International Institute of Refrigeration
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Life Cycle Climate Performance Working Group

Guideline for Life Cycle Climate Performance

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1. Introduction

1.1 Introduction

Climate change is an increasingly important global concern with far reaching effects. The heating, ventilation, air conditioning, and refrigeration (HVAC&R) industry is allotting a significant amount of effort to reduce the environmental impacts of HVAC&R systems. Discussions about the climate impact is often limited to the GWP of the fluids used, but this is far too restrictive, as it does not take into account the real emissions of fluids, and ignores indirect emissions, especially those related to energy use over the life time of the equipment. Focusing solely on GWP can lead to irrational and counterproductive decisions. This is why it is so important to use more comprehensive indicators of the real Green House Gases emissions of systems over their life time.

Additional holistic indices have been developed to measure this impact, including Total Equivalent Warming Impact (TEWI), Life Cycle Analysis (LCA), and Life Cycle Climate Performance (LCCP). However, these indices are still not widely used. The International Institute of Refrigeration (IIR) established a working group in January 2012 to assess the merits of the LCCP methodology [1], and to propose evaluation methods to promote the use of the LCCP index. The working group developed this guideline and an abbreviated guideline for performing LCCP calculations for air conditioning, heat pumping and refrigeration systems with recommended assumptions and data sources for different types of units.

This guide provides a harmonized method to calculate the LCCP for all types of stationary air conditioning, heat pumping and refrigeration systems. The process and assumptions by which LCCP should be approached are discussed in later chapters. This guide aims to provide designers, facility operators, manufacturers, and policy makers a way to effectively evaluate and compare the environmental impact of different systems over the course of their lifetimes. A sample calculation and excel tool are included for a residential heat pump.

1.2 Life Cycle Climate Performance

Life Cycle Climate Performance is an evaluation method by which HVAC&R systems can be evaluated for the global warming impact over the course of their complete life cycle. It is calculated as the sum of direct and indirect emissions generated over the lifetime of the system "from cradle to grave". Direct emissions include all effects from the release of refrigerants into the atmosphere during the lifetime of the system. This includes annual leakage and losses during the disposal of the unit. The indirect emissions include emissions from the manufacturing process, energy consumption, and disposal of the system [2-8].

1.3 Comparison to TEWI

The Total Equivalent Warming Impact (TEWI) is a known metric that measures the global

warming impact of a HVAC&R system by quantifying the amount of greenhouses gases it emits during its usage phase, from commissioning to end of life. It takes into account the direct and indirect emissions over this period. The direct emissions result from the leaks, and the fluid that is not recovered at the end of life ("EOL"). The indirect emissions result from the energy use over the same period.

LCCP is a more comprehensive evaluation than TEWI. It includes all the direct and indirect emissions generated by the system during its complete lifetime from "cradle to grave." To do this, in addition to TEWI, LCCP accounts for energy embodied in the product materials, greenhouse gas emissions from chemical manufacturing and end-of-life disposal of the unit [4-9]. LCCP can also account for minor emission sources that are not accounted for in TEWI such as transportation leakage, manufacturing leakage, and refrigerant manufacturing emissions [2-10]. This comparison is further discussed in Chapter 5.

1.4 Relevance of LCCP

Electricity usage constitutes the largest factor in LCCP comparisons. According to the United States Energy Information Administration (EIA), the world residential energy use will increase by 1.5% per year from $1.5x10^4$ tWh in 2010 to $2.4x10^4$ tWh in 2040, while the commercial energy use will increase by 1.8% per year [11]. This increase reflects the growing use of electricity worldwide. On average, households in developed countries use 53% of their energy consumption for space heating and cooling [11]. The overall usage of electricity has increased with the number of appliances and the increased prevalence of HVAC systems in all buildings. A careful accounting of the related emissions is vital in slowing the current and future emissions of greenhouse gases.

1.5 Limitations of LCCP

Like for TEWI, LCCP calculations are dependent on a number of assumptions about the system performance, manufacturing emissions, typical system characteristics, and energy generation emissions. These values are all subject to a certain amount of uncertainty. LCCP should be used as a comparison tool for systems with similar performance and function. It is not intended to be used as a definitive estimate of lifetime emissions. Small variations between different units may not have significance because of the inherent uncertainty in the assumed emission values.

