

Q_0 is the refrigerating capacity (cooling mode) or heating capacity (heating mode) including an allowance for losses in any secondary circuit (kW), and

[2] It is important that the standard conditions represent the situation in which the equipment will be used; for example it would not be appropriate to use standard test results gained at an ambient temperature of 15°C when the real ambient temperature of operation of the equipment is 35°C.

[3] In European standards and some ISO standards the term EER (Energy Efficiency Ratio) is used for the cooling mode of the cycle and COP (Coefficient Of Performance) is used for the heating mode. For the purpose of this report only one term is used, COP. Where this term is used, it should be specified whether it relates to cooling or heating.

P is the total power consumption (kW) of the compressors, controls, fans and pumps required to deliver that capacity to the place where it is used.

The COP primarily depends on the working cycle and the temperature levels (evaporating/condensing temperature) but is also affected by the properties of the refrigerant and the design of the system. Energy consumption estimated from known models does not usually take into account the effects due to different 'real-world' handling practices, imperfect design, assembly, capacity control and maintenance. Small fluid leakage, for example, not only impacts direct emission but also indirect emission due to a decrease in the COP of equipment. Figure 3.3 gives an example of the real world spread of measured energy consumptions for a large group of homogenous refrigeration systems. Another typical example is the use of capacity control technologies to optimize the energy consumption. Good capacity control results in smaller pressure differences (evaporating/condensing temperature) leading to improvements of the overall energy efficiency of the system.

Insulation foams

There are two fundamental approaches to assess the effects on energy consumption of using insulation materials with differing insulation properties as a result of a changed blowing agent (Table 3.3).

Further the specific usage pattern of the system should be noted and addressed if it is material to the calculation. One example might be the effect of day to night temperature changes on a cold store that has traffic through it 24 hours per day as opposed to one that is shut up all night. Both approaches need to be documented with references to standard calculation methods and sources of information.

Approach B in Table 3.3 depends on more assumptions than approach A and is conceptually more challenging. However circumstances can arise in which thickness compensation is technically not possible due to space constraints and then approach B is the only feasible method. Even if partial thickness compensation is possible, the calculation of energy impacts will still require approach B.

In general these comparisons are limited to identical systems where only one element has been changed. Comparisons between completely different systems are much more difficult

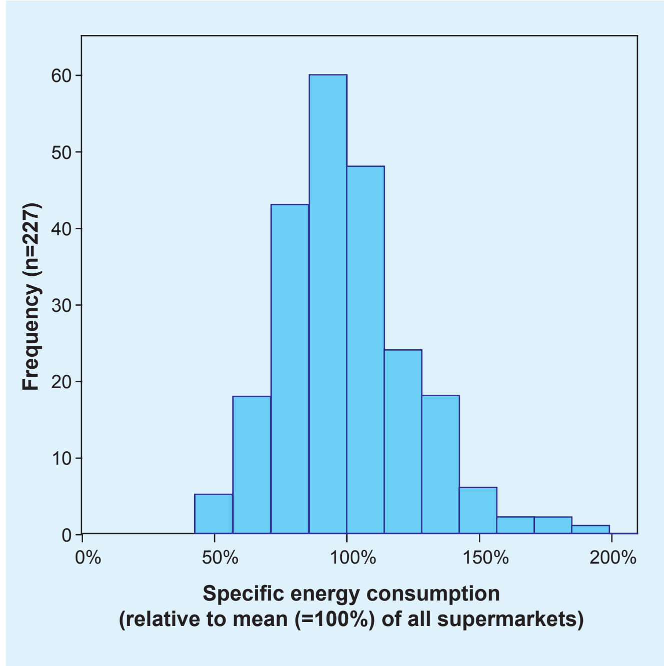

Figure 3.3. Distribution of measured specific energy consumptions (originally expressed as kWh d^{-1} m^{-1} of cooled display cases) expressed as percentage of the mean for 227 standard stores using standard HFC technology of a German supermarket chain – after Harnisch *et al.* (2003).

Table 3.3. Comparison of two approaches for comparing the impact of blowing agent choice on energy consumption.

Approach A) Thickness compensation:

The thickness is increased for any loss of insulation value so that unchanged energy consumption is assumed to be achieved by a material penalty. This may have an environmental impact due to increased direct emissions and the energy used for production. However, for the energy consumption during the usage phase, the key requirements are relatively simple and involve characterization of:

- The functional unit and its desired service (e.g. required common additional heat resistance R value m^{-2} of application and time);
- The insul
respective thickness and density or mass);
- The insulation properties of the foam(s) using a test appropriate to the duty (e.g. respective thermal conductivity values).

Approach B) Comparative energy modelling:

Where it is not possible to com pensate for a change in insulation value, the energy consumption of the system in which the foam is used is calculated for both the reference case and alternative case. This is a more complex process and, in addition to the parameters outlined above, it will require definition of:

- The type and efficiency of the process supplying heat or cold (to accommodate change in efficiency with temperature);
- The appropriate ambient conditions and the internal temperature profile require or alternatively a description of an appropriate proxy (for example heating or cooling degree days);
- Internal sources of heat or cold and how the demand will change with temperature.

to interpret. Examples of comparisons of different foam types, where the model assumptions are clear and do not compromise the results, are given in Caleb (1998, 1999), Enviros March (1999), ADL (1999), Krähling and Krömer (2000), Harnisch and Hendriks (2000) and Harnisch *et al*. (2003).

3.2.2.2 Production energy of fluids and fugitive emissions

Table 3.4 details the small number of estimates of production energy (also known as embodied energy) and fugitive emissions associated with the production of the materials used in systems covered by this report. These estimates are also summarized and applied in Frischknecht (1999a and 1999b) and Harnisch *et al*. (2003). It is worth noting that the newer study shows lower values for HFC-134a due to more widespread application of vent gas treatment to destroy 'fugitive' HFC streams (in previous studies these were emitted into the atmosphere). In-use emissions usually dominate environmental impact and production energy, whereas fugitive emissions only make small contributions.

3.2.2.3 Indirect emissions from energy use

Indirect emissions (of carbon dioxide) from the energy used to operate a system comprise those arising from the generation of the electricity consumed (for example by the compressor, controls, pumps and fans of a building air-conditioning system) and any fuel used directly by the system (e.g. gas used for gas-driven compressors, fuel used by absorption systems or the additional gasoline usage associated with automobile air conditioning). The total lifetime emission of carbon dioxide from the energy used to operate the system (E_I) is:

$$E_I = Q_E \text{ x } I_E + \sum(Q_{Fi} \text{ x } I_{Fi}) \qquad (3.2)$$

Where:
Q_E is the total lifetime use of electricity;
I_E is the carbon dioxide intensity of electricity production (from Table 3.5);
Q_{Fi} is the total lifetime use of fuel *i*, and
I_{Fi} is the carbon dioxide intensity of that fuel (from Table 3.5)

Carbon dioxide emissions associated with the generation of electricity vary greatly between countries depending on the specific mix of generation technologies and fuels (e.g. coal, natural gas, combined cycle systems, hydroelectricity, etc.) used. Increasingly complex calculations could be performed to define the minute details of energy-related emissions of carbon dioxide and other greenhouse gases. However for the generic approach described here, it is assumed that the most important emission is carbon dioxide and that the methods employed by the International Energy Agency (IEA) will give internationally consistent estimates. Accordingly, national and regional carbon dioxide intensities of electricity are shown in Table 3.5. These intensities are calculated as the ratio of national carbon dioxide emission from electricity generation, taken from IEA (2002b), to the quantity of electricity used nationally, obtained from IEA (2002a) or IEA (2003). The IEA statistics take into account electricity trading between countries, in the form of an annual average.

For those countries or regions not shown in Table 3.5, the national carbon dioxide intensity of their electrical power (I_E) may be calculated as the sum of the total of each fuel used in electricity generation, multiplied by its carbon dioxide intensity (also quoted in Table 3.5), divided by the total national quantity of electricity *delivered* to customers.

$$I_E = \sum (Q_{Fi} \text{ x } I_{Fi}) / D_E \qquad (3.3)$$

Where:
Q_{Fi} is the total annual quantity of fuel *i* used in electricity generation and I_{Fi} is the carbon dioxide intensity of that fuel (from Table 3.5), and

Table 3.4. Overview of production energy requirements and associated CO_2 emissions.

Material	Production Energy Requirement MJ kg^{-1}	Equivalent Production CO_2 Emissions kg CO_2-eq kg^{-1}	Reference
Aluminium	170	-	Lawson (1996)
		7.64	Ingots : SAEFL (1998)
		2.06–6.56	Pira (2001)
Steel/iron		2.95	Sheet: SAEFL (1998)
		1.60–2.78	Pira (2001)
Stainless Steel	38	-	Lawson (1996)
Copper	100	-	Lawson (1996)
Brass		2.97	Plate: SAEFL (1998)
		11.4–16.1	Norgate and Rankin (2000)
Glass	13	-	Lawson (1996)
HFC-134a (I)	64–105	6–9	Campbell and McCulloch (1998)
HFC-134a (II)	-	4.5	McCulloch and Lindley (2003)
Cyclopentane	24	1	Campbell and McCulloch (1998)
Ammonia	37	2	Campbell and McCulloch (1998)

Table 3.5. Carbon dioxide intensities of fuels and electricity for regions and countries.

Region	Carbon Dioxide Intensity Of Electricity kg CO_2 kWh^{-1}	Note
		a
Africa	0.705	b
Asia	0.772	b
EU	0.362	c
Europe (OECD)	0.391	c
Europe (non-OECD)	0.584	b
Latin America	0.189	b
Middle East	0.672	b
N America	0.567	c
Pacific	0.465	c
Former USSR	0.367	c

Carbon Dioxide Intensities Of Fuels Used In The Calculations	g CO_2 MJ^{-1}	
Fuel		
Natural gas	56.1	d
Gasoline	69.3	d
Kerosene	71.5	d
Diesel Oil	74.1	d
Liquefied Petroleum Gas	63.1	d
Residual Fuel Oil	77.4	d
Anthracite	98.3	d
Bituminous Coal	94.6	d
Sub-bituminous coal	96.1	d
Lignite	101.2	d
Oil Shale	106.7	d
Peat	106.0	d

Country	Carbon Dioxide Intensity Of Electricity kg CO_2 kWh^{-1}	Note
Argentina	0.319	b
Australia	0.885	c
Austria	0.187	c
Belgium	0.310	c
Brazil	0.087	b
Canada	0.225	c
China	1.049	b
Denmark	0.385	c
Finland	0.222	c
France	0.078	c
Germany	0.512	c
Greece	0.876	c
India	1.003	b
Indonesia	0.715	b
Ireland	0.722	c
Italy	0.527	c
Japan	0.389	c
Malaysia	0.465	b
Mexico	0.689	b
Netherlands	0.487	c
New Zealand	0.167	c
Norway	0.003	c
Pakistan	0.524	b
Philippines	0.534	b
Portugal	0.508	c
Russia	0.347	b
S Africa	0.941	b
Saudi Arabia	0.545	b
Singapore	0.816	b
Spain	0.455	c
Sweden	0.041	c
Switzerland	0.007	c
UK	0.507	c
USA	0.610	c

Notes:

a. Regions as defined in IEA (2002a) and IEA (2003).

b. Carbon dioxide from “Public Electricity and Heat Production”5 (units Mtonnes CO_2) in summary tables of IEA (2002b), divided by Total Final Consumption electricity and heat6 given as ktonne Oil Equivalent in IEA (2002a), further divided by 11.63 to convert to kg CO_2 kWh^{-1}.

c. Carbon dioxide as in 2 above, divided by Total Final Consumption[4] given as GWh in IEA (2003), multiplied by 1000 to convert to kg CO2 kWh^{-1}.

d. Values from Table 3 of IEA (2002b) multiplied by 44/12 to convert to mass of CO_2.

e. Using this category has the effect that all energy inputs to systems that generate electricity and heat are counted against both the electricity and heat generated.

f. Total Final Consumption is electricity or heat available at the consumer net of transmission and distribution losses.

D_E is the total annual national delivery of electricity. Table 3.6 shows examples of the application of this method.

Where there is a nationally agreed energy plan for the future, figures from this may be used for assumptions about future indirect emissions from energy use.

3.3 Categories of costs

The cost of climate change mitigation is an important input to decision-making about climate policy goals and measures. This section provides an oerview of key concepts and assumptions that can be applied to the assessment of policy options related

Table 3.6. Carbon dioxide intensity calculation for representative countries.

