CONF-970687--1

Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies: TEWI-III

J. R. Sand
S. K. Fischer
V. D. Baxter

to be presented at
The International Conference on Climate Change
Baltimore, Maryland
June 12-13, 1997

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
managed by
LOCKHEED MARTIN ENERGY RESEARCH CORP.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-96OR22464

Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies: TEWI-III

J. R. Sand **S. K. Fischer** **V. D. Baxter**

Oak Ridge National Laboratory
Building Equipment Technology Program
Oak Ridge, Tennessee

ABSTRACT

The use of hydrofluorocarbons (HFCs) which were developed as alternative refrigerants and insulating foam blowing agents to replace chlorofluorocarbons (CFCs) is now being affected by scientific investigations of greenhouse warming and questions about the effects of refrigerants and blowing agents on global warming. A Total Equivalent Warming Impact (TEWI) assessment analyzes the environmental affects of these halogenated working fluids in energy consuming applications by combining a ***direct effect*** resulting from the inadvertent release of HFCs to the atmosphere with an ***indirect effect*** resulting from the combustion of fossil fuels needed to provide the energy to operate equipment using these compounds as working fluids. TEWI is a more balanced measure of environmental impact because it is not based solely on the global warming potential (GWP) of the working fluid. It also shows the environmental benefit of efficient technologies that result in less CO_2 generation and eventual emission to the earth's atmosphere. The goal of TEWI is to assess total global warming impact of all the gases released to the atmosphere, including CO_2 emissions from energy conversion.

Alternative chemicals and technologies have been proposed as substitutes for HFCs in the vapor-compression cycle for refrigeration and air conditioning and for polymer foams in appliance and building insulations which claim substantial environmental benefits. Among these alternatives are:

- Hydrocarbon (HC) refrigerants and blowing agents which have zero ozone depleting potential and a negligible global warming potential,
- CO_2 as a refrigerant and blowing agent,
- Ammonia (NH_3) vapor compression systems,
- Absorption chiller and heat pumping cycles using ammonia/water or lithium bromide/water, and
- Evacuated panel insulations.

This paper summarizes major results and conclusions of the detailed final report on the TEWI-III study.

INTRODUCTION

The concept of total equivalent warming impacts, or TEWI, was developed to combine the effects of the direct emissions of refrigerants and polymer foam insulation blowing agents in end use applications with the indirect effects of energy consumption from the combustion of fossil fuels and generation of electricity used for heating and/or cooling. Direct contribution to TEWI is based on the use of the global warming potentials (GWPs) developed by the Intergovernmental Panel on Climate Change (IPCC) that use carbon dioxide (CO_2) as a reference gas (GWPs of CO_2 = 1.0 regardless of time horizon). TEWI provides a measure of the environmental impact of greenhouse gases from operation, service and end-of-life disposal of equipment. TEWI is the sum of the ***direct*** contribution of greenhouse gases used to make or operate the systems and the ***indirect*** contribution of carbon dioxide emissions resulting from the energy required to run the systems over their normal lifetimes.

The TEWI concept provides a useful tool in the assessment of various competing technologies. However, it is only one of many criteria that must be considered. Safety, health, and other environmental concerns, system initial and operating costs, regional energy considerations, and ease of maintenance are among other important factors that must be evaluated in the selection of the "best technology" for any given application.

The Alternative Fluorocarbons Environmental Acceptability Study (AFEAS)[1] and the U.S. Department of Energy (DOE) undertook this current study to assess the significant developments that have occurred in HFC blends and the application of non-fluorocarbons like HCs, CO_2 and NH_3 as refrigerants or foam insulation blowing agents. New data on the thermal performance of these compounds made it possible to perform an objective evaluation of the energy and global warming impacts of these "third generation" refrigerants and blowing agents. Refrigerant and equipment manufacturers have also made significant advances in the use of high pressure blends of HFCs as alternatives to HCFC-22 in both refrigeration and air conditioning applications. Analytical and experimental results are available to perform quantitative comparisons between HFC blends and the application of hydrocarbons, ammonia, and carbon dioxide as refrigerants. Additionally, new technologies for gas-fired air conditioning systems are being commercialized and operating data are available. This paper summarizes the major findings of this third study (Sand, et al. 1997)