1.6 Creation of LCCP

LCCP was first proposed by the Technology and Economic Assessment Panel (TEAP) of the United Nations Environmental Program (UNEP) [12] in 1999 to calculate the "cradle to grave" climate impacts of the direct and indirect greenhouse gas emissions. This methodology was then applied by the government and industry researchers in several facets such as evaluating potential refrigerants to replace HCFCs [4].

1.7 Existing Tools

There are several LCCP and TEWI tools in existence. GREEN-MAC-LCCP was the first comprehensive excel based tool to use the LCCP methodology to evaluate mobile air conditioning (MAC) units [6]. This model is globally used by the automobile industry and is publically available. It has become the standard tool in the MAC industry.

The Air Conditioning, Heating, and Refrigeration Technology Institute (AHRTI) sponsored a project to develop an Excel-based tool for residential heat pump applications [8, 14, 15]. The tool includes both detailed and simplified calculations for residential heat pumps. The model includes direct and indirect impacts of refrigerant emissions, indirect impacts of energy consumption, energy to manufacture and dispose of the system and refrigerants. The annual energy consumption calculation uses performance data as defined by AHRI Standard 210/240 [13]. This method is typical of TEWI or LCCP calculations based on the standards for energy consumption.

Beshr et al. [14-15] developed a web based open source LCCP tool for air conditioning and refrigeration applications. Both a web tool and desktop application with expanded capabilities were created. The tool can be used with any system simulation software, load calculation tool, and weather and emissions data types.

IPU Pack Calculation Pro is a commercially available tool which uses the TEWI and Life Cycle Cost (LCC) methodologies to evaluate refrigeration systems and heat pumps for various locations around the world [16].

1.8 Emissions Values

The emissions values presented in this guideline for various industries represent the latest research and technology in the sectors available at the time of publication. The values need to be updated continuously as new research becomes available.

2. Calculation Method

The methodology for calculating LCCP is applicable to stationary refrigeration, air conditioning, and heat pumps systems that operate using the vapor compression cycles and are powered primarily by electricity from the electricity grid. LCCP is calculated in kg CO_{2e} or in kg CO_{2e}/kWh for "specific" LCCP.

Different systems can be compared when all the calculations use the same assumptions and calculation method as presented. This methodology can be applied to all HVAC&R applications, such as commercial refrigeration systems, residential heat pumps, and chillers. This guide uses a residential heat pump as an example.

LCCP is comprised of two general emissions categories: direct and indirect emissions. The breakdown of these factors is shown in Equation 1. Each factor is calculated separately. These factors are further explained in Chapters 3 and 4.

Direct emissions account for the refrigerant leaked over the course of the unit's lifetime including annual leakage, catastrophic leaks, and losses when the unit is disposed of. It also includes atmospheric degradation products created by the refrigerant when it decomposes in the atmosphere during its usage time and afterwards.