	Fuel mix (for electricity generation only)											
	Coal			Fuel oil		LPG		Natural gas				
Type	Usage	Calorific value	*Emission factor*	Usage	*Emission factor*	Usage	*Emission factor*	Usage	*Emission factor*	**Total CO_2 emissions**	**Electricity generated less distribution losses**	**Carbon intensity**
	kt	TJ/kt	*tCO_2/TJ*	kt	*tCO_2/TJ*	kt	*tCO_2/TJ*	kt	*tCO_2/TJ*	$ktCO_2$	GWh_e	$kgCO_2/kWh_e$
A	B	C	D	E	F	G	H	I	J	K	L	M
First Country Example												
Sub bituminous	112,775	18	*96.1*	118,712	*77.4*	0	*63.1*	127,574	*56.1*	21,0558	234,000	0.900
Second Country Example												
Bituminous	11,430	27	*94.6*	57,173	*77.4*	304	*63.1*	47,558	*56.1*	36,288	62,059	0.585
Third Country Example												
None				3,892	*77.4*	0	*63.1*	3,160	*56.1*	48	1,750	0.273

Notes:

Values in italics are constants available from standard tables (see Table 3.5 here)

A. Both the calorific value and the carbon content (and thus emission factor) vary with the quality of coal.

B. More than one quality of coal may be used (and separate rows should be used, then added together).

C. Calorific value varies between sources and should be determined by testing.

D, F, H, J. CO_2 emission factors are shown in Table 3.5

K. The value in K is equal to (B x C x D + E x F + G x H + I x J) divided by 1000.

L. This is the total electrical production minus only the amount lost in distribution.

M. The carbon intensity is equal to K divided by L.

to technologies and production processes using fluorinated gases. The use of consistent and well-defined cost concepts is recommended for the assessment of the various technologies and options described in detail in various parts of this Special Report, and for reporting the assumptions and concepts applied in mitigation studies in a thorough and transparent manner.

3.3.1 Introduction

Actions to abate emissions of fluorinated gases generally divert resources from other alternative uses, and the aim of a cost assessment is to measure the total value that society places on the goods and services foregone due to resources being diverted to climate protection. Where possible the assessment should include all resource components and implementation costs and should therefore take into account both the costs and benefits of mitigation measures.

A key question in cost analysis is whether all relevant dimensions (e.g. technical, environmental, social) can be measured in the same units as the costs (i.e. monetary). It is generally accepted that some impacts, such as avoided climate change, cannot be fully represented by monetary estimates and it is imperative that the cost methodology is supplemented by a broader assessment of impacts measured in quantitative and if needs be qualitative terms.

In any economic analysis of climate change mitigation, the cost of mitigation is calculated as a difference in costs and benefits between a baseline case and a policy case that implies lower emissions. Where possible, the definitions of the baseline and policy cases should include all major social, economic and environmental impacts (at minimum from GHG emissions and ODP emissions). In other words, the system boundary of the cost analysis should facilitate the inclusion of all major impacts. The system boundary can be a specific project, one or more sectors, or the entire economy.

The project, sector and macroeconomic levels can be defined as follows:

1. *Project*. A project level analysis considers a 'stand-alone' investment that is assumed not to have significant impacts on markets beyond the activity itself. The activity can be the implementation of specific technical facilities, demand-side regulations, technical standards, information efforts, and so forth. Methodological frameworks to assess the project level impacts include cost-benefit analysis, cost-effectiveness analysis and Life Cycle Assessment.

2. *Sector.* Sector level analysis considers sectoral policies in a 'partial equilibrium' context, for which all other sectors and the macroeconomic variables are assumed to be as given.

3. *Macroeconomic.* A macroeconomic analysis considers the impacts of policies across all sectors and markets.

Costs and benefits can be reported in present values or as levelized values (alternative ways to generate time-consistent values for flows of costs and benefits that occur at different points in time). Further details about these approaches can be found in Box 3.1.

This report focuses on project level cost analysis in particular because a); the scale of the mitigation policies analyzed can be considered small enough to exclude significant sectoral and economy-wide impacts; b) the basis for conducting a sectoral level cost analysis is weak since the literature does not include sectoral modelling studies for activities which involve the production and use of ODSs and their substitutes; c) and finally the current section is a first attempt to define consistent cost concepts applied to the assessment of climate change and ODS mitigation policies.

3.3.2 Direct engineering and financial cost approach

At the project level, the simplest cost assessment considers the financial costs of introducing a new technology or a production process that has lower emissions than the baseline case. Such practices can imply capital costs of new investments and changed operation and maintenance costs. When the system boundary is defined to include only the financial costs associated with the project implementation, some studies been termed this the direct engineering or financial cost approach.

Policy implementation can require upfront capital costs and changes (decreases or increases) in operation and maintenance costs compared with the baseline case over the lifetime of the project. Major categories of costs accounted in a financial cost assessment are capital, labour, land, materials, maintenance and administrative costs. The various costing elements need to be transformed into values that are comparable over the time frame and as such the cost assessment depends on assumptions about discount rates. The time dimension of costs can be dealt with using various policy evaluation approaches and an overview of some of those applied to the cost-effectiveness analysis of projects is given in Box 3.1.

3.3.2.1 Discounting

There are two approaches to discounting (IPCC, 1996b). One approach (known as ethical) gives special attention to the wealth of future generations and uses a social discounting rate. Another approach (known as descriptive) is based on the discount rates savers and investors actually apply on their day-to-day decisions and uses a higher, private cost discount rate. The former leads to relatively low rates of discount (around 2–3% in real terms) and the latter to relatively higher rates (at least 6% and in some case very much higher rates) (IPCC, 2001b, pp. 466).

For climate change, a distinction needs to be drawn between the assessment of mitigation programmes and the analysis of impacts caused by climate change. The discount rate applied in cost assessment depends on whether the social or private perspective is taken. The issues involved in applying discount rates in this context are addressed below. For mitigation effects, the

BOX 3.1 – The NPV and Levelized Cost Concepts

Guidelines for project assessment use a number of different concepts to compare the cost-effectiveness of projects. The most frequently used concepts are net present value (NPV) and levelized cost. These concepts basically provide similar project ranking.

The NPV concept

The NPV concept can be used to determine the present value of net costs, *NPVC*, incurred in a time period T, by discounting the stream of costs (C_t) back to the beginning of the base year (t = 0) at a discount rate I:

$$NPVC = \sum_{t=0}^{T} C_t / (1+i)^t$$

The levelized cost concept

The levelized cost represent a transformation of the *NPCV* into constant annual cost values, C_0, over the lifetime of the project. The levelized costs are calculated as a transformation of the *NPVC* using the formula:

$$C_0 = NPVC\left(i / \left(1 - (1+i)^{-n}\right)\right)$$

where n is the time horizon over which the investment is evaluated.

The levelized costs can directly be compared with annual emission reductions if these are constant over the project lifetime.

The use of NPV and levelized costs as project ranking criteria is valid, given a number of assumptions:

NPV

An investment I_1 is more favourable than another investment I_2 if $NPVC_1/GHG\ reduction < NPVC_2/GHG\ reduction$. It should here be noticed that the use of NPVCs to compare the cost-efficiency of projects requires that some discounting criteria be applied to the annual greenhouse-gas emission reductions. The NPVC/GHG ratio can be used to rank investments with different time horizons.

Levelized cost

An investment I_1 is more favourable than another investment I_2 if the levelized cost of I_1 per unit of annual emission reduction is less than the levelized cost of I_2 per unit of annual emission reduction. The levelized costs should be calculated for similar investment lifetimes. The lifetimes of the investments if necessary can be made uniform by adding terminal values to investments with relatively long life time, or by replicating investments that have a relatively short lifetime.

country must base its decisions, at least in part, on discount rates that reflect the opportunity cost of capital. In developed countries, rates of around 4%–6% are probably justified (Watts, 1999). In developing countries the rate could be as high as 10–12%. These rates do not reflect private rates of return, which typically need to be considerably higher to justify the project, potentially between 10% and 25%.

For climate change impacts, the long-term nature of the problem is the key issue. The specific benefits of a GHG emission reduction depend on several factors such as the timing of the reduction, the atmospheric GHG concentration at the time of reduction and afterwards.. These are difficult to estimate. Any 'realistic' discount rate used to discount the impacts of increased climate change impacts would render the damages, which occur over long periods of time, very small.

3.3.3 Investment cycle and sector inertia

In the area of technologies associated with the manufacture and use of fluorinated gases, observations about replacement rates of old products have shown that it has been possible to undertake investments with a payback period as low as 1 to 5 years. This evidence suggests that from an economic and technical point of view[4], it is possible to rely on mitigation policies that are fully implemented over less than a decade. However, social structures and personal values also interact with society's phys-

[4] There are some concerns about the capacity to maintain such fast technical transitions for future technical evolution in these sectors. Transition from CFCs to HCFCs was relatively easy because the chemistry was already known.

ical infrastructure, technology applications and institutions, and these combined systems have in many cases evolved relatively slowly. An example of such system inertia is seen in relation to the energy consumption for heating, cooling and transport, and the impacts of urban design and infrastructure. Markets sometimes tend to 'lock in' to specific technologies and practices that are economically and environmentally suboptimal, because the existing infrastructure makes it difficult to introduce alternatives. Similarly the diffusion of many innovations can be in conflict with people's traditional preferences and other social and cultural values (IPCC, 2001a, pp. 92-93).

At the same time, it should also be recognized that social and economic time scales are not fixed. They are sensitive to social and economic forces, and are influenced by policies as well as the choices made by individuals and institutions. In some cases behavioural and technological changes have occurred rapidly under severe economic conditions, for example during the oil crises of the 1970s (IPCC, 2001a, pp. 93). Apparently, the converse can also be true: In situations where the pressure to change is small, inertia is large.

Both of these issues should be considered when building scenarios about future GHG emissions from a sector. These lessons suggest that new policy approaches are needed. Instead of looking solely for least-cost policies given current preferences and social norms, policies could also aim at reshaping human behaviour and norms. This could support fast technology penetration and from a longer time perspective in particular, could imply cost reductions through learning and market development.

3.3.4 Wider costing methodologies – concepts

Up until now we have only considered the direct engineering and financial costs of specific technical measures. However, the implementation of policy options that mitigate climate change and ODSs will often imply a wider range of social and environmental impacts that need to be considered in a cost analysis.

3.3.4.1 Social and financial costs

In all work on costs, a basic distinction can be drawn between the social cost of any activity and the financial cost. Social cost is the full value of the scarce resources used in the activity measured from the point of view of society. Financial cost measures the costs from the perspective of a private company or an individual and bases its values on the costs that actually face these agents. A difference between social and financial costs arises when private agents do not take full account of the costs that they impose on other agents through their activities – such a cost is termed an external cost. Positive impacts which are not accounted for in the actions of the agent responsible, are referred to as external benefits.

External costs and benefits are distinct from the costs and benefits that companies or other private agents take into account when determining their outputs such as the prices of fuel, labour, transportation and energy, known as conventional company costs, and also from environmental costs usually accounted in more complete evaluations of company costs (see Table 3.7). Categories of costs that influence an individual's decision-making are referred to as private costs. The total cost to society is the sum of the external and private costs, which together are defined as social cost:

$$\text{Social Cost} = \text{External Cost} + \text{Private Cost} \qquad (3.4)$$

The scope of the social and private costs is illustrated in Figure 3.4.

External costs typically arise when markets fail to provide a link between the person who creates the 'externality' and the person who is affected by it, or more generally when property rights for the relevant resources are not well defined. Externalities do not necessarily arise when there are effects on third parties. In some cases, these effects may already be recognized, or 'internalized' and included in the price of goods and services. Figure 3.4 illustrates different subcategories of environmental costs, including external costs and private costs as faced by a private company. The centre box represents company costs that are typically considered in conventional decision-making. The next box (private costs) includes the typical costs plus other internal environmental costs that are potentially overlooked in decision-making, including regulatory, voluntary, up-front, operational, back-end, overhead, future, contingent and image/relationship costs. These 'private costs' include internal intangible costs (e.g., costs that could be experienced by a company related to delays in permitting, and so forth, and due to disputation with regulators and others). The box labelled societal includes environmental costs that are external to a company. These are costs incurred as a result of a company affecting the environment or human health, but for which the company is not currently held legally or fiscally responsible. These 'externalities' include environmental degradation and adverse effects on humans,

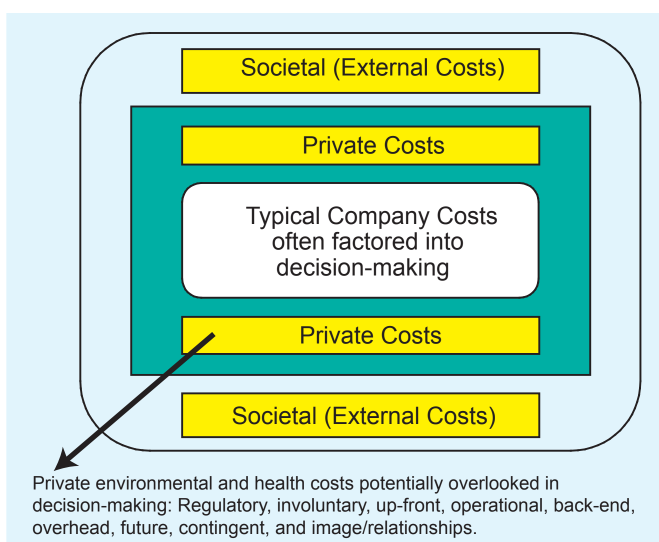

Figure 3.4. Scope of full costs (Adapted from US EPA, 1995).

Table 3.7. Examples of environmental costs incurred by firms.