The study focuses on evaluating the energy and global warming impacts of refrigeration and air conditioning technologies that could be commercialized during the phaseout of HCFCs. These alternatives include HFCs, hydrocarbons, ammonia, and carbon dioxide as refrigerants in conventional (and transcritical[2]) vapor-compression equipment, absorption chillers and heat pumps, and evacuated panel insulations for refrigerator cabinets.

As with the previous studies, analyses for end use applications in North America, Europe, and Japan account for cultural and technical differences in each region. The differences included such things as the ambient room temperatures and internal compartment temperatures for refrigerator/freezers, the sizes of refrigerators and thicknesses of insulation used, annual driving distances for automobiles, fuel types used for generating electricity, and climate differences for building heating and cooling loads. The results in this paper expand the work in the initial studies and indicate important regional differences in TEWI for some applications.

---

1 AFEAS is an international consortium of fluorochemical manufacturers

2 The term transcritical is used to describe a vapor compression (reverse Rankine) cycle in which the working fluid is heated above its critical temperature in the compression step, and is cooled by ambient conditions prior to throttling and evaporation rather than being condensed to a liquid in a condenser as in a normal reverse Rankine cycle.

Analysis Limitations

TEWIs are calculated using "published" values for power plant emission rates. This report did not use heat content of various fossil fuels, regional generating capacities, plant efficiencies, and electric distribution efficiency to calculate a value for kg CO_2/kWh of electricity delivered to the end-user. TEWI calculations have become widespread enough that good published data are available in the open literature for regional and national power plant emission rates. Slightly different trends are observed or conclusions can be drawn when calculations are performed using low regional emission rates as compared to the national averages. The range of rates is important for setting and achieving national CO_2 emission goals.

It is difficult to calculate an *absolute* value for TEWI. Most of its value comes from using it as a *comparative* tool for meeting a given refrigeration or air conditioning need under a standardized/controlled set of assumptions. A minimum of ±20% uncertainty exists for the GWP values assigned to refrigerants and blowing agents by the Intergovernmental Panel on Climate Change. These uncertainties, when taken in combination with the other estimates and assumptions of the analysis, make TEWI differences of ±10% statistically comparable. In many cases, established technologies with far fewer uncertainties and variables are being compared to systems under development for which significant uncertainties exist. When TEWI values are within 10% of each other, the technologies which show better energy efficiency should be favored as long as safety and environmental considerations are adequately addressed and costs are reasonable.

TECHNICAL EVALUATIONS

Alternative and Next Generation Technologies

Several alternative technologies for the conventional vapor compression (reverse Rankine) cycle employing halocarbons were identified in the Phase II (TEWI-2; Fischer et al. 1994) report that had been laboratory tested or had been developed to a point where they were considered as potential alternative technologies for those currently used. For example, employing CO_2 in a transcritical vapor compression cycle or using a high efficiency absorption cycle heat pump showed sufficient promise that they were revisited as potential alternatives in this study. Additional development work has occurred on triple-effect, direct-fired absorption chillers and absorption heat pumps for residential or light-commercial applications so that estimates of TEWI for this equipment are included in the appropriate sections of this paper. Alternative technologies which showed little near-commercial promise in the TEWI-2 report, such as thermoelectric cooling, magnetic heat pumps, thermoelastic heat pumps, etc., are not considered here.