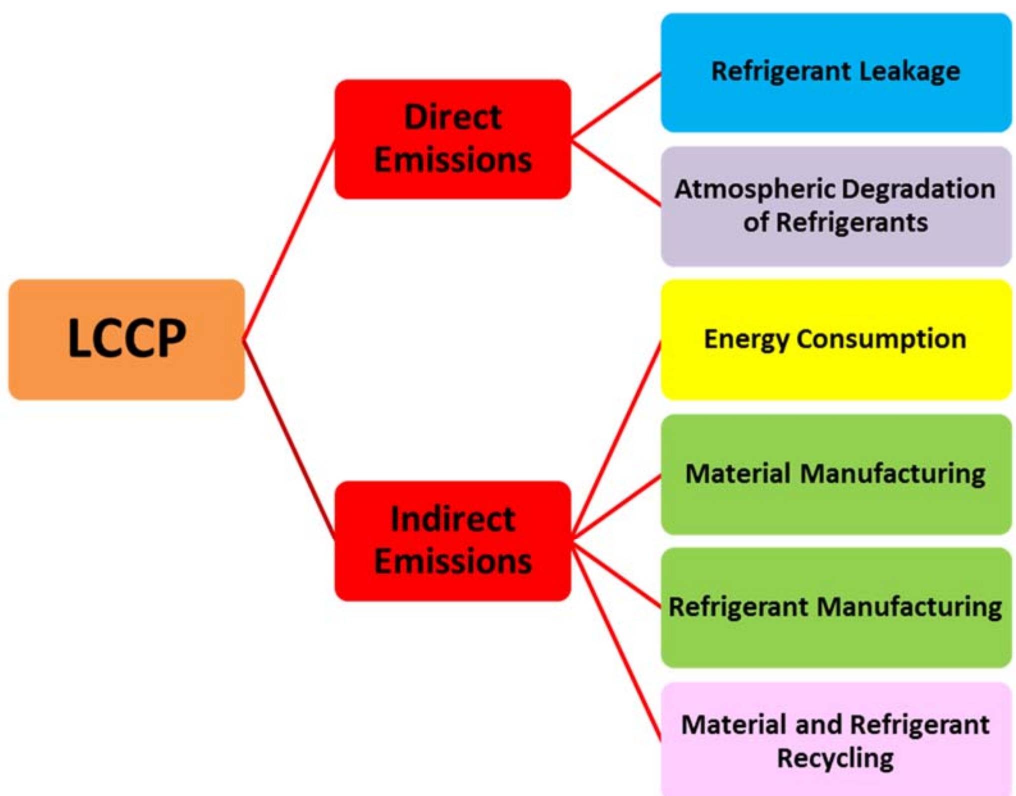

Figure 2.1: LCCP Components

$$LCCP = Direct\ Emissions + Indirect\ Emissions$$

$$Direct\ Emissions = C * (L * ALR + EOL) * (GWP + Adp.\ GWP)$$

$$Indirect\ Emissions = L * AEC * EM + \sum(m * MM) + \sum(mr * RM) + C * (1+ L * ALR) * RFM + C * (1-EOL) * RFD$$

C = Refrigerant Charge (kg)
L=Average Lifetime of Equipment (yr)
ALR = Annual Leakage Rate (% of Refrigerant Charge)
EOL = End of Life Refrigerant Leakage (% of Refrigerant Charge)
GWP = Global Warming Potential (kg CO_{2e}*/kg)*
Adp. GWP = GWP of Atmospheric Degradation Product of the Refrigerant (kg CO_{2e}*/kg)*
AEC = Annual Energy Consumption (kWh)
EM = CO_2 *Produced/kWh (kg* CO_{2e}*/kWh)*
m = Mass of Unit (kg)
MM = CO_{2e} *Produced/Material (kg* CO_{2e}*/kg)*
mr = Mass of Recycled Material (kg)
RM = CO_{2e} *Produced/Recycled Material (kg* CO_{2e}*/kg)*
RFM = Refrigerant Manufacturing Emissions (kg CO_{2e}*/kg)*
RFD = Refrigerant Disposal Emissions (kg CO_{2e}*/kg)*

Equation 1: LCCP Equation

Indirect emissions account for all other sources of emissions generated by the manufacture use and disposal of the unit. This includes the emissions from the generation of electricity, manufacturing of materials to build the unit, manufacturing of the refrigerant, and the end of life emissions when the unit is disposed of. The equation for calculating LCCP is shown above in Equation 1. The assumptions and data sources for each variable are discussed in the following chapters.

3. Direct Emissions Factors and Assumptions

3.1 Direct Emissions

Direct emissions are comprised of the effects of refrigerant released into the atmosphere over the lifetime of the unit and afterwards. This includes:

- Annual refrigerant loss from gradual leaks during usage
- Losses at the end of life disposal of the unit
- Large losses during operation of the unit
- Atmospheric reaction products from the breakdown of the refrigerant in the atmosphere

These four categories are calculated using the rate of refrigerant leakage multiplied by the refrigerant charge and the global warming potential (GWP) of the refrigerant. The resulting equation is shown in Equation 2.

$$\text{Direct Emissions} = C * (L * ALR + EOL) * (GWP + Adp.\ GWP)$$

C = Refrigerant Charge (kg)
L = Average Lifetime of Equipment (yr)
ALR = Annual Leakage Rate (% of Refrigerant Charge)
EOL = End of Life Emissions (% of Refrigerant Charge)
GWP = Global Warming Potential (kg CO_{2e}/kg)
Adp. GWP = GWP of Atmospheric Degradation Product of the Refrigerant (kg CO_{2e}/kg)

Equation 2: Direct Emissions Equation

3.1.1 Global Warming Potential

Global Warming Potential (GWP) of a refrigerant is defined as an index that compares the relative radiative forcing of different gases without directly calculating the changes in atmospheric concentrations. GWPs are calculated as the ratio of the radiative force that would result from the emission of one kilogram of a greenhouse gas to that from the emission of one kilogram of carbon dioxide over a fixed period of time [17].