Potential Hidden Costs		
Regulatory	**Upfront**	**Voluntary (Beyond Compliance)**
Notification	Site studies	Community relations/outreach
Reporting	Site preparation	Monitoring/testing
Monitoring/testing	Permitting	Training
Studies/Modelling	R&D	Audits
Remediation	Engineering at procurement	Qualifying suppliers
Record keeping	Installation	Reports (e.g., annual environmental reports)
Plans		Insurance
Training		Planning
Inspections	Conventional Costs	Feasibility Studies
Manifesting	Capital equipment	Remediation
Labelling	Materials	Recycling
Preparedness	Labour	Environmental studies
Protective equipment	Supplies	R&D
Medical surveillance	Utilities	Habitat and wetland protection
Environmental insurance	Structures	Landscaping
Financial assurance	Salvage Value	Other environmental projects
Pollution control		Financial support to environmental groups and/or
researchers		
Spill response	Back-End Costs	
Storm water management	Closure/decommissioning	
Waste management	Disposal of inventory	
Taxes/fees	Post-closure care	
	Site survey	
Contingent Costs		
Future compliance costs	Remediation	Legal expenses
Penalties/fines	Property damage	Natural resource damage
Response to future releases	Personal injury damage	Economic loss damages
Image and Relationship Costs		
Corporate image	Relationship with professional staff and workers	Relationship with lenders
Relationship with customers	Relationship with insurers	Relationship with communities
Relationship with investors	Relationship with suppliers	Relationship with regulators

Note. In upfront cost category, the centred box surrounded by dashed lines represents conventional costs, which are usually accounted.
Source: US EPA (1995).

property and welfare associated with emissions/activities that are performed in compliance with regulatory requirements. The figure does not directly portray the benefits that may be associated with alternative decisions.

3.3.4.2 Welfare basis of costs

The external effects described above cannot be valued directly from market data, because there are no 'prices' for the resources associated with the external effects (such as clean air or clean water). Indirect methods must therefore be used. Values have to be inferred from decisions of individuals in related markets, or by using questionnaires to directly determine the individuals' willingness to pay (WTP) to receive the resource or their willingness to accept payment (WTA) for the environmental good.

3.3.4.3 Ancillary costs and benefits

Projects or policies designed for GHG and ODS mitigation frequently have significant impacts on resource use efficiency, reductions in local and regional air pollution, and on other issues such as employment (IPCC, 2001b, pp. 462). When estimating the social costs of using technologies that impact climate change and/or ODS, all changes in cost arising from this activity have to be taken into account. If some of them imply a reduction (increase) in external costs, they are sometimes referred to as secondary, indirect benefits (costs) or ancillary benefits (costs).

3.3.5 Wider costing methodologies – cost categories

3.3.5.1 Project Costs

This item has already been discussed in the introduction of Section 3.3.2. However, the cost categories listed there may need to be adjusted when carrying out the wider cost methodology. Adjustments in land costs, labour, investments, materials, energy costs, environmental services and foreign exchange may be needed for private costs and external costs, and a detailed list is provided by Markandya and K. Halsnæs (2000).

3.3.5.2 Implementation cost

In addition to the above, the costs of implementation deserve special attention. Many aspects of implementation are not fully covered in conventional cost analyses (see Table 3.7). A lot of work needs to be done to quantify the institutional and other costs of programmes, so that the reported cost figures represent the full costs of policy implementation. As shown in Table 3.7, implementation costs depend on institutional and human capacities, information requirements, market size and the learning potential, as well as on market prices and regulations in the form of taxes and subsidies.

3.3.6 Key economic drivers and uncertainty

For various reasons cost estimates are shrouded by uncertainty and therefore any presentation of cost estimates should include transparent information about various keys to uncertainty that relate to both the baseline case and the new project case. Uncertainty in baseline cases is best dealt with by reporting cost estimates for multiple as opposed to single baselines. With this costs will not be given as single values, but as ranges based on the full set of plausible baselines (see for example IPCC, 2001b, pp. 30-37).

Uncertainties in cost estimates are related to both private and external cost components. Private cost figures tend to be less uncertain than external cost components, since the private costs primarily relate to market-based economic transactions. However, there is a particular uncertainty related to projections of future efficiency, and the costs and penetration rates of new technologies. One way to handle this uncertainty is to undertake a sensitivity analysis based on scenarios for high, low and medium case values (Markandya and Halsnæs, 2000). Another way of accounting is to consider some kind of 'learning curve', that is an expected cost reduction as a function of the increasing amount of products using the technology.

3.3.7 Other issues

3.3.7.1 Baseline Scenarios

Quite often the costs of a programme are evaluated against a situation where the programme is not implemented. This situation is defined by a baseline scenario, which tries to infer future conditions without the implementation of the programme. There are assumptions embedded in the baseline to forecast the future, for example, inefficient baseline, or 'business-as-usual' baseline. It is important to note that a programme's cost and benefit will vary according to this baseline scenario definition. For a mitigation programme, the cost will be larger if an economically efficient baseline is set rather than an inefficient one.

3.3.7.2 Macroeconomic costs

The cost of a programme can be measured using a macroeconomic analysis based on dynamic models of the economy. These models examine the impacts of a programme at an integrated level and allow for intersectoral effects. This means that they are more suitable for programmes large enough to produce impacts on other sectors of the economy.

On the other hand macroeconomic cost estimates generally provide less detail about technological options and externalities than project or sectoral cost estimates.

3.3.7.3 The equity issue

Equity considerations are concerned with the issues of how the costs and benefits of a programme are distributed and the climate change impacts avoided, as input to a more general discussion about the fairness of climate change policies. Equity concerns can be integrated in cost analysis by reporting the distribution of costs and benefits to individuals and society as a supplement to total cost estimates. Some authors also suggest applying income distribution weightings to the costs and benefits to reflect the prosperity of beneficiaries and losers (Ray, 1984; Banuri *et al*., 1996).

3.3.8 Conclusions

For most of the mitigation measures discussed in this Special Report, the specific measures (e.g. technical facilities, infrastructure, demand-side regulation, supply-side regulation, information efforts, technical standards) can be considered to have relatively small economic impacts outside of a narrow project border and can therefore be regarded as 'stand-alone' investments that are assessed using a project assessment approach. However, this does not imply that the cost assessment should solely limit itself to a consideration of the financial cost elements. A project system boundary allows a fairly detailed assessment of GHG emissions and the economic and social impacts generated by a specific project or policy. Accordingly various direct and indirect social costs and benefits of the GHG reduction policies under consideration should be included in the analysis.

Furthermore, it should be realized that as industrial competition increases, an increasing number of companies might become interested in using the most advanced production paradigms. For example, this was the case for lean production, an approach which evolved in Japan during the post-war period and implied greater flexibility in production and working partners. Many typical company features have included environmental concerns as well as broader issues of sustainable development as an evolving feature of the lean production paradigm.

In other words the companies have expanded the view about the boundaries of their own production.

Companies set boundaries around the activities they manage directly as well as those they do not control or manage. A distinctive feature of the lean production system has been an increasing transparency across firms that are dealing with different elements of the production chain. There has also been a tendency towards integrating management functions along the supply chain in order to examine the entire production chain for added value sources, irrespective of the current legal company boundaries along the chain. The application of information technology to business processes has facilitated the introduction of these new management systems. Without this the application of quantitative methods would have proved too complex (Wallace, 1996).

This new integrated management approach is illustrated in Figure 3.5. The figure shows a typical production chain, where the dotted line represents the boundary within the production process. Within that boundary, the management of the process may be integrated, irrespective of the number of companies involved or their exact legal relationship. This boundary might also include the extraction of raw materials, various product end-uses and even the disposal of the materials after use.

Every stage of production and consumption implies important environmental impacts. Companies are increasingly being required to explicitly manage these environmental impacts in response to formal regulations and pollution charges. Alternatively they might voluntarily adopt cleaner production technologies and tools, such as eco-auditing, in response to increasing expectations from society. Another driving force can be the increasing legislative liabilities of companies with respect to pollution. It is therefore useful for analysts to consider a system-wide company boundary that includes all stages of production in life cycle assessment, as shown in Figure 3.5.

3.4 Consideration of health and safety issues

Health and safety issues are an integral aspect of deciding the choice of fluids when alternatives are available, and the decisions can have far-reaching consequences for the workforce, domestic consumers, industry, the environment and the economy. Assessment methods for health and safety should first of all focus on minimizing negative health and safety impacts, and then consider risk management, policy and regulatory controls. This approach should be used for each step of the life cycle of the product including production, distribution, use, maintenance, repair and the end-of-life treatment such as destruction, re-use or recycling. Sometimes it can be wise to accept an increase in one life-cycle stage so as to arrive at an overall improvement in the impact accumulated over the life cycle. During the switch from ozone-depleting substances (CFCs and HCFCs) to HFCs, the health and safety risks of both groups of chemicals were similar. Here the main concern was energy efficiency and reliability. During the switch from higher GWP fluids to lower GWP fluids, health and safety often become a key issue. Some of the key considerations are examined in the following sections.

3.4.1 Prevention of negative health and safety impacts

Chemical exposure can cause or contribute to many serious health effects such as heart ailments, damage to the central nervous system, kidney and lungs, sterility, cancer, burns and rashes (US DoL, 1998). The impact of these effects includes lower productivity, absenteeism, increased health-care costs, litigation, and economic downturn at both the enterprise and national levels. Most countries have passed occupational health and safety laws in response to this, but the enforcement of such legislation is difficult, particularly in developing countries. This is borne out by the fact that only 5–10 % of workers in developing countries and 20–50 % of workers in industrialized countries (with a few exceptions) are estimated to have access to adequate occupational health services (Chemical Hazard communication: US Department of Labour (1998 revised). However, given the potential negative impacts in the absence

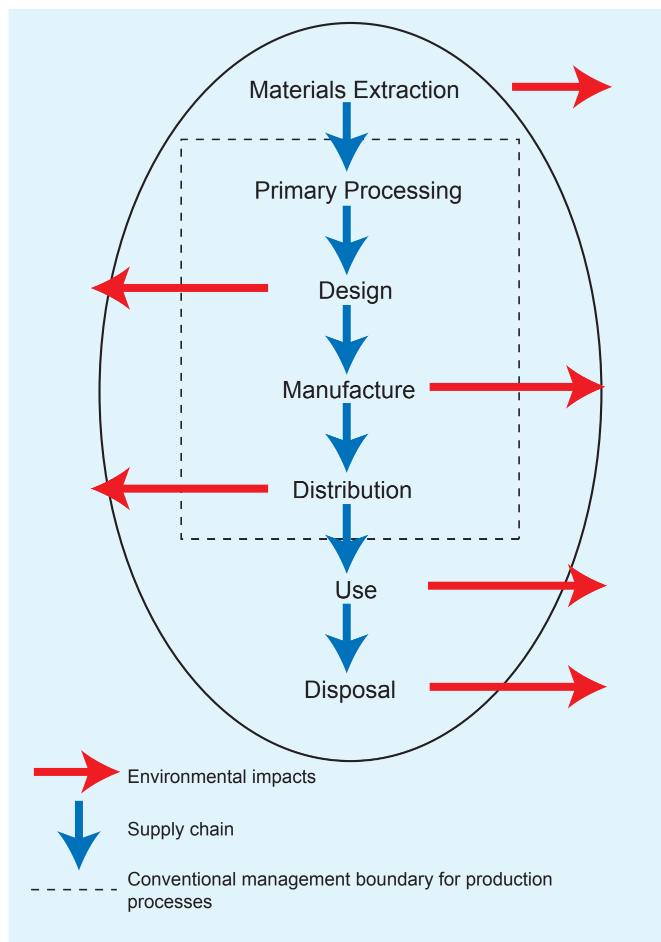

Figure 3.5. Environmental impacts along the supply chain (Wallace, 1996)

of adequate health and safety precautions, it is in the interest of both businesses and government to minimize these. Periods in which businesses are undergoing technological changes provide good opportunities to institute measures for preventing negative health and safety impacts on their workers and operations. They also provide governments with opportunities to implement measures to ensure that these matters are considered during the period of change.

3.4.2 Risk assessment of chemicals

Risk assessment is central to safety. It provides the scientifically sound basis for actions, including policy and regulatory actions to manage potential risks from the production, storage, transportation, use and disposal of chemicals. A number of parameters must be considered when undertaking risk assessments, such as chemical composition, stability and reactivity, hazards identification and classification, transportation, storage and handling, ecological impacts, physical and chemical properties, routes of exposure, effects of exposure, exposure limits, and toxicological information. As well as guiding the decision on the choice of a chemical to be used for a particular application, the assessment will also inform decisions on risk management as well as policy and regulatory controls.

3.4.3 Risk management of systems

Risk management is a broad term for the process that uses the outcomes of a scientific risk assessment to implement best practices, which are usually supported by appropriate policy and regulatory frameworks. A number of options are usually available for managing risk. These depend on the nature of the risk and the technological, economic and policy options available to address this. Effective risk management includes a wide range of measures such as information provision, training and/or retraining, risk assessment training, redesignated work practices, use of personal protective equipment, evaluation and monitoring of both the immediate and wider environments, redefinition of exposure limits and standards, and medical examinations.

3.4.4 Policy and regulatory controls

Most countries have occupational health and safety laws that require employers (as far as it is reasonable and practicable) to provide safe working environments and to develop and implement policies and measures to educate and protect their employees. In general, laws are developed on the principles of precaution and reasonableness, and these need to be adjusted when new processes, technologies or inputs are introduced into the economy that have health and safety implications not covered under the existing framework. Governments are responsible for ensuring that an appropriate regulatory and policy framework exists to protect human and ecological health and safety as well as property, and to ensure compliance. When such a framework and the associated legal requirements are compiled, the health and safety of the user, worker and those in the locality must be the main priorities. Product liability laws have been established in several areas of the world to protect users, workers and members of the public with respect to health and safety or any other damage. The liability legislation in a country is an important factor in the choice of the system and fluid chosen for the application, irrespective of what the safety standard specifies. When drawing up regulations, the combination of several regulatory requirements, including product liability, needs to be taken into account.