Engine Driven Systems. Engine driven chillers and heat pumps are considered which employ the same reverse Rankine cooling cycle as conventional electric powered systems, but the electric motor is replaced by an internal combustion engine. This change has very little or no effect on the *direct* contribution to TEWI resulting from inadvertent releases of the working fluid to the environment, but it can change the *indirect* contribution associated with CO_2 emissions. Factors affecting the *indirect* contribution result from the primary energy source used to drive the cycle and any inherent differences in cycle efficiencies such as changes in part load efficiencies or waste heat recovery, resulting from this substitution. Thermally driven air conditioning and refrigeration equipment allows consumers to select natural gas as the primary fuel source in situations where there are significant differences in energy prices, utility rebates, prohibitive peak charges, or an opportunity for waste heat recovery. These opportunities have prompted considerable support for research and development (R&D) at HVAC manufacturers and other organizations for gas-driven technologies and have resulted in the commercial availability of packaged, natural gas engine-driven chillers and residential heat pumps. Since this equipment does represent a significant departure from conventional practices, TEWI calculations are presented for gas engine-driven chillers and heat pumps for comparison with electric-driven technologies.

Absorption Chillers. Absorption chillers are commercially available and represent a major share of the commercial air conditioning market in Japan and a portion of the market in the United States. Absorption equipment is often used in "hybrid" plants working together with electric centrifugal chillers to reduce electric peak demands and utility demand charges. Even though absorption chillers generally have lower cycle efficiencies than electric chillers, absorption equipment is an effective component for managing utility demand charges and customer energy costs. Single-effect absorption chillers are also used in applications powered by waste heat, in which case the lower efficiency is not important. Direct-fired, double-effect chillers can simultaneously provide chilled water for air conditioning and hot water for cleaning or space heating thereby alleviating some requirements for a boiler. Gas fired single- and double-effect absorption chillers show higher TEWI than electric driven centrifugal chillers for the operating conditions used in this work. Triple-effect absorption chillers are under development which will be 50% more efficient than current double-effect equipment.

Absorption Heat Pumps. Absorption heat pumps are under development for heating and cooling in residential and light commercial applications. One or two manufacturers have prototype units undergoing laboratory and field testing in 1998, with a goal commercialize this technology in the 1999-2000 time frame. Seasonal performance data are available for these prototype units. Compared to current electrically driven heat pumps, these systems have a slightly lower TEWI in areas where heating load dominates, but show larger TEWIs in areas where cooling loads dominate.

Advanced Vapor Compression. Conventional vapor compression technologies continue to be improved and efficiencies of refrigeration and air-conditioning equipment will be higher in the future. Developments leading to these improvements include the use of higher efficiency motors and compressors, more effective heat exchangers, and adaptive controls. Refrigerant losses from applications such as automobile air conditioning and supermarket refrigeration have been, and will continue to be, reduced. Supermarket equipment now under development and entering the market, such as systems that circulate a chilled secondary fluid or distributed compressor rack designs, show promise of dramatically reduced refrigerant charge and emissions. Regulations and refrigerant costs provide an incentive to reduce emissions of refrigerant by eliminating intentional venting during servicing, improving maintenance practices and procedures, mandating charge recovery and recycling, and minimizing leaks.

Compression systems will continue to improve, but it is not known how quickly or how significant these improvements will be. TEWI calculations for fluorocarbon compression systems summarized in this paper are based on demonstrated production, modeled efficiencies, historically verified refrigerant loss rates, or proven performance from R&D research laboratory tests (which would probably show different efficiencies than optimized production designs). Refrigerant loss rates used in the two previous studies in the series (Fischer et al. 1991, Fischer et al. 1994) were from a time when it was standard practice to simply vent the refrigerant charge during servicing. These practices are now prohibited in the United States and elsewhere and it is clear that historical emission rates are no longer appropriate. Current and projected refrigerant make-up rates based on information from industry were used for cases presented in the third study (Sand et al. 1997).

TEWIs of viable, commercially available compression systems are compared in some cases to estimated TEWIs for emerging technologies which have not been developed beyond laboratory prototypes. In these instances the best available laboratory or computer modeled performance data are used for new technologies. While helpful in identifying future technologies that may have lower global warming impacts, the reader must be careful not to attribute too much significance to comparisons with minor differences in TEWI because of the more speculative nature of the data used for these non-commercialized, emerging technologies.