This guide uses the GWP values obtained from the United Nations Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment: Climate Change (AR5) [18]. These values are calculated using a 100 year timeline for policy and consistency purposes. If the refrigerant is not included in AR5 [18], the manufacturer's GWP values may be used. To calculate refrigerant mixtures, a weighted average of the mass fraction of the component refrigerants should be used. Table 3.1 shows several common refrigerant GWP and adaptive GWP values.

3.1.2 Adaptive GWP

Adaptive GWP is a measure of the effects of refrigerant decomposition in the atmosphere and the degradation effects of that refrigerant. It includes the atmospheric reaction products from the breakdown of refrigerants in the atmosphere [6]. This value should be included in the calculation when it is available. Several values are shown in Table 3.1 from the open literature [19].

Table 3.1: GWP and Adaptive GWP

Refrigerant	GWP ($kg\ CO_{2e}/kg$)	Adaptive GWP ($kg\ CO_{2e}/kg$)
CO_2	1	0
HFC-32	677	Not available
HFO-1234yf	< 1	3.3 [6, 19,41]
HFC-134a	1,300	1.6 [6, 19,41]
HC-290	3	Not available
HFC-404A	3,943	Not available
HFC-410A	1,924	Not available

3.1.3 Charge

The unit's charge of refrigerant should be denoted in kilograms. The charge should be obtained from the manufacturer of the units being compared. If a split system is used, the refrigerant charge calculation should include the average piping length between indoor and outdoor units.

3.1.4 Unit Lifetime

Average unit usage lifetimes (L) are taken from AR4, AR5 reports, and the United Nation Environmental Program (UNEP) Technical Options Committee 2002 report [18, 20, 21]. Units have become more reliable over the past decades and continue to improve. These values are displayed in Table 3.2 for various types of units.

3.1.5 Annual Leakage Rates

Annual leakage rates (ALR) are the sum of the gradual leakage of a system over the course of a year. These averages also include catastrophic leaks spread out over the lifetime of the unit. This term does not include refrigerant lost when the unit is disposed of. These rates vary widely for different types of systems, equipment design, workmanship when the unit was installed, quality of maintenance, and various other factors. The annual leakage rates shown in Table 3.2 are taken from AR4, AR5, UNEP Technical Options Committee's 2002 report, and previous researches [2, 7, 18, 20, 21]. Like for the losses at the end of life, efforts are constantly being made to reduce leak rates, due to the growing awareness of the importance of good practices for management of refrigerants. Work is ongoing from various sources to determine more accurate rates.

The baseline equation as written in the guideline assumes that the system is recharged to its optimal refrigerant charge annually, and the effects of the energy consumption on the system are minimal. However, the equations could be modified to account for a longer period between recharging of the unit and its effects.

3.1.6 End of Life Leakage Rates

The end of life leakage (EOL) rates include the amount of refrigerant that is lost when the unit is disposed of. The rates shown in Table 3.2 are averages for developed countries from AR4, AR5, and UNEP Technical Options Committee 2002 report [18, 20, 21].

Table 3.2: System Information

System Type	L (years)	ALR (%)	EOL (%)
Residential Packaged Units [2, 21]	15	2.5	15
Residential Split Units [2, 21]	15	4	15
Packaged Refrigeration [2, 21]	15	2	15
Supermarket - Direct System [2, 7, 21]	7-10	18	10
Supermarket - Indirect System [2, 7, 18]	7-10	12	10
Commercial Refrigeration - Stand Alone [18, 20, 21]	15	5	15
Commercial - Packaged Units [18, 20, 21]	10	5	15
Commercial - Split Units [18, 20, 21]	10	5	15
Chillers [18, 20, 21]	15	5	15
Marine [18, 20, 21]	15	20	15

4. Indirect Emissions Factors and Assumptions

4.1 Indirect Emissions

Indirect emissions result from the use of the unit over its lifetime and include:

- Emissions from electricity generation
- Emission from the manufacture of materials
- Emissions from the manufacture of refrigerants
- Emissions from the disposal of the unit

Each emission factor is calculated separately. The resulting equation is shown in Equation 3.

$$\text{Indirect Emissions} = L * AEC * EM + \sum(m * MM) + \sum(mr * RM) + C * (1 + L * ALR) * RFM + C * (1 - EOL) * RFD$$

L=Average Lifetime of Equipment (yr)
AEC = Annual Energy Consumption (kWh)
EM = CO_2 Produced/kWh (kg CO_{2e}/kWh)
m = Mass of Unit (kg)
MM = CO_{2e} Produced/Material (kg CO_{2e}/kg)
mr = Mass of Recycled Material (kg)
RM = CO_{2e} Produced/Recycled Material (kg CO_{2e}/kg)
C = Refrigerant Charge (kg)
ALR = Annual Leakage Rate (% of Refrigerant Charge)
RFM = Refrigerant Manufacturing Emissions (kg CO_{2e}/kg)
EOL = End of Life Refrigerant Leakage(% of Refrigerant Charge)
RFD = Refrigerant Disposal Emissions (kg CO_{2e}/kg)

Equation 3: Indirect Emissions Equation

The primary factor in the indirect emissions equation is the emissions from the electricity consumption of the unit. In the Equation 3, the factor L*AEC*EM is included in the standard TEWI calculation. All other factors are added to TEWI to get LCCP.

4.2 Annual Energy Consumption Calculation

The preferred method to calculate the annual energy consumption of the system is to use an annual load model in accordance with ISO and ASHRAE standards [22-23]. This model takes into consideration unit performance characteristics, unit load information, and local weather. A temperature bin method should be used to analyze the weather data. An example demonstrating this is shown in Chapter 6 for a residential heat pump. A sample excel tool was built for this example problem and is available on IIR LCCP Working Group's website [1]. Other available tools are detailed in Chapter 7.

The cooling and heating loads should be calculated using the International Organization for Standardization (ISO) Standard [22] or ANSI/AHRI Standard for the type of system being evaluated. Most of the standards are available in SI and IP units. For air conditioning, heating, refrigeration units, and chillers whose performance is dependent on the ambient weather conditions, a minimum of four temperature bins for cooling and four bins for heating should be used. The load should be calculated for each bin, and then added to determine the total energy consumption per year. For units whose energy consumption is not dependent on ambient weather conditions, the calculation procedure in the respective standard should be used and summed for the unit's lifetime. Once the total energy consumed is calculated, this should be multiplied by the electricity generation emissions rate for the area to obtain the indirect CO_{2e} emissions from power consumption. A sample calculation for a residential heat pump using ANSI/AHRI Standard 210/240-2008 [13] is shown in Chapter 6.

Standby power or compressor crankcase heaters may also consume a significant amount of energy. These devices should be considered in climates where the compressor is off or in standby for a significant amount of time such, as Canada or Scandinavia. The methodology to account for this energy consumption is stated in some standards such as European standard EN-14825 [24].

4.2.1 Weather Data

Multiple sources for accurate weather data exist. The International Weather for Energy Calculations datasets (IWEC), 2013 and the National Renewable Energy Laboratories (NREL) – Typical Meteorological Year database (TMY3), 2015 [25-28] should be used whenever possible. The International Energy Agency and the U.S. Department of Energy provide lists of alternative sources if the location being modeled is not included in the IWEC datasets or TMY3 [29].

4.2.2 Electricity Generation Emissions

The emissions due to electricity generation are the dominant factor in the LCCP calculation. The International Energy Agency (IEA) and the North American Electricity Reliability Corporation (NERC) provide current electrical power generation emissions [21-31]. The emission rate to be chosen depends on the purpose of the calculation. For a specific user, who wants to minimize a specific application's emissions, the local rates can be used. In general, it is relevant to use a common rate over an area where the electrical networks are interconnected. For example, the average for the European Union is 0.454 kg CO_{2e}/kWh [31]. If the purpose is to compare products intended to be sold worldwide, the global average value (0.623 kg CO_{2e}/kWh

[31]) should be used. Emissions rates should be measured in kg CO_{2e}/kWh.