3.4.5 Health and safety criteria

For the purposes of this report, health and safety issues are considered under the following criteria:

Flammability: Ability to support combustion; a high capacity for combustion; burning velocity and expansion ratio.

Acute toxicity: Adverse effects are observed within a short time after exposure to a chemical. This exposure may be a single dose, a short period of continuous exposure, or multiple doses over a period of 24 hours or less.

Chronic toxicity: Adverse effects observed following repeated exposure to a chemical during a substantial fraction of an organism's lifespan. For human chronic toxicity typically means exposure over several decades; for experimental animals it is typically more than 3 months.

Carcinogenicity: The ability of a substance or agent to produce or provoke cancer.

Acute ecotoxicity: Adverse effect on ecosystems and/or the organisms within the ecosystem within a short period of time after exposure to a chemical.

Chronic ecotoxicity: Adverse effects to an ecosystem and/or the organisms within the ecosystem following exposure to a chemical during a substantial fraction of the ecosystem's or organism's lifespan.

Accumulation: The action or process of accumulating within biological tissues.

Persistence: Continued presence of a chemical or its effects in the environment after source or cause has stopped.

3.4.6 Health and safety data for relevant substances

The data for health and safety are extensive and this report only includes references to the databases. Most data can be found on the site of the International Programme on Chemical Safety (IPCS) (www.inchem.org), a collaborative venture of the World Health organization (WHO), the United Nations Environment Programme (UNEP) and the International Labour Organization

(ILO). The IPCS site refers to the ICSCs, CICADs, and EHCs. The International Chemical Safety Cards (ICSCs) (www.inchem.org/pages/icsc.html) provide a structured overview of the data for most of the substances under consideration. The Concise International Chemical Assessment Documents (CICADs) (www.inchem.org/pages/cicads.html) provide extensive data for a very limited number of substances. They are similar to the Environmental Health Criteria Monographs (EHC) (www.inchem.org/pages/ehc.html) which provide internationally accepted reviews on the effects of chemicals or combinations of chemicals on human health and the environment.

Additional data and substances can be found in the databases of the IPCS INTOX Programme, the US EPA, the US National Institute for Occupational Safety and Health (NIOSH), the University of Oxford Physical and Theoretical Chemistry Laboratory, the Programme for Alternative Fluorocarbon Toxicity Testing (www.afeas.org/paft/) and documents from ISO Technical Committees TC 86 "Refrigeration and air conditioning" and ISO TC 21 "Equipment for fire protection and fire fighting". If the data are not available from these sources, then national standards or the material safety data sheet from the supplier can be used as the source of information. Care is needed when using material safety data sheets from suppliers, as these data are not always peer reviewed. The most recent peer-reviewed data agreed at an international level (IPCS, PAFT or ISO) should be used in preference to other data.

The information required for health and safety considerations depend on the subsector and application involved. For example, the data required for refrigeration and air conditioning are different from that for fire protection and medical aerosols. Even within a sector, regional differences exist for detailed data. Each sector shall use the appropriate data valid for it to perform the risk assessment and management with respect to health and safety. For refrigeration and air conditioning an ISO work item has been approved to unify the data and resolve the regional differences (ISO TC 86/SC8/WG5). For fire protection this is handled by ISO TC 21.

3.5 Assessing climate and environmental impacts

This chapter describes approaches in which the environmental comparisons are made systematically using standardized procedures and factors. They are most suitably used for making comparisons between individual installations or items of equipment and do not provide 'generic' information. There is a hierarchy among the system-based approaches, which depends on the scope of treatment, but they all seek to apply data in the same rigorous manner. In every case, care should be taken to examine and clearly define the scope of the analysis, taking into account the requirements of those who commissioned the study.

3.5.1 Environmental impact categories and respective indicators including approaches for their ranking

A rational choice of systems, such as heating and cooling, to provide for societal needs should include an assessment of their environmental impact so that excessive demands on the environment can be identified and avoided. Environmental impact depends as much on the quantity of the material emitted as it does on the material's properties. Climate change and ozone depletion are clearly prioritized in this report. Within another framework, other impact categories such as energy-related acidification or resource depletion could be emphasized. An exhaustive list of potential impact parameters or a definition of the process of life cycle assessment fall outside of the scope of this report. However, the principal environmental impacts that may be considered for systems using HFCs, PFCs and other replacements for ozone-depleting substances are:

Climate Change The radiative effects of CFCs and their alternatives on climate is discussed in detail in Chapter 2 and, for the purposes of comparisons between climate impacts, the most important parameter is *global-warming potential*. This is a conversion factor that relates the climatic impact from an emission of particular greenhouse gas to that of an equivalent amount of emissions of carbon dioxide. It is calculated by integrating the radiative forcing from an emission of one kilogram of the greenhouse gas over a fixed time period (the *integration time horizon, ITH*) and comparing it to the same integral for a kilogram of carbon dioxide; units are (kg CO_2 equivalent)(kg emission)$^{-1}$. Commonly quoted integration time horizons are 20, 100 and 500 years with impacts beyond each ITH being ignored (see Table 2.1). The calculation has to be performed in this way because the reference gas, carbon dioxide, has a very long environmental lifetime; for example its impact up to 20 years is only 9% of that up to 500 years (IPCC, 1996a). The standard values for the emissions accounting required by the Kyoto Protocol are those in the Second Assessment Report of the IPCC (IPCC, 1996a) at the 100-year time horizon. The 20-year time scale does not meet the time criterion for judging sustainability; focusing on 20 years would ignore most of the effect on future generations (WCED, 1987). GWPs from the Second Assessment Report at the 100-year time horizon represent the standard for judging national performance. For the purpose of system comparisons the most recent IPCC GWPs could be used, for example, as presented earlier in this report. However, it should be noted that GWPs are parameters constructed to enable the ranking of emissions of greenhouse gases and do not reflect absolute environmental impact in the same way as, for example, the calculated future radiative forcing described in Chapter 2.

Ozone depletion gases that contain reactive halogens (chlorine, bromine and iodine) and are sufficiently unreactive to be transported to the stratosphere, can cause the halogen concentration in the ozone layer to rise. They are therefore *ozone-depleting substances*. For any given gas the efficiency of ozone depletion depends on the extent to which material released at ground level is transported into the stratosphere, how much halogen each molecule carries and the potency of that halogen for ozone depletion, and how the gas decomposes in the stratosphere and hence how much of its halogen content can affect the ozone layer. These factors are combined in mathematical models of the atmosphere to give relative *ozone depletion potentials (ODPs)* based on a scale where the ODP of CFC-11 (CCl_3F) is unity (Daniel *et al*., 1995; Albritton *et al*., 1999); values important for Life Cycle Assessments are shown in Table 1.1.

Acidification: The two groups principally involved in acidification are sulphur and nitrogen compounds and, with the exception of ammonia, neither the ODS nor their substitutes have a direct effect in this category. However, energy-related emissions can exhibit significant acidification potential, and degradation products of substances such as HF or HCl could have considerable acidification potential. Indicators for potential acid deposition onto the soil and in water have been developed with hydrogen ions as the reference substance. These factors permit computation of a single index for potential acidification (in grams of hydrogen ions[5] per functional unit of product), which represents the quantity of hydrogen ion emissions with the same potential acidifying effect:

$$\text{acidification index} = \sum i \; mi \times APi \qquad (3.5)$$

Where:
mi is the mass (in grams) of flow *i*, and
APi are the millimoles of hydrogen ions with the same potential acidifying effect as one gram of flow i, as listed in Table 3.8.

However, the acidification index may not be representative of the actual environmental impact, as this will depend on the susceptibility of the receiving systems (soil and water, in this case).

Photo-oxidant formation: The relative potencies of compounds in atmospheric oxidation reactions are characterized by their photochemical ozone creation potentials (POCP), on a scale where ethene is 100 (Derwent *et al*., 1998). The hydrocarbon substitutes for ODSs have POCPs ranging from 30 to 60 but HFCs and PFCs are not implicated in any significant photo-oxidant formation (Albritton *et al*., 1989) and are among the lowest priority category for volatile organic compound regulation (UN-ECE, 1991).

Resource depletion: The production of all of the chemicals considered in this report will deplete resources and the extent of this should become apparent in a Life Cycle Assessment. For example, an important consideration for fluorinated gases is the extraction of fluorspar mineral, as most of this is destined for the manufacture of fluorochemicals (Miller, 1999).

Eutrophication is the addition of mineral nutrients to soil or water. In both media, the addition of large quantities of mineral nutrients (such as ammonium, nitrate and phosphate ions) results in generally undesirable shifts in the number of species in ecosystems and a reduction in ecological diversity. In water it tends to increase algal growth, which can cause a depletion in oxygen and therefore the death of species such as fish.

[5] The hydrogen release potentials are criticized by some authors. They have proposed alternative factors based on UN-ECE-LRTAP models. See www.scientificjournals.com/sj/lca/pdf/aId/6924.

Table 3.8. Acidification-potential characterization factors (Alternatively, in the literature sulphuric oxides are often used as reference).

Flow (i)	***AP_i* (hydrogen-ion equivalents)**
Ammonia (NH_3)	95.49
Hydrogen chloride (HCl)	44.70
Hydrogen cyanide (HCN)	60.40
Hydrogen fluoride (HF)	81.26
Hydrogen sulphide (H_2S)	95.90
Nitrogen oxides (NO_x as NO_2)	40.04
Sulphur oxides (SO_x as SO_2)	50.79
Sulphuric acid (H_2SO_4)	33.30

Source: Lippiatt, 2002

Characterization factors for potential eutrophication have been developed, in a similar vein to those for the global-warming potential, with nitrogen as the reference substance. These factors permit the computation of separate indices for the potential eutrophication of soil and water (in grams of nitrogen per functional unit of product), which represent the quantity of nitrogen with the same potential nutrifying effect:

$$\text{eutrophication index (to water)} = \sum i \; mi \times EPi \qquad (3.6)$$

Where:
mi is the mass (in grams) of inventory flow *i*, to water, and
EPi are the grams of nitrogen with the same potential nutrifying effect as one gram of inventory flow i, as listed in Table 3.9.

The calculation for soil eutrophication is similar but, for both soil and water the actual impact will vary, dependent on the ability of the local environment to cope with an additional stress of this sort, as was the case for acidification.

Ecotoxicity is the introduction of a compound that is persistent, toxic and can accumulate in the biosphere (commonly shortened to PTB). All three attributes are required for environmental releases to accumulate to the point at which there is a toxic response. No such compounds are known to be directly associated with the production and use of any of the fluorocarbons considered in this report. An in-depth discussion of ecotoxicity issues can be found in Hauschild and Wenzel (1998), Heijungs (1992) and Goedkoop (1995).

3.5.2 System-based approaches

In these approaches the environmental comparisons are made systematically using standardized procedures and factors. They

Table 3.9. Eutrophication Potential Characterization Factors. (Alternatively, in the literature PO4+ is often used as a reference).

Flow (i)	*EPi (nitrogen-equivalents)*
Ammonia (NH_3)	0.12
Nitrogen Oxides (NOx as NO_2)	0.04
Nitrous Oxide (N_2O)	0.09
Phosphorus to air (P)	1.12
Ammonia (NH_4^+, NH_3 as N)	0.99
BOD5 (Biochemical Oxygen Demand)	0.05
COD (Chemical Oxygen Demand)	0.05
Nitrate (NO_3^-)	0.24
Nitrite (NO_2^-)	0.32
Nitrogenous Matter (unspecified, as N)	0.99
Phosphates (PO_4^{3-}, HPO_4^{2-}, $H_2PO_4^-$, H_3PO_4, as P)	7.29
Phosphorus to water (P)	7.29

Source: Lippiatt, 2002

are best used for making comparisons between individual installations or items of equipment and do not provide ‘generic’ information. There is a hierarchy among the system-based approaches, which depends on the scope of treatment, but they all seek to apply data in the same rigorous manner. In every case, the scope of the analysis should be clearly examined and defined, taking into account the requirements of those who commissioned the study.

Life Cycle Assessment (LCA) is clearly the most comprehensive and formal approach to assessing and comparing the environmental impacts of technologies. The methodology for LCAs has been developed and formalized in the ISO 14040 series of international standards. On the other hand, TEWI (Total Equivalent Warming Impact) has the most limited scope, but has been applied most widely for the technologies within the remit of this report. It addresses the climatic impact of equipment operation and the disposal of operating fluids at end-of-life but, although it may be appropriate for most of the common systems, it does not consider the energy embodied in the fluid or equipment. This energy may be important in some cases and this consideration has led to the concept of LCCP (Life Cycle Climate Performance).

In LCCP a more complete climatic impact of the fluid is calculated and includes the impacts from its manufacture, the impacts from operating and servicing the system and finally those associated with disposal of the fluid at the system’s end of useful life. However, both TEWI and LCCP consider just the climatic impact; this is reasonable for cases where the predominant environmental impact is on climate. Life cycle assessment (LCA) is the broadest-based approach and this includes the environmental impacts of other inputs and outputs to the system, in addition to those associated with energy.

LCCP can be seen as a submethod of LCA and TEWI as a submethod of LCCP. To a large extent the approach chosen will depend on the context. If the information required is the relative climate impacts of a number of alternative approaches for achieving a societal good, then TEWI or LCCP are likely to provide adequate information. However this will ignore all other environmental impacts that are addressed in LCA, assuming that these will be similar for the alternative technologies. Although the three approaches differ in their scope, all of data should be derived and all of the analyses performed with the same rigour.