Evacuated Panel Insulation. Evacuated panels which can be used to improve appliance and building insulations have very low thermal conductivities. Thin, flat panels are constructed using a filler material such as aerogel, diatomaceous earth, or glass fibers enclosed by one or more plastic or metal membranes under a vacuum. "Total panel" thermal conductivities are usually significantly higher than the "center-of-panel" measurements usually cited, because heat transfer through the plastic or metal membranes along the surfaces and near the edges of the panel is enhanced. Evacuated panels, at last report, are being used by a Japanese refrigerator-freezer manufacturer for a commercial product. While evacuated panel insulation could be an effective means to reduce TEWI especially for refrigerator-freezers, these panels are quite expensive compared to the foamed polyurethane insulations usually used. There continues to be doubt that panels used for cabinet insulation will retain a vacuum and maintain high thermal resistances over the 15-20 year lifetime of an appliance. Such panels could be used in conjunction with blown foam insulation to improve the thermal properties of appliance cabinets or to achieve comparable performance using thinner walls, thereby permitting more usable internal volume.

Refrigerator-Freezers. The latest available published information indicates no significant difference between the measured energy efficiency of refrigeration circuits utilizing HFC-134a or iso-butane (HC-600a) as the refrigerant despite ideal cycle calculations which show a 2 to 5% thermodynamic efficiency advantage for HC-600a depending on specific operating conditions.

Insulating foams blown with cyclopentane or pentane isomers consistently show higher thermal conductivities than HCFC-141b blown foams; refrigerators produced with these HC foams would have 8 to 10% higher energy consumption assuming the same foam thickness. Most of the R&D work for this application has centered around finding an alternative for HCFC-141b, which is scheduled for a 2003 phaseout date in the United States. Current data shows HCFC-141b blown foam has the lowest thermal conductivity and highest insulating value of the foam blowing agents investigated, which results in the lowest energy consumption for the refrigerator design when equivalent wall thicknesses and internal volumes are assumed. Optimized HFC-245fa or HFC-365mfc blown foam is expected to show similar conductivity and insulating values. Vacuum panel technology can further improve cabinet thermal performance but with significantly increased costs. Designs consistent with the "average" models prevalent in each region were postulated based on data from manufacturers and industry associations and consistent assumptions on components, wall thicknesses, and internal volumes were applied.

The direct contribution of HFC-134a and the various halocarbon blowing agents range from 8% to 15% of the TEWI for refrigerator-freezers in North America. Only one-tenth of the TEWI of refrigerators using HFC-134a as the refrigerant and HCFC-141b as the blowing agent is due to fluorocarbon emissions. Almost all of the direct effect is due to the foam blowing agent. Mandatory refrigerant recovery results in a 1 to 2% decrease in total lifetime TEWI (direct and indirect).

The direct contribution due to fluorocarbons in European refrigerator-freezers is about 19% of TEWI, primarily because their refrigerators are smaller and have lower annual energy use. The lower CO_2 emissions rate for electric power generation in Europe, which has a higher percentage of nuclear and hydroelectric power generation than North America, is also a factor.

In 1996 hydrocarbon refrigerators were available in both manual and automatic defrost models in parts of Europe, particularly Germany. Iso-butane (HC-600a) frost-free refrigerator designs which incorporate a foamed-in evaporator and explosion proof electrical devices or switches located outside of the food compartments are now being built and sold. These additional safety precautions and system components have resulted in higher manufacturing, purchasing, and servicing costs for refrigerators using HCs. Flammable refrigerants are not used in United States or Japanese refrigerators because the associated safety risks are considered unacceptable.