4.2.3 Comparing LCCPs for Different Refrigerants

When comparing solutions using different refrigerants, care must be taken to make "apple to apple" comparisons. For instance, inter-comparisons are only meaningful between systems having similar capacities. It is often difficult to have precisely the same capacity at the same conditions with different technologies. In that case, the use of "specific LCCP" provides a more relevant comparison.

4.2.4 Effects of Refrigerant Leakage on Energy Consumption

The baseline equation as written in the guideline assumes that the system is recharged to its optimal refrigerant change annually and that the effects to the energy consumption on the system are minimal. However, refrigerant leakage will have a negative impact on the performance of HVAC&R units over their lifetime. This performance degradation may be considered when calculating the energy consumption of the unit. The performance degradation can be determined using unit test data or data from previous research.

4.3 Material Manufacturing Emissions

Material manufacturing emissions were gathered from various industry sources in the United States and the European Union. These sources included trade associations, governmental departments, and previous research efforts. The four most common materials in the manufacture of HVAC&R units are included in LCCP. The average percentage of the mass composition of a residential heat pump is shown in Table 4.1 [3, 5, 8]. Each type of unit will have different breakdown of percentages. These percentages should be used to calculate the manufacturing emissions for the unit.

Table 4.1: Residential Heat Pump Percentage of Mass Composition

Material	Percentage of Unit Mass Composition
Steel	46% [3, 5, 8]
Aluminum	12% [3, 5, 8]
Copper	19% [3, 5, 8]
Plastics	23% [3, 5, 8]

4.3.1 Virgin Material Manufacturing Emissions

Virgin material manufacturing emissions were gathered from government agencies, international organizations, and trade associations from the United States and the European Union. The values shown in Table 4.2 represent the average values of those gathered [32-40]. These need to be updated as manufacturing methods improve. Virgin material manufacturing

emissions values should be used if the amount of recycled materials used in the unit is unknown.

4.3.2 Mixed Manufacturing Emissions

Many materials today are manufactured with a mixture of virgin and recycled materials. The average values of virgin material to recycled material are shown in Table 4.3. The emissions values for recycled materials were then taken and weighted to develop the mixed manufacturing emissions shown in Table 4.2 [32-40].

Table 4.2: Material Manufacturing Emissions

Material	Virgin Manufacturing Emissions ($kg\ CO_{2e}/kg$)	Mixed Manufacturing Emissions ($kg\ CO_{2e}/kg$)
Steel	1.8 [32]	1.43 [40]
Aluminum	12.6 [33-35]	4.5 [34]
Copper	3.0 [36]	1.64 [36]
Plastics	2.8 [39]	2.61 [37-40]

Table 4.3: Recycled Material Manufacturing Emissions

Material	Percentage of Mixed Material Composition	100% Recycled Material Manufacturing Emissions ($kg\ CO_{2e}/kg$)
Steel [32,40]	29%	0.54
Aluminum [33-35]	67%	0.63
Copper [36]	40%	2.46
Plastics [37-39]	7%	0.12

4.4 Refrigerant Manufacturing Emissions

Refrigerant manufacturing emission rates are shown in Table 4.4 for selected refrigerants. These values were gathered from various studies and manufacturer's information [6, 41-45]. These values are averages of the available sources. They need to be updated as more efficient methods of manufacturing are developed.

Table 4.4: Refrigerant Manufacturing Emissions

Refrigerant	Manufacturing Emissions (kg CO_{2e}/kg)
HFC-32 [6, 43]	7.2
HFO-1234yf [44]	13.7
HFC-134a [42,44]	5.0
HC-290 [44]	0.05
HFC-404A [6]	16.7
HFC-410A [41,45]	10.7

4.5 Recycling Emissions

Material disposal emissions include all emissions up to the production of recycled material. For metals and plastics, this includes the shredding of the material [6, 40, 45-46]. These emissions may be included in the manufacturing emissions if the material is produced from recycled materials. The values are shown in Table 4.5. For refrigerants that are recycled, this includes energy required to recover the refrigerant.