3.5.2.1 Total equivalent warming impact (TEWI)

Arguably the largest environmental impact from many refrigeration and air-conditioning applications arises from their energy consumption and emissions during their operation. Similarly, the energy saved by thermal insulating foam is the principal offset for any effect due to fluid emissions. In order to help quantify these effects, TEWI sets out to standardize the calculation of climate-change impact in terms of emissions over the service life of the equipment, including emissions arising from the disposal of the fluids it contains. The units of TEWI are mass of CO_2 equivalent.

TEWI using generic or default data.

The analysis is performed by calculating the direct emissions of the fluids contained in each system from leakage during operation over its entire service lifetime. This includes servicing and the system’s eventual decommissioning and disposal. In this context, the system does not cover the full life cycle (ISO, 1997) but includes the operation, decommissioning and disposal of the application.

The total mass emission of each greenhouse-gas component is converted to CO_2-equivalent emissions using GWP (see discussion in Section 3.5.1) as the conversion factor (see Table 2.1). These figures are then added to the emissions of actual carbon dioxide arising from the energy used during operation (see 3.2.2.3) to give a TEWI value for the lifetime of the equipment. Examples of ‘equipment’ are a refrigeration or air-conditioning system, or a building (particularly if it is insulated). There is often a combination of energy-consuming and energy-conserving parts, and different direct releases of greenhouse gases. Typically:

$$TEWI_S = \sum OR_i \text{ x } GWP_i + \sum DR_i \text{ x } GWP_i + E_I \qquad (3.7)$$

Where:

- $TEWI_S$ is the total equivalent warming impact from system S (for example, a particular refrigeration system or building installation) the units of which are mass of CO_2 equivalent;
- OR_i is the operational release of each greenhouse gas i (the mass total of the releases of each gas during the system’s operating lifetime);
- GWP_i is the global-warming potential of greenhouse gas i (at the 100-year integration time horizon, as discussed below);

DR_i is the total mass of each greenhouse gas *i* released when the system is decommissioned, and
E_I is the indirect emission of carbon dioxide resulting from the energy used to operate the system (for its whole lifetime), already discussed in Section 3.2.1.3 and calculated according to Equation 3.2, above.

While this is apparently an absolute value, it can carry a high uncertainty associated with the assumptions and factors used in the calculation. TEWI is most effectively used to compare alternative ways of performing a service, where the same assumptions apply to all of the alternatives and the effect of these on relative ranking is minimized. A TEWI value calculated for one system using one methodology (i.e. set of assumptions, equations, procedures and source data) is not comparable with a TEWI value calculated for another system using another methodology. Then a comparison of TEWI is meaningless.

Depending on the quantity of information available and the needs of the study, there are several levels of complexity in the application of TEWI. At the simplest level, a default emission function could be used for the fluid release together with calculated energy requirements and regional carbon dioxide intensity. Default emission functions have been developed by AFEAS to calculate global emissions from refrigeration and closed-cell (insulating) foams (AFEAS, 2003). One feature of these functions is that all of the substance used is eventually released (in some cases after many years service) and this can have a profound effect on the application's impact.

In this case, the quantity released is equal to the amount originally charged into the system, plus any amount added during the system's period of service:

$$OR_i + DR_i = C_i + QA_i \tag{3.8}$$

Where OR_i and DR_i are the operational and decommissioning releases of substance *i* as described above;
C_i is the mass of *i* originally charged into the system, and
QA_i is the mass of *i* added into the system during its service life.

For hermetic refrigeration systems (such as domestic refrigerators and window air conditioners), units are rarely, if ever, serviced and therefore QA_i is set at zero because of its insignificance. Yet for systems which require frequent servicing, such as mobile air conditioning, that default condition is not appropriate and a value for QA_i could be derived by analogy from the operation of similar systems.

Energy (either as power required to operate the system or the energy saved by thermal insulation) can be calculated using standard engineering methods. In many cases, electricity is used to power the equipment and this will have been produced by technologies that vary between countries and regions, with large differences in the fossil fuels used as primary sources (for more information see Section 3.2.1.3). Table 3.5 lists some regional and national carbon dioxide intensities for electricity. Such a calculation is only suitable for showing major differences (say within a factor of two) due to the extensive use of default factors. Nevertheless, it is useful for identifying the more important areas of the calculation that would repay further refinement (Fischer *et al*., 1991 and 1992; McCulloch, 1992 and 1994a). Uncertainties can be significantly reduced by using appropriate specific data.

GWP and integration time horizon
For the conversion of other greenhouse-gas emissions into their CO_2-equivalents, GWPs at the 100-year integration time horizon are usually used and the source of the GWP values must be clearly stated. For example, TEWI analyses are now usually performed using the most recent GWP values published by the IPCC, even though this is not the normative standard. To ensure that the results are as portable as possible and to facilitate intercomparisons, the standard values from the Second Assessment Report of the IPCC (IPCC, 1996a) as used in the emissions accounting reported under the Kyoto Protocol and UNFCCC, have frequently been used in existing TEWI analyses.

TEWI using specific data
The next level of complexity goes beyond the use of generic data. It requires real emission patterns obtained from field trials and operating experience and, preferably, the range of values obtained from such studies should be indicated and used in a sensitivity analysis (Fischer *et al*., 1994; ADL, 1994 and 2002; Sand *et al*., 1997; IPCC/TEAP, 1999). As the disposal of the fluid can have a significant impact, it is important to incorporate the real emissions on disposal. If the systems under consideration do not yet exist, the methods for calculating emissions patterns should have been verified against real operating systems.

Similarly, the actual energy consumption based on trials should be used in the more thorough analysis, together with the carbon dioxide intensity of the energy that would actually be used in the system. Many systems are powered electrically and therefore the procedures already discussed in Section 3.2.1.3 should be applied so as to facilitate comparisons between similar systems operated in different countries.

As in many cases electrical energy is the most important energy carrier, the sum of the other fuel usages and intensities can be neglected so that Equation 3.2 becomes:

$$E_I = Q_E \times I_E \tag{3.9}$$

Where
E_I is the total indirect lifetime emission of carbon dioxide from the energy used to operate the system;
Q_E is the total lifetime use of electricity, and
I_E is the average carbon dioxide intensity of national electricity production (from Table 3.5)[6].

Uncertainty
When most of the impact arises from fluid emissions, the crite-

rion for significance is set by the uncertainty of the GWP values and this is typically 35% (IPCC, 1996a). Where the impact is a combination of fluids and CO_2 from energy, the more common case, the total uncertainty should be assessed. A rigorous uncertainty analysis may not be meaningful in all cases or might not possible due to the poorly quantified uncertainties of emission factors, emissions from the energy supply systems, specific energy consumption and the like. However, the sensitivity of uncertainty in the data is valuable because the effort required to gather the information needed for increasingly detailed calculations, will only be repaid if these show significant differences.

Uses

TEWI is particularly valuable in making choices about alternative ways of performing a function in a 'new' situation but it also can be used to minimize climate impact in existing operations by providing information on the relative importance of sources, so that remedial actions can be prioritized. This is, however, methodologically restricted to those cases in which the original and alternative technologies remain reasonably similar throughout their life cycles.

A standard method of calculation which includes the concepts and arithmetic described here has been developed for refrigeration and air-conditioning systems, and the principles of this may be applied to other systems (BRA, 1996, consistent with EN378, 2000). TEWI can also be used to optimize the climate performance of existing installations and methods of working (McCulloch, 1995a; DETR, 1999). A particularly valuable application is in the construction or refurbishment of buildings, where TEWI can be used to facilitate the choice between different forms of insulation, heating and cooling. The affect of the design on both the TEWI and cost can be investigated, and significant greenhouse-gas emissions abated (DETR, 1999). The interaction between TEWI and cost is particularly useful when additional equipment is required to achieve an acceptable level of protection. For example, the cost of that safety equipment could have been invested in efficiency improvements (ADL, 2002; Hwang *et al*., 2004).

If sufficient information is available, TEWI can also be used to examine the climate and cost incentives of targeting operations at particular periods of the day or year when the carbon dioxide intensity of electrical power is lower (Beggs, 1996).

3.5.2.2 Life cycle climate performance (LCCP)

Like TEWI, this form of analysis concentrates on the greenhouse-gas emissions from direct emissions of operating fluids together with the energy-related CO_2 but, it also considers the fugitive emissions arising during the manufacture of the operating fluids and the CO_2 associated with their embodied energy. Like TEWI, LCCP is most effective when applied to individual installations, and a 'generic' LCCP will only be representative only if the data used to calculate it are representative of the types of installation being examined.

A comprehensive study has been made of representative LCCPs for alternative technologies in the areas of domestic refrigeration, automobile air conditioning, unitary air conditioning, large chillers, commercial refrigeration, foam building insulation, solvents, aerosols (including medical aerosols) and fire protection (ADL, 2002). The results were very similar to those of the TEWI analyses (see particularly Sand *et al.* (1997)). For example, the LCCP of domestic refrigerators was dominated by their energy use and there was no clear difference between the refrigerant fluids or blowing agents used in insulating foams. However the end-of-life disposal method has a significant impact on the LCCP (Johnson, 2003). As long as the disposal of all of the systems was treated in the same way, automobile air conditioning was most heavily influenced by the conditions under which it was operated (the climatic and social conditions of different geographical areas). Thus the highest LCCP values arose for vehicles in the southern USA, and this value was higher still if the fluid chosen did not allow for efficient operation (ADL, 2002).

LCCP is a useful addition to the TEWI methodology, even though in many cases the influence of fugitive emissions and embodied energy (which account for most of the difference between TEWI and LCCP results) can be small compared to the lifetime impact of using the system.

$$LCCP_S = TEWI_S + \sum OR_i \text{ x } (EE_i + FE_i) + \sum DR_i \text{ x } (EE_i + FE_i) \quad (3.10)$$

Where:

$LCCP_S$ is the system Life Cycle Climate Performance;

$TEWI_S$ is the system TEWI, as defined by Equation 3.5.1 above;

OR_i and DR_i are, respectively, the quantities of fluid i released from the system during operation and at decommissioning;

EE_i is the embodied energy of material i (the specific energy used during the manufacture of unit mass, expressed as CO_2 equivalent), and

FE_i is the sum of fugitive emissions of other greenhouse gases emitted during the manufacture of unit mass of i (expressed as their equivalent CO_2 mass), so that:

$$EE_i = \sum (EE_j \text{ x } I_{Fj}) \quad (3.11)$$

for j sources of energy used during the production of material i, each with a carbon dioxide intensity of I_{Fj} (see also Equation 3.2), and:

[6] The differing practice of using the carbon intensity of the most expensive fuel in an attempt to show the situation for an additional demand in a deregulated energy market, could be misleading. This carries unwarranted assumptions: the demand may not be additional, even if the system represents a new load. It is most probable that the effect of the new system on the energy balance would be, at least in part, to replace demand from elsewhere. And even if demand is additional, it may not result in the most expensive energy being used. That would depend on the daily, weekly and seasonal demand pattern, which is beyond the scope of this level of TEWI analysis.

$$FE_i = \sum (FE_j \text{ x } GWP_j) \quad (3.12)$$

for j greenhouse gases emitted during the production of material i, each with a global-warming potential at 100 years of GWP_j.

A comparison of Equations 3.7, 3.10, 3.11 and 3.12 shows that the difference between LCCP and TEWI is that the GWP of each greenhouse-gas component is augmented by the embodied energy and fugitive emissions of that component. However, the effect of these is now generally quite small as in much of the world the practice is to minimize or destroy process emissions (compare Section 3.2.1.1).

A relatively straightforward application for TEWI and LCCP analyses is the study of emissions attributable to a household refrigerator. In this case, either the refrigerant choice or the blowing agent choice may be studied, or both. Table 3.10 gives a summary of the items that would typically be considered in such studies.

3.5.2.3 Life Cycle Assessment (LCA)

LCA is a technique for assessing the environmental aspects of a means of accomplishing a function required by society (a 'product or service system' in LCA terminology) and their impacts. A life cycle assessment involves compiling an inventory of relevant inputs and outputs of the system itself and of the systems that are involved in those inputs and outputs (Life Cycle Inventory Analysis). The potential environmental impacts of these inputs and outputs are then evaluated. At each stage it is important to interpret the results in relation to the objectives of the assessment (ISO, 1997). Only an assessment which covers the full life cycle of the product system can be described as an 'LCA'. The methodology is also applicable to other forms of assessment, such as TEWI described above, provided that the scope of the assessment and its result are clearly defined. So whereas LCA studies describe the environmental impacts of product systems from raw material acquisition to final disposal, studies that are conducted to the same rigorous standards for

Table 3.10. Items considered in TEWI and LCCP studies for a refrigerator (Johnson, 2003).