Unitary Air Conditioning Equipment. HFC mixtures and hydrocarbons have been proposed and tested as substitutes for HCFC-22 in unitary equipment. Building codes and safety concerns in most developed countries limit the use of hydrocarbons in applications where a refrigerant leak could result in explosive mixtures at atmospheric conditions. These restrictions apply to air-to-air heat pumps and air conditioners in North America and Japan (90-95% of the approximately 214 million unitary heat pumps and air conditioners in the world). Hydrocarbon refrigerants might be able to satisfy safety requirements for the air-to-water or water-to-water unitary systems used in Europe where the entire refrigerant charge remains outdoors, but leakage rates for these hydronic units are typically small, therefore any refrigerant choice results in a small direct TEWI effect.

Comparisons were made for HCFC-22 and two non-flammable HFC mixtures identified as likely HCFC-22 replacements in the Air-Conditioning and Refrigeration Institute (ARI) HCFC-22 Alternative Refrigerants Evaluation Program (AREP). The direct TEWI effects for both HCFC-22 and HFC alternative mixtures are a small fraction of the total in each case. Energy efficiency is very important for this application and contributions to global warming from energy usage with HFC blends are about the same as current technology air conditioners using HCFC-22; engineering optimization is expected to reduce energy use and resultant CO_2 emissions with the mixtures in future systems. An intermediate heat transfer loop was used with heat pump systems using propane as a refrigerant as a means to keep this flammable refrigerant out of the occupied space. Compared to conventional, electrically-driven heat pumps, engine driven heat pumps and Generator Absorber Heat Exchange (GAX) absorption heat pumps give lower TEWIs in areas where heating loads predominate and larger TEWIs in cooling-dominated regions.

Refrigerant make-up rates and end-of-life losses assumed in this study for 1996 vintage equipment were suggested by industry experts in each region and are the same as those used for the 1994 study; a 4% annual make-up rate and 5% loss of charge upon equipment decommissioning.

Supermarket Refrigeration Systems. These systems have historically used large refrigerant charges and experienced high leakage rates. The current high costs of refrigerants and environmental regulations are resulting in better efforts at refrigerant containment and lower loss rates. The most likely substitutes for CFCs and HCFCs in supermarket refrigeration are mixtures of HFCs, although use of ammonia chillers with indirect heat transfer loops is seeing some use in Europe. Alternative refrigerants and technologies are considered as replacements for R-502 in low temperature refrigeration (e.g. freezers and ice cream display cases) and HCFC-22 in medium temperature refrigeration (e.g. meat, fish, and dairy cases). The alternatives include HFC mixtures in direct expansion systems using remote and distributed compressor racks and HFC mixtures or ammonia in secondary loop refrigeration systems.

Secondary loop systems are a means of reducing refrigerant charge and controlling leakage and emissions, albeit with first cost and efficiency penalties. This approach to commercial refrigeration avoids long, field erected refrigerant lines which run to individual cases in the store and confines the refrigerant charge to a smaller, more leak-tight refrigeration circuit in the store's equipment room. The secondary loop approach must operate over a larger temperature lift to accommodate the intermediate level of heat exchange and has an additional parasitic load associated with a fluid circulating pump. Building codes in many countries make it expensive, or in some cases prohibitive, to use ammonia in most supermarkets because of the public safety risks in the densely populated areas near the stores. When ammonia is used, secondary loops are usually mandatory so that the refrigerant lines do not enter the retail sales areas of the building .

Another alternative commercial refrigeration design, usually referred to as the *distributed system* approach, moves the compressor with its associated high pressure liquid and suction gas lines as close as practical to the case evaporator loads and utilizes a closed-loop, water circuit to reject the heat of condensation. The distributed system with compressors located near or in the refrigeration cases requires a larger number of smaller compressors located throughout the store. It, too, has a parasitic load associated with the heat rejection water loop and pump albeit smaller than for the secondary loop system. Both the distributed system and secondary loop approaches drastically reduce the refrigerant charge (by as much as 75-90%) and make it more practical to minimize refrigerant leaks and maintain system efficiency.