	Considered in	
	TEWI	**LCCP**
Refrigerant		
Emissions of refrigerant:		
• During manufacturing of the refrigerant		X
• Fugitive emissions at the refrigerator factory	X	X
• Emissions during the life of the product (leaks and servicing)	X	X
• Emissions at the time of disposal of the product	X	X
Emissions of CO_2 due to energy consumption:		
• During manufacturing of the refrigerant		X
• During transportation of the refrigerant		X
Blowing agent		
Emissions of blowing agent:		
• During manufacturing of the blowing agent		X
• At the refrigerator factory	X	X
Emissions of blowing agent from the foam:		
• During the life of the product	X	X
• At the time of disposal of the product	X	X
• After disposal of the product	X	X
Emissions of CO_2 due to energy consumption:		
• During manufacturing of the blowing agent		X
• During transportation of the blowing agent		X
The refrigerator		
Emissions of CO_2 due to energy consumption related to the product:		
• During manufacturing of components		X*
• During assembly of the refrigerator		X*
• During transportation of the refrigerator		X*
• By the refrigerator during its useful life	X	X
• During transportation of the refrigerator for disposal		X*
• During disposal of the refrigerator (usually shredding)		X*

* These items are relatively small in comparison with emissions related to the power consumed by the refrigerator and those related to emission of the blowing agent, and are independent of the refrigerant and blowing agent. They may therefore be neglected in some LCCP studies.

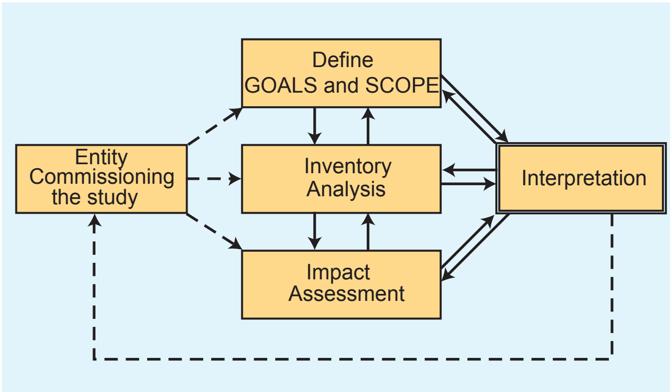

Figure 3.6. Outline phases of a Life Cycle Assessment and interactions with the commissioning entity.

subdivisions of the product chain (for example up to the sale of a unit to a customer) or subdivisions of the environmental impact (for example LCCP and TEWI) are just as valid, and may better meet the requirements of those commissioning the study. Indeed as the use phase usually dominates the environmental impact of the CFC substitutes, the LCA will be application-specific. However, attempts to provide 'generic' LCA results can help to identify the most relevant life-cycle stages and impact categories. These attempts will also tend to be tests of the extent to which the assumptions made about this use phase actually match the real performance of the application.
Figure 3.6 shows the steps in the general methodology.

For any given analysis it is essential that the objective is clearly defined. This should include the application, reasons for the study and the intended recipients of the results. To meet this objective, the scope of the study needs to specify the performance characteristics of the product and to define a 'functional unit' that will be used to quantify these characteristics (ISO, 1997 and 1998). This is a particularly important step and is best illustrated with examples:

Once a functional unit that is practical and meets the needs of those commissioning the assessment has been defined, a reference flow can be established from which all of the ancillary inputs and outputs may be calculated. For example, in a cold store this could be the annual throughput of foodstuff from which the number of receipts and deliveries, the energy load, and so forth can be estimated. In any LCA it is essential that the system boundaries are clearly and unambiguously defined. This includes not only the boundaries of the primary physical system under assessment (in this example the cold store) but also the extent to which inputs and outputs will be traced back to elementary flows (material drawn from or placed into the environment). The documentation for the decisions on system boundaries should be sufficient to judge whether or not more detailed examination is desirable and to permit subsequent changes to the assessment if new information becomes available.

Once the system has been defined, it should then be described in terms of its unit processes and their interrelationships. Each of these unit processes has its own set of inputs and outputs, enabling a matrix of flows, based on the reference flow, to be constructed. This constitutes the Life Cycle Inventory. In the subsequent stages of LCA, the environmental impacts of the inputs and outputs identified in the inventory are assessed. For the materials addressed in this report, the most obvious impact categories are climate change and ozone depletion but some or all of the additional categories described in 3.5.1 above may be important (ISO, 2000a and 2000b). The end product is a description of the environmental impacts of a defined product system in terms of the effects on the most appropriate individual categories, together with an indication of how significant that impact is for each category. There is no scientific basis for reducing LCA results to a single overall score or number (ISO, 1997) and, similarly, there is little justification for closely ranking impacts (although it is worth noting when one impact, such as that on climate change, clearly outweighs the rest). A data documentation format for Life Cycle Assessments has been developed (ISO, 2002) to facilitate common input. Data collection formats have also been developed for specific applications, such as motor vehicle manufacture (Finkbeiner *et al*., 2003) and plastics (O'Neill, 2003) and, similarly, large consistent databases are now sold (for example at www.ecoinvent.ch/).

It is difficult to characterize the uncertainty in LCA; there are a large number of variables with varying degrees of autocorrelation and for which formal uncertainty analyses may not exist. However, it should be possible to perform sensitivity analyses with comparatively little effort so as to provide a commentary on the significance of the impacts determined in the assessment (Ross *et al.,* 2002). The requirements for data quality assessment are described in ISO (1997, 1998, 2000b).

In order to facilitate complete LCA studies involving refrigerants and foam blowing agents, several studies have been performed to characterize the environmental impacts of fluid manufacture. The general conclusion was that the impact from producing the fluids was small compared to that arising from their use during service and their eventual disposal (Banks *et al*., 1998; Campbell and McCulloch, 1998; McCulloch and Campbell, 1998; McCulloch and Lindley, 2003). The most significant contribution to the impact for producing fluids comes from material, such as other fluorocarbons, released during the manufacturing process and there is a wide variation in the values used. The highest values were calculated by Banks *et al.* (1998) who used maximum permitted emissions rather than real values. The other studies used actual process records so that the amount of material released was not only lower but also decreased substantially in recent years as the treatment of vent gases to avoid their release to the atmosphere became more commonplace, particularly in the new plants to manufacture HFCs (Campbell and McCulloch, 1998; McCulloch and Campbell, 1998; McCulloch and Lindley, 2003).

As for studies of complete systems, Yanagitani and Kawahari (2000) confirmed that for air-conditioning systems the largest source of environmental impact arose from energy use, but that proper waste management at end-of-life could significantly reduce the impact. The predominant influence of energy production on the impact on global warming, acidification, aquatic ecotoxicity, photochemical ozone creation, terrestrial toxicity and the proliferation of radionuclides was demonstrated by Frischknecht (1999) in LCA studies of generic heat pumps, building air conditioning, and industrial and commercial refrigeration.

3.5.2.4 Other system-based approaches

Environmental burden
Environmental burden is a method for assessing the environmental impact of a production facility. Mass emissions of individual compounds released from the site are multiplied by a 'potency' that characterizes the impact of the compound on a particular environmental end-point (for example ozone depletion or global warming). The sum of these values in each impact category is the environmental burden of the facility (Allen *et al.,* 1996). The resulting site-specific review of environmental impact can be used in environmental management (as described in ISO 14001).

Eco-efficiency
This combines Life Cycle Assessment of similar products or processes with a total cost determination of each alternative. Economic and ecological data are plotted on an x/y graph, with costs shown on the horizontal axis and the environmental impact on the vertical axis. The graph reveals the eco-efficiency of a product or process compared to other products or processes, with alternatives that have high cost and high impact occupying the upper right-hand quadrant. Similarly, those with low impact and low-cost occupy the lower left-hand quadrant, close to the origin. (BASF, 2003). However, such analyses demand a great deal of accurate data.

3.6 Regional dimensions

The use of fluorocarbons is specific to certain technical sectors. The technology selection in these sectors, their customers and product developments are influenced by a number of factors, which are of a local, national or regional nature (e.g. EU regulation (COM(2003)0492), under preparation). In addition to technical requirements, those factors can also include cost, environmental considerations, legal requirements, health and safety issues, energy inputs and costs and market characteristics. Therefore prescriptions on how to arrive at these decisions are not possible, as each country, and each enterprise within it, must make its own decision. Against this background, this section presents some of the more general characteristics and considerations that will influence the choice of technology at both the national and enterprise levels.

This section also highlights some of the regional differences that influence technology choice. For these purposes, countries are considered in groupings recognized under the Montreal Protocol, namely:

- Latin America and the Caribbean;
- Africa and the Indian Ocean;
- Asia/Pacific region;
- Countries with economies in transition; and
- Developed countries.

Table 3.11 gives an overview of regional variations in key methodological issues.

3.6.1 Sector characteristics

3.6.1.1 Refrigeration and air conditioning
Growth in the demand for refrigeration has paralleled the demand for food preservation, processing, freezing, storage, transport and display, as well as final storage in homes. The more centralized food production becomes, and thus further removed from the consumer, the greater the amount of refrigeration. Consequently, societies with a more complex food supply structure and countries with a higher urban population will have a higher demand for refrigeration than countries supplying food from more local sources.

Large air-conditioning systems with capacities of about 1 MW cooling capacity upwards, are used in most of the large commercial buildings, hospitals and hotels around the globe, irrespective of the local climate (UNEP, 2003c). The occurrence of such systems roughly matches the occurrence of the type of buildings described. Smaller air-conditioning systems are largely desired in countries with warm climates (UNEP, 2003c), but there is an increasing market for these in areas with a more moderate climate, for example Central and Northern Europe. Therefore, the influencing factors for the spread of such systems are the occurrence of high ambient temperatures, and high humidity, as well as available income.

There is an almost universal preference for mobile air conditioning, even in colder climates. The only limiting factor is the cost of the system, which typically has to be covered when purchasing the vehicle. Certain types of systems – refrigerators, unitary air conditioning products and water chillers – have universal usage characteristics and can therefore be manufactured in centralized facilities. This simplifies quality control and reduces the likelihood of leaks, and thus the need for service. Nevertheless, since high ambient temperatures create an increased demand for servicing due to higher mechanical stress on the systems and longer periods of operation, and considering that most repairs currently lead to emissions of the refrigerant, hot climates tend to have higher levels of refrigerant emissions than cooler climates. In other sectors, for example most commercial refrigeration systems, the installations are too custom- or location-specific to be manufactured in a centralized facility, although research is underway to change this (UNEP, 2003c).

Maintenance philosophies which encourage preventive maintenance of refrigeration equipment, have lower emissions and maintain a stable energy-efficiency performance. The decision to have preventive maintenance or to request service

Table 3.11. Overview of regions and specific methodological dimensions.

Region **Dimension**	**Latin America and Caribbean**	**Africa and Indian Ocean**	**Asia-Pacific**	**Countries with economies in transition**	**Developed countries**
3.2 Key Technical Performance Indicators					
3.2.1 lifetime perspectives	No specific differences with the exception that the more expensive equipment generally has a longer lifetime. Such expensive equipment is sold more in developed countries, where standards are higher, and enforced.				
3.2.2 Fluid emission rates	Some care during fluid production. Frequent maintenance requirement due to high ambient temperature, yielding more fluid emissions. Poor care for fluid emissions at service and disposal, but this is being addressed under initiatives funded by the Multilateral Fund of the Montreal Protocol.	Frequent maintenance requirement due to high ambient temperature, yielding more fluid emissions. Poor care for fluid emissions at service and disposal, but this is being addressed under initiatives funded by the Multilateral Fund of the Montreal Protocol.	Some care during fluid production. Poor care for fluid emissions at service and disposal, but this is being addressed under initiatives funded by the Multilateral Fund of the Montreal Protocol.		Significant care during fluid production. Significant care during servicing and some during disposal of equipment.
3.2.3 Energy aspects	The energy aspect is not the driving factor when buying new equipment and material. Main factor is initial cost.				High concern with use of highly-efficient equipment. Average use (60%)[1] of fossil fuels for electricity.
	Significant share (72%)[1] of renewable electricity. Some concern about energy efficiency.	Moderate share (19%)1 of renewable electricity.	Significant use of fossil fuel (79%)[1] for electricity. Some concern about energy efficiency.	Average use (63%)[1] of fossil fuel for electricity	
3.3 Categories Of Cost					
3.3.2 Direct engineering and financial cost	Always considered. Focus on manufacturing, mostly assembly.		Always considered. Some R&D and component manufacturing.	Always considered Some component manufacturing.	Includes liability provision. Significant R&D and component manufacturing.
3.3.2.1 The time dimension in cost 3.3.2.2 Discounting	High interest rate.	High interest rate.	Average interest rate.	Average interest rate.	Low interest rate.
3.3.3 Investment cycle and Sector Inertia	Shortage of capital. Large inertia due to unavailability of resources for transition away from HCFC.		High economic development/ modest inertia. Little emphasis on transition away from HCFC.	Shortage of capital/large inertia. Transition away from HCFC according to Montreal Protocol schedule.	Strong pressure from legislation/low inertia.

Table 3.11. Continued

Region / Dimension	Latin America and Caribbean	Africa and Indian Ocean	Asia-Pacific	Countries with economies in transition	Developed countries
3.3.4 Wider costing Methodologies-Concepts	Not accounted.				Modest consideration.
3.3.5 Wider costing methodologies- cost categories	Life Cycle Cost (LCC) generally not considered.				LCC used as a marketing tool.
3.3.6 Economic Key drivers and technology uncertainty	Montreal Protocol Fund; Growing domestic and export markets; Low uncertainty since technology is generally imported; High uncertainty on HCFC future price. Large fluid producer.		Montreal Protocol Fund; Growing equipment market (domestic and export) Medium uncertainty due to fast transition. Large fluid producer.	GEF support for transition based on Montreal Protocol schedule, but some difficulties to achieve targets. Large fluid producer.	Market Leadership; Medium uncertainty due to fast transition.
3.3.7 Other issues	Increasing legislative framework to control trade in ODSs and trade in related technologies under the Montreal Protocol.				National and regional legislation more restrictive than Montreal Protocol.
3.4 Health And Safety Issues					
3.4.1 Health and Safety considerations	Modest concern due to modest liability. Main influence is from the USA.	Modest concern due to modest liability. Mainly influenced by Europe.	Growing concerns in production facilities. Mainly influenced by Europe.	Growing concerns in production facilities. Mainly influenced by Europe.	These two issues are the driving factors in USA and Europe policy design.
3.5 Climate And Environmental Impacts	Modest contribution; Main driver is ozone layer protection.		Significant contribution; Main driver is ozone layer protection.		Large contribution. Europe and Japan are taking a leading role in mitigation.

[1] Assessments based on data from International Energy Agency database, and considers electricity production from fossil and non-fossil (including nuclear) fuels.

only in the case of system failures, is not only dependent on the labour costs but also the business culture and the use-specific importance of uninterrupted delivery of refrigeration capacity. Labour costs, business culture and the value of reliable services are country-specific.

The widespread use of refrigeration and air-conditioning technology, and the accompanying high demand for service and repairs, makes the diffusion of improved techniques important. However, the large number of servicing companies makes it difficult to introduce new maintenance practices and to ensure that these are adhered to (UNEP, 2003c). Through the Montreal Protocol, networks of service technicians have been established in several countries for the diffusion of information within the service sector enterprises, and in some cases there are also mechanisms in place to facilitate a certain maintenance quality. For low-cost, factory-manufactured equipment, such as refrigerators or small- and medium-sized, air-conditioning systems, high labour costs reduce the demand for servicing and instead favour early replacement. Although this results in lower emissions during maintenance, there is the potential of repair-worthy systems being dumped in countries with a lower level of income. This further complicates the situation in poorer countries as ageing refrigeration systems tend to have higher emissions and energy consumptions, and require more frequent repairs (UNEP, 2003c).

Methods of disposal at the end-of-life of the equipment also have implications for the life-cycle GHG emissions of the equipment. (IPCC, 2001b, Chapter 3 Appendix). Given the widespread ownership of refrigeration systems and the high costs associated with recycling, appropriate disposal at end-of-life is at present (2004) more the exception than the rule in most regions. However, several countries have established legislation requiring certain disposal practices, although enforcement is still generally a challenge. For example in Japan, a recent system of CFC coupons compulsorily acquired by car owners when the car reaches end-of-life and are transferred to car dismantlers as they recover the fluid, is not performing well (www.yomiuri.co.jp/newse/20030511wo12.htm). The need for enforcement is further amplified by the fact that users have purchased the equipment many years, if not decades, before the disposal takes place, making data availability and the link between the manufacturer and the user fairly weak.

Customs tariffs have, according to experience gained under the Montreal Protocol, not significantly hindered the spread of new technologies. A further complication is the adherence to different national or regional regulations and standards, which are often mandatory in nature. These might not be compatible with the use of alternative technologies and their characteristics, or might hinder supplies of refrigerants and spare parts. These difficulties can be both substantial and long-lasting, thereby delaying the introduction of new technologies by several years.

In the case of mass-produced refrigeration systems, in particular refrigerators and air-conditioning systems, high labour costs in some regions have made the migration of industrial production an issue. With decreasing freight tariffs, refrigerators are also being increasingly transported over long distances, although differences in local requirements mean that the product is less standardized than air conditioners.

Investment capacities and interest to invest are also significant drivers for technology diffusion, for both manufacturers and consumers. Typically, manufacturers invest in new technology in response to consumers' demands and/or legal requirements[7]. For small manufacturers and technicians in the informal sector, investments are very complicated, especially as there are often few options for obtaining loans in many less-developed countries.

3.6.1.2 Foam sector

During the implementation of the Montreal Protocol, the consumption of CFCs in foam manufacture was largely phased out, and these were replaced by different technologies. In closed-cell rigid insulating foams, hydrocarbons including cyclopentane, n-pentane, isopentane and blends have been widely used in foam subsectors, where energy efficiency, safety and product performance criteria can be met. In flexible foams, CO_2 (water) technology has been successfully introduced. Currently, the most significant uses of HCFCs (developing countries) and HFCs (mostly developed countries) are in rigid insulating foam subsectors, where safety, cost, product performance and energy conservation are important (UNEP-TEAP, 2003).

[7] See for example the EU regulation on Fluorinated Gases under discussion (COM(2003) 0492).

For closed-cell rigid insulating foams, a large portion of the blowing agent remains in the foam until the end of its useful life (UNEP, 2003b). Consequently, the disposal practice (landfill compared with incineration) has a large influence on the direct emissions from a system (i.e., a refrigerator or a building) insulated with foams blown with fluorocarbons. Foam disposal requires collection from a large number of individual users or retrieval from a large quantity of mixed solid waste such as demolished building rubble. This is further complicated by the fact that, in some cases, the foams are integrated with other materials, for example, when used as building material it is adhered to substrates. These factors will make collection a major logistical and legal undertaking, which has not been mastered except in certain subsectors like domestic refrigeration, and even there, only a few countries are implementing such measures (UNEP, 2003b). As most foam products are lightweight compared to their volume, transportation costs prohibit their transportation over long distances, unless the foam is only a small fraction of the final product or system (i.e., a refrigerator). Addition, the movement of foam products, in particular building insulating foams, is further hindered by building construction traditions and building code requirements, which differ significantly between countries.

3.6.1.3 Solvents

The solvent sector is characterized on the one hand by the small scale, open use of solvents and on the other hand by use in industrial processes or closed machines. Both industrial uses and closed machine uses have undergone significant improvements as part of the efforts to reduce the use of ODSs under the Montreal Protocol. A completely different issue is the open use of solvents. For some open uses in medium-size consuming operations, investments might lead to a transition towards closed uses with internal recycling of the solvents. In other uses, in particular cleaning in smaller workshops, the solvent will evaporate into the atmosphere. Low labour costs and, thus, less automated production tend to support the open use of solvents. As in the case of the refrigeration sector, the large number of users in non-homogenous solvent applications makes the spreading of know-how a complex and labour-intensive undertaking (UNEP, 2003d). There are no substantial technical barriers to phasing out ODSs in the solvent sector. Alternatives are available that will meet the needs of all solvent users with very few exceptions. The main barrier to overcoming the obstacles in developing countries is communication and education about suitable alternatives. (UNEP, 2003d).

3.6.1.4 Aerosols/MDIs

Since the beginning of the Montreal Protocol, most aerosol uses of fluorocarbons have been converted to other motive agents, particularly hydrocarbons (UNEP, 2003e). Even so in Japan alone, 1850 tonnes of HFCs were distributed in about 4.5 million cans in 2003. This is a considerable increase compared to the 1050 tonnes distributed in 1995. It is estimated that 80% of these cans are used to blow away dust. The fluid used (HFC-

134a) has a high GWP and measures adopted by the government to replace it with a fluid with a lower GWP (HFC-152a) are only slowly having an effect (www.asahi.com/english/business/TKY200405270126.html). Furthermore, certain critical technical and/or laboratory uses of CFCs remain that are not controlled under the Protocol. For the users of such specialised aerosols the associated costs are less important. In these specific sectors, the introduction of alternatives to fluorocarbons is very knowledge intensive. However, due to the limited number of manufacturers, the number of specialists needed for technology transfer is limited (UNEP, 2003e). National legislation with respect to imports and standards is important because several products, in particular pharmaceuticals, need to adhere to national or regional standards. Most countries require intensive testing of new pharmaceuticals before the lengthy approval process is initiated and this can delay the introduction of new technologies. For all specialized products, manufacturers will often face very significant investments for research and development, testing, licenses and approval. The cost of converting production facilities to utilize alternative technologies could also be high.

3.6.1.5 Fire protection

Fire protection is a knowledge-intensive sector, which only needs a few specialists to service the limited amount of facilities. The diffusion of new technologies can therefore be undertaken with a limited amount of effort. Appropriate servicing of fire protection equipment and, where applicable, the subsequent appropriate disposal and destruction are key elements in the overall climate impact of these applications. The specific nature of this sector provides good opportunities for implementing containment measures for remaining applications, for example the banking of halons under the Montreal Protocol. For the introduction of new technologies, fire protection has a similar characteristic requirement to pharmaceuticals. The safe and efficient use of the agents has to be proven before new technologies can be accepted. This can cause significant delays in technology transfer. The costs of the systems are, within certain limits, secondary for the user because fire protection systems are required and/or essential and form an integral part of the purchase of buildings, military equipment or aircraft.

3.7 Emission projections

HFC and PFC emissions arise from two distinct sources (process emissions and releases when the product is in use (including disposal)) that require different methodologies for accounting historic and current mass emissions or for projecting mass emissions in the future.

Process emissions that occur during chemical production are subject to pollution-control regulations in many countries. These originate from a relatively small number of large facilities and are potentially simple to monitor. For example, there are some thirteen companies throughout the world that produce HCFC-22 and hence could be sources of the HFC-23 byproduct (AFEAS, 2003; EU, 2003). Together with their subsidiaries and associates, and the other independent facilities in a small number of developing countries, these constitute a set of 50 potential emission sites, which are point sources. A standard methodology exists to monitor the release of HFC-23 from these facilities (DEFRA, 2003; IPCC, 2000a) and future emissions will depend on production activity and the extent to which byproducts are abated at the sources.

Emissions arising during use of a fluorocarbon, or on disposal of the system containing it, occur over a much wider geographical area than the point source emissions described above. Furthermore, the losses are spread out over the service lifetime of the system with system-dependent rates of release; for most applications this will result in an emissions pattern that covers several years after the system is charged. Future releases will therefore depend on the release pattern from the current deployment, future changes in the number of systems, how widespread the use of fluids is and the extent to which the fluids are contained during usage and disposal. Methodological guidance is available for monitoring current releases of HFCs and PFCs from refrigeration and air-conditioning systems, foam blowing, aerosols, solvents and fire-fighting applications (IPCC, 2000a) and there is a standard methodological protocol for calculating releases from refrigeration systems (DEFRA, 2003).

Almost all predictions of future emissions are extrapolations of current quantities and trends and, the primary difference in methodology is the extent to which this is based on either:
a) An appreciation of the details of the market for the systems and the way those, and the emission rates of fluids, will change in the future (bottom-up approach)[8], or b) A view of the economy as a whole and the emissions arising from the niches filled by HFCs and PFCs, so that trends are governed by overall economic parameters (top-down approach).

3.7.1 Process emissions

This category includes emissions of HFC-23 from the production of HCFC-22 which, in recent years, has been the largest fluorocarbon contribution to potential climate change. This release of HFC-23 is used to exemplify the requirements for forecasting emissions.

In general, process emissions can be related to process activity:

$$E_i = A_i \text{ x } F_i \qquad (3.12)$$

Where:
E_i is the annual emission in year i;
A_i is the activity in that year, and
F_i is a factor relating activity to emissions.

8 This terminology is widely applied but has a variety of meanings. In this part of the report, all predictions based on study of HFC and PFC markets will be called bottom-up. Top-down will be used only for predictions based on macroeconomic parameters.

In the case of HFC-23, A_i is the annual rate of production of HCFC-22 for all uses, whether or not the HCFC-22 is released into the atmosphere or used as feedstock for fluoropolymer manufacture; so that the calculation of future activity will be a projection of both dispersive and feedstock end-uses. The global estimates of the production of HCFC-22 for dispersive use that were made for comparison with atmospheric measurements (McCulloch *et al*., 2003) can be extrapolated in accordance with the provisions of the Montreal Protocol as outlined in Montzka and Fraser (2003). It is important that such estimates include the significant changes in production in the developing world that are evident from UNEP (2003a). The fluoropolymers are products in their own right and have different markets and growth rates from that of HCFC-22, which, in this case, is simply a raw material. These growth parameters will need to be extrapolated separately and explicitly for developed and developing economies in order to calculate a credible total activity.

HFC-23 (trifluoromethane) is formed at the reactor stage of the manufacture of HCFC-22 (chlorodifluoromethane) as a result of over-fluorination. Its formation is dependent upon the conditions used in the manufacturing process and amounts to between 1.5–4.0 % of the quantity of HCFC-22 produced. Its production can be minimized by optimizing process conditions but the most effective means of elimination is destruction by thermal oxidation (Irving and Branscombe, 2002). Thus, the emission factor F_i for HFC-23 lies between zero and 4%. Use of a single value (3%) as the default emission rate (Irving and Branscombe, 2002), although allowed in the methodology for calculating national greenhouse-gas emissions (IPCC, 2000a), is not likely to give a credible forecast. In many cases, actual HFC-23 emission rates are recorded in national greenhouse-gas inventories (UNFCCC, 2003) and these can be used as information on the trends in emission rate (either the absolute rate or the rate relative to HCFC-22 production). It should also be possible to take into consideration national regulations that will affect such emissions in order to generate more robust predictions.

3.7.2 Calculating releases of fluorocarbons during use and disposal from sales data

Models used for extrapolation of emissions need to match historical data, including trends and, at the simplest level this means that the extrapolated data must start from the recorded baseline. Furthermore, the projections need to match the shape of the historical growth (or decline) in the sales from which emissions are calculated.