Chillers. The air conditioning loads of larger commercial buildings are generally met with water cooled chillers which use cooling towers for condenser cooling and distribute chilled water or a water/antifreeze mixture to building fan coil units. Centrifugal or screw compressors are used for larger, 350 to 75,000 kW (100 to 10,000 ton), chillers because of the high volumetric flow rates of refrigerant required. Replacement of CFC refrigerants in chillers with HCFC and HFC alternatives has had the most significant impact on the direct contribution for this equipment. An increased awareness of the environmental impact of refrigerants, recently enacted legislation which requires extensive record keeping, increasing refrigerant prices, and improved equipment designs have all served to dramatically reduce refrigerant loss rates from chillers. Typical annual loss rates of low pressure refrigerant from new centrifugal chillers has been reduced more than 50- fold in seven years. New systems are equipped with electronic alarms alerting operators to the first indications of leaks or unusual purge pump operation. Refrigerant leak and annual make-up rates have been improved to the point where the GWP of all chiller refrigerants has very little effect on the total TEWI.

The TEWI of chillers has been reduced through remarkable improvements in chiller efficiencies as well. Rating point COPs for new electric chillers have increased by about 30% (from 5.0 to 7.0) over the last ten years which has resulted in a proportional decrease in the indirect contribution from CO_2 emissions. Market competition and a greater emphasis on lower life cycle operating costs, as opposed to governmental legislation, are responsible for these dramatically improved efficiencies. Even with these improved efficiencies, lifetime energy consumption is the predominant factor influencing TEWI for this equipment. The direct contribution to TEWI for fluorocarbon-based technologies is less than 6 to 7% of the total (less than 1% for the HCFC-123 machines) even when the maximum annual leak/make-up rate is assumed.

Efficiency of natural-gas-engine-driven chillers and of absorption chillers has also been improved. Gas-powered chillers are sometimes used together with electric chillers to decrease peak electrical demand and lower building operating costs. TEWI results for gas-engine-driven and electric-driven chillers are essentially equal when the CO_2 emission rates from electric power plants are in the 0.60 to 0.70 kg CO_2/kWh range. Gas-fired absorption chillers (double- and triple-effect) continue to have TEWIs 25 to 50% higher than comparable vapor-compression technologies. The decision to utilize absorption chillers is based on operating costs when favorable conditions exist.

TEWI calculations were made for both vapor compression and absorption chillers of two discrete capacities - 1,200 and 3,500 kW (350 and 1,000 tons) - in North America. These calculations were based on the use of Integrated Part Load Values (IPLVs) and annual operating hours for an Atlanta, Georgia office building. Direct contributions to TEWI were computed for centrifugal and screw chillers using HCFC-123, HFC-134a, HCFC-22, and NH_3 as refrigerants for a range of annual make-up rates up to 4%. 1993 vintage CFC-11 and CFC-12 machines were included for comparison purposes. Similar computations were made for 1,055 kW (300 ton) chiller options in Japan. In this case, rated full-load performance data and associated annual operating hours for a Tokyo location were used. Vapor compression chillers using HCFC-123 and HFC-134a and direct- and indirect-fired absorption chillers were considered.

Automobile Air Conditioners. Automobile air conditioning was identified in the two previous studies as one of the few applications in which the direct contribution of fluorocarbon refrigerant emissions was a significant fraction of total TEWI. While the conclusion has not been contested, the approach taken in those studies has been criticized because of reliance on efficiency data at a single design point coupled with estimates of equivalent full-load operating hours. These two assumptions greatly simplified the analysis but cannot account for varying performance over a range of operating conditions or the effects of different climates. The present analysis addresses these concerns by incorporating efficiency differences across a wide range of operating conditions, regional variations in ambient temperature, and changes in air conditioner on-time with ambient temperature.

Three fundamentally different cooling systems were considered; a conventional HFC-134a-based system, an HC-600a-based system, and a transcritical vapor compression system using CO_2 as the refrigerant. The hydrocarbon system in this study includes the use of a secondary heat transfer loop to isolate the flammable refrigerant outside the passenger compartment. This essential safety feature reduces cycle efficiency relative to direct expansion systems, adds parasitic energy consumption due to the fluid pump, and increases overall system weight.