There is a long record of historic data for audited production for all of the major CFCs, HCFCs and HFCs (AFEAS, 2003). These data are consistent with the aggregated values for CFC and HCFC production and consumption reported under the Montreal Protocol (UNEP, 2002). The annual releases of CFC-11 and CFC-12, HCFC-22 and HFC-134a have been calculated from the audited production and sales (which are reported in categories having similar emission functions), and been shown to be consistent with the atmospheric concentrations observed for these species (McCulloch *et al.,* 2001; 2003). This indicates that the emission functions for these compounds from use in refrigeration, air conditioning, foam blowing, solvent applications and aerosol propulsion are robust. Comparisons between atmospheric concentrations and production or sales can also be used to refine emission functions (Ashford *et al*., 2004).

The primary variables that respond to economic parameters are the activities for the product, which in this case is the use (or sales) of that product in the categories listed above. Emissions are then secondary variables calculated from the deployment in these categories (commonly called the banks) according to models of the time pattern of the extent of emissions. These time patterns may change in response to factors such as legislation (McCulloch *et al.,* 2001).

Consideration of the long-term production databases for a wide range of industrial halocarbons, including CFCs and HCFCs, has shown that the compound growth model can be seriously misleading. It fails to replicate the shape of the demand curve over time for any of the materials examined (McCulloch, 2000). This appears to be because it does not address the changes which occur over the product lifetime. Therefore whereas growth during the early stages of product life may be compound, and hence directly related to an economic parameter such as GDP, it assumes a linear relationship with time when the product becomes more mature and then starts to assume an asymptote at full maturity. As S-curve has been shown to best represent the actual shape of the demand curve over time, the curve used to describe the growth and decline of biological populations (Norton *et al*., 1976; McCulloch, 1994b, 1995b and 1999). There is however no fixed time cycle and some products reach maturity far sooner than others. In the short term (say ten to fifteen years) it may be permissible to forecast future demand on the basis of a relatively simple function based on the historical demand. A product in its early life could be forecast to grow at a rate governed by the growth in GDP (the compound growth model); similarly, one that has reached more mature status may have a linear growth rate, increasing by the same mass rate each year. The completely mature product will have reached a constant demand (and may, in fact, be subject to falling demand if there is replacement technology).

3.7.3 Modelling future sales and emissions from bottom-up methodologies

The first step is to construct a history of the demand for the material in its individual end-uses, both those where it is currently used and those where it has the potential to be used. These demands may then be extrapolated from starting points that reflect the current status. Although it is possible, given sufficient resources and access to much information that may be considered confidential, to construct separate demand models for each new compound (Enviros March, 1999; Haydock *et al*., 2003), the most common methodology involves constructing models of the overall demand in a particular sector, for example hermetic refrigeration. Extrapolation of that demand into the future can be based on a mathematical analysis of the prior changes in functions with time (as outlined above in McCulloch, 1994b, 1995b and 1999) or on the application of an external economic function, such as a compound growth rate (for example the growth in GDP as detailed in McFarland, 1999). Although over the relatively short time-period considered in this report (up to the year 2015), the difference between linear and compound growth for future demand may be small, any robust model should show the sensitivity of the forecasts to assumptions about future growth rates and should justify those rates by reference to the historic growth or models of comparable systems.

Once a forecast for the overall demand for a function has been established, the extent to which the HFC or PFC is deployed in that function can be estimated using a substitution fraction and a view of how that fraction might change in the future. There is now a body of data that describes recent substitution fractions and the changes expected in the coming decades (Enviros March, 1999; Forte, 1999; McFarland, 1999; Harnisch and Hendriks, 2000; Harnisch and Gluckman, 2001; Haydock *et al*., 2003). The most accurate substitution data will be found by examining current technical data for each compound in each application. In almost all cases, the potential for substitution is greater than the actual extent of substitution. Enforced changes in technology have provided the opportunity to switch to completely different materials and techniques (the not-in-kind solutions), to improve recovery and recycling (McFarland, 1999) and to significantly reduce charge in each installation (Baker, 1999). The requirements for continuing economic and environmental improvements will serve to drive these in the direction of further reductions in the substitution fractions.

Emission functions, factors applied to the quantities of material in use at each stage of the equipment life cycle, can also be predicted. In many studies the functions are based on AFEAS methodology, or variants of it. This allows for an initial loss, a loss during use and a final loss on disposal (AFEAS, 2003; McCulloch *et al*., 2001, 2003; Haydock *et al*., 2003; Enviros March, 1999; Harnisch and Hendriks, 2000). Default values for the emission functions for each category of end-use are provided in the IPCC Guidance on Good Practice in Emissions Inventories (IPCC, 2000a). However these emission functions have been shown to change in response to changes in technology and regulations (McCulloch *et al*., 2001) and predictions should take this into account, either explicitly or as a sensitivity case.

Finally the future evolution of emissions for each compound may be calculated by combining the temporally developed emission functions with the forecast demands. This approach of building a quantified description of emissions from databases that can be separately verified, requires a large body of information to be gathered. However, this can be reduced by making assumptions and by estimating quantities and parameters by analogy. During the course of this process it will be relatively easy to identify the parts of the analysis that rely on such assumptions and to calculate the sensitivities of the results to changes in them. This is much more difficult if 'top-down' methods are used because the assumptions are unlikely to be explicit.

3.7.4 *Modelling future sales and emissions using top-down parameterization*

This form of methodology uses forecast changes in major econometric parameters, such as GDP, to predict future emissions. A typical example is the series of scenarios for future emissions of HFCs and PFCs contained in the IPCC Special Report on Emissions Scenarios (IPCC, 2000b). Such long-term forecasts of emissions are desirable for predicting future climate change but the real implications of these forecasts need to be established and the predictions then need to be modified accordingly.

One significant advantage of top-down forecasting is that it depends on a parameter that should be common to all other forecasts of greenhouse-gas emissions – GDP or similar. It is therefore readily scaleableas expectations for the economic parameter change. However, the assumptions must be completely clear and the sensitivity of the result to changes in the assumptions must be an integral part of the analysis.

In the ideal case, the historical connection should be established between economic parameters and the demand for refrigeration, insulation and other categories in which HFCs and PFCs can be used, so that the parameter with the best fit can be chosen. Preferably, the analysis should be done on a regional or even a national basis, but it is unlikely that sufficient data would be available for this. Then the same methodology as used in the bottom-up models should be applied to translate this demand into emissions of individual compounds. In the form of this model it is unlikely that the timing of emissions can be rigorously estimated and so the sensitivity of the result to changes in the assumptions about the timing of emissions is essential. This allows the major failing of top-down models (that deviations from reality are perpetuated throughout the modelled period) to be addressed, with the possibility of making changes in the light of technological developments.

Technology change, diffusion and transfer

In all forms of modelling it is essential to establish the drivers of technological change and to assess their effects on demand. In the case of refrigeration and air conditioning as a whole, continuing improvements to system engineering have resulted in significant reductions in the absolute rates of leakage. In turn, this has allowed similar reductions in charge size, so that the inventory of refrigerants has been reduced together with the quantities required by original equipment manufacturers (OEMs) and for servicing. The scope for such reductions was reported in IPCC/TEAP (1999). Changes of this nature may originate in developed economies but is by no means confined to them. Furthermore, the adoption of new technology in the rest of the world could be expected to accelerate as the manufacturing base shifts from North America, Europe and Japan towards developing economies.

Predictions of future emissions need to take into account the probability of technical change, in terms of both the primary innovation and its diffusion and transfer into the global manufacturing sector. At the very least analyses of the sensitivities to such changes should be incorporated, which address both the magnitude and rate of change, and take into account both geographical and economic factors. Ideally a system should be developed to simply calculate their effects on the predictions.

Uncertainty

As the results are predictions, formal statistical analyses have relatively little meaning. The key to the exercise is how well these predictions will match the future reality and this cannot be tested now. However, the models can be subjected to certain tests and the simplest is replicating the current situation; models that cannot match this from historic data are likely to give meaningless predictions. If the model output does match with reality, then the sensitivity of the result to changes in the historic parameters will provide useful information for predictions of the future. Sensitivity analyses are likely to be the most that will be necessary. Given sufficient resources it may be possible to apply Monte Carlo methods to the predictions in order to derive a more statistically rigorous uncertainty for the result. However, the value of going to such lengths is questionable bearing in mind that the models are based on assumptions and not observations.

3.8 Outlook: Future methodological developments

Some of the assessment methodologies described in this chapter are very comprehensive. For example Life Cycle Assessment was developed for high volume products in mass markets and not for the customized systems found, for example, in commercial refrigeration or fire-protection. for certain areas of application or regions, the amount of resources required for some of these assessment methods will probably be considered inappropriate. There is an evident need for simple and pragmatic assessment methods in many world regions. TEWI and LCCP analyses – using standard assumptions and boundaries – are likely to have a strong role in fulfilling this need.

An important future task in using assessment methods such as TEWI and LCCP lies in achieving consistency and comparability among different studies from different authors and years. One example for this is the choice of weighting factors for the climate impact of emissions of different substances, for example, the choice of sets of GWP values which can come from the second or third IPCC assessment report or from other more recent sources, or the application of other metrics for the radiative impact of substance emissions (see Fuglestvedt *et al.* (2003) for an overview). It would therefore seem advisable for authors to publish enough interim results to allow the recalculation of modified parameters, such as more recent emission factors or values for indirect emissions from a country's electricity production.

In the past little attention was paid to ensuring the comparability and transferability of results from different technology assessments. The treatment of uncertainties was often incomplete and the resulting recommendations were often not robust enough to be transferred across a sector. Researchers and the users of their results should therefore pay more attention to determining the circumstances under which clear and robust conclusions on the relative performance of different technologies can be drawn, and on where uncertainties preclude such rankings. Carefully designed and performed sensitivity tests of the results for variations of key parameters are crucial for obtaining these insights.

In view of the many assumptions and different methodologies, an important role has been identified for comparisons between technologies using a common set of methods and assumptions as well as for the development of simple and pragmatic standard methodologies and the respective quality criteria. A future international standardization of simple as well as more complex or comprehensive evaluation methodologies will be important. An advanced level of international consistency has already been achieved in the field of health and safety. However, international standardization processes consume considerable amounts of time and resources (from scoping, via drafting and review to finalization). More timely and flexible processes will therefore be required as well. Whereas current standards are mainly based on low-toxicity, non-flammable fluids, standardization committees must also prepare proper standards which consider the limits and conditions for the safe use of fluids that are flammable or show higher toxicity. An essential input for this is the global standardization of international levels of requirements in respect to health, safety and environmental performance as well as respective test methods and classifications.

Policymakers need to have such information that is valid for entire sectors and this warrants additional methodology development. Future work will need to bridge the gap between application-specific comparisons and results which are robust enough to be used for policy design in entire subsectors. These analyses will have to be based on extensive databases on equipment populations, which comprise empirical data on fluid emissions and energy consumption. These databases should ideally be consistent and compatible with national greenhouse-gas emission inventories. Information on fluid sales to the different parties involved in the subsector will need to be made available. Significant resources will be required for these fairly comprehensive data requirements to support robust sectoral policies, and a number of resulting confidentiality issues will need to be addressed cautiously. In their efforts to achieve acceptability across subsectors, decision-makers could focus on increasing the involvement of relevant stakeholders and introducing additional measures to increase the transparency for outside users by means of more extensive documentation.

It is important to bear in mind that the methodologies and policies discussed above may be subject to misuse and neglect. For example, although industry uses such assessments, they are rarely determining factors in selecting a particular alternative. In fact, environmental assessment methods that are sensitive to inputs are often employed to justify the suitability of a technology that has already been selected for other reasons.

Policymakers should therefore recognize other parameters industry uses to choose technologies, so that they are aware of the factors affecting the outcomes of an analysis and of the market forces which may counter the spirit of environmental policies.

Cost is clearly one of the most important factors driving decisions for or against certain technologies. Private decision-makers usually take a life-cycle cost perspective based on their enterprises' rules for depreciation times and capital costs for their investment. Policymakers commonly use different rules and parameters to judge the cost-effectiveness of different measures. As this Special Report has shown, there is still little public cost information available which policymakers can use to reach a judgement about the cost-effectiveness of measures. Many firms give considerably less weight to social costs than to private costs in making their decisions. Initial exploratory studies would seem to be a worthwhile means of filling this gap. In the future it might be useful to apply uniform costing methodologies with common standards for transparency and data quality.

In summary the following points can be highlighted as key results:

A systems perspective is usually used to select a technology. This takes into account the system's life-cycle costs, its energy consumption and associated emissions, health and safety impacts, and other environmental impacts. The available assessment methods for each of these attributes have been described in this chapter. These will often need to be adapted to the specific application region concerned. A decision-maker can avoid inconsistencies by initiating concerted technology comparisons of competing technologies under common rules. In any case decision-makers need to make their decisions in the light of the remaining uncertainties and limitations of the available assessment methods, such as Total Equivalent Warming Impact (TEWI), the Life Cycle Climate Performance (LCCP) or a Life Cycle Assessment (LCA).

Ensuring the faithful application of existing assessment methodologies by all players in order to provide information relevant for decisions, is an ongoing challenge. A decision-maker may want to ensure that the full life cycle of the application has been considered, that all relevant stakeholders have been involved in the scoping and execution of the analysis and in the review of its results, that accepted emissions monitoring protocols have been applied for direct and indirect emissions, that all costs are properly accounted based in the best available figures, and that the uncertainties, sensitivities and limitations of the analysis have all been clearly identified.

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