Though the analysis includes much more detailed information than the earlier studies, it relies on the same approach of evaluating energy use for operating and transporting the air conditioner and the direct contribution of refrigerant emissions. Results are computed for thirteen different countries. Depending on the location and assumptions about lifetime refrigerant emissions, the alternative systems show some potential for lower TEWI than the HFC-134a system. Prototypes of both alternatives are being studied by manufacturers (the CO_2 system to a much greater extent than the HC system), however more extensive prototype and field trial testing will be needed before fully developed, reliable commercial designs will be available.

Conclusions

Several broad conclusions can be drawn from the study.

TEWI evaluations emphasize the combined environmental effect of the direct emission of greenhouse gases with the indirect effects of CO_2 emissions from energy use by equipment using these fluids as refrigerants or blowing agents. This is only one criterion in selecting technologies to meet any given application. System costs, operating costs, regional energy costs, ease of maintenance, etc., are equally important factors to consider in selecting the most appropriate technology for any specific application.

Reductions in TEWI through the use of ammonia or hydrocarbons as refrigerants are insignificant for refrigeration systems with low emissions and may lead to an increase in energy use when applications must meet the same safety design criteria currently defined as acceptable for fluorocarbon refrigerants.

The direct effect of HFC refrigerant and blowing agent emissions in refrigeration and insulation applications appears greater when 100 year GWP values are used in calculating the TEWI (the 100 year GWP values are approximately three times the 500 year values used in the 1991 report).

Non-fluorocarbon technologies may penetrate into mainstream refrigeration and air condition application areas, but it appears unlikely that this penetration will be significant in the near future.

Alternative/non-fluorocarbon technologies need to compete with improving energy efficiencies of conventional refrigeration, air conditioning and insulation technologies. Both electric and gas-driven technologies will continue to improve. Efficiencies of conventional technologies are likely to increase as equipment and foam formulations are further optimized for replacement refrigerants and blowing agents.

Innovative design and modifications of standard practice can lead to significant reductions in TEWI for refrigeration systems using ammonia, fluorocarbon, or hydrocarbon refrigerants. These include mandatory refrigerant recovery and recycling, distributed refrigeration systems, charge reduction, elimination of flared fittings and fewer brazed connections, highly efficient purge units, improved heat transfer surfaces, high-efficiency compressors, etc.

Average annual CO_2 emissions from electricity generation vary over a wide range for individual regions and countries -- from 0.0 to over 1.0 kg CO_2/kWh compared to the 1993 World average of 0.58. Emission rates also vary with season and time of day depending on how the generation fuel mix changes. Overall TEWI values in any particular location will be peculiar to the local electrical power generating efficiency and generating characteristics. The direct contribution can range from all (or nearly all) of the TEWI for all applications in areas with low CO_2 emission rates [using mostly nuclear or hydro power] to a minor fraction of total TEWI for areas with high rates [using coal].

References

K. Fischer, P. J. Hughes, P. D. Fairchild, C. L. Kusik, J. T. Dieckmann, E. M. McMahon, and N. Hobday, 1991. ***Energy and Global Warming Impacts of CFC Alternative Technologies,*** AFEAS and DOE. AFEAS Program Office, The West Tower – Suite 400, 1333 H. Street NW, Washington, DC 20005 USA.

S. K. Fischer, J. J. Tomlinson, and P. J. Hughes, 1994. ***Energy and Global Warming Impacts of Not-In-Kind and Next Generation CFC and HCFC Alternatives***, AFEAS and DOE. AFEAS Program Office, The West Tower – Suite 400, 1333 H. Street NW, Washington, DC 20005 USA.

J. R. Sand, S. K. Fischer, and V. D. Baxter, 1997. ***Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies: TEWI Phase 3***, **[in print]**, AFEAS and DOE. AFEAS Program Office, The West Tower – Suite 400, 1333 H. Street NW, Washington, DC 20005 USA.