Table 4.5: Recycling Emissions

Material	Recycling Emissions (kg CO_{2e}/kg)
Metal [6, 40, 46]	0.07
Plastic [6, 45-46]	0.01

5. LCCP versus TEWI

5.1 Comparison to TEWI

LCCP is a more comprehensive accounting tool than TEWI. TEWI ignores the energy embodied in product materials, greenhouse gas emissions during chemical manufacturing, and end of life disposal of the unit. The small sources of emissions generated over the course of the lifetime of the unit are explicitly accounted for in LCCP. This allows for a more holistic picture of the environmental impact of the unit.

As more accurate methods of measuring greenhouse gas emissions are developed, it becomes more important to evaluate the minor emissions sources from the units. Methods of producing electricity with a lower carbon foot print are becoming a larger percentage of the total production. As the emissions from energy consumption decrease, other factors in LCCP will become more influential.

LCCP method should be used when a more in depth analysis of the environmental impact of a unit is warranted. TEWI could be used when a quicker analysis of the unit is desired. A visual comparison of TEWI and LCCP is shown in Figure 5.1.

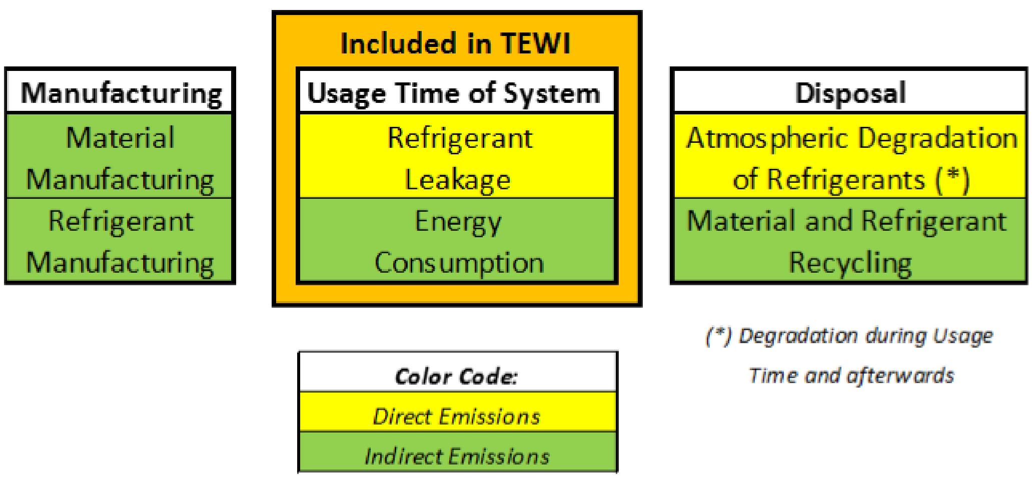

Figure 5.1: LCCP vs. TEWI Comparison

5.2 Strength and Weaknesses of the TEWI

As of today, TEWI is the benchmark for the evaluation of total emissions. It offers a great improvement compared to assessments based solely on GWP. It has a well standardized calculation method. It is described, for instance, in the European standard EN-378 Refrigerating systems and heat pumps — Safety and environmental requirements [47]. The output of the calculation is the number of tons of equivalent CO_2 emitted by the system over its life time. It is

also straightforward when evaluated "specific TEWI". That is the average kilograms of CO_2 emitted per kWh of cooling energy generated by the system (or of heating for a heat pump). The use of the specific TEWI allows for easy comparisons of various technologies used for similar applications.

Barriers to the use of TEWI include the difficulties in assessing some key input parameters such as the leakage rates, EOL fluid recovery, or the carbon foot print of the energy used. Therefore, some do not want to use it, claiming that it is too complicated to be practical. This guideline aims to reduce the difficulty of finding key input parameters by providing current average values with traceable data sources for all parameters.

TEWI is also criticized because it is not comprehensive enough. It only covers the usage phase of the system, ignoring other phases of the cycle like manufacturing, transportation, or disposal. It is another purpose of this guideline to extend TEWI to the more comprehensive LCCP analysis by evaluating emissions that are not accounted for in TEWI.

6. Residential Heat Pump Sample Calculation

6.1 Residential Heat Pump

A representative residential heat pump was evaluated in five locations in the continental USA, representing different climatic conditions. The cities evaluated are: Miami, FL, Phoenix, AZ, Atlanta, GA, Seattle, WA and Chicago, IL. The heat pump has the characteristics shown in Table 6.1. The heat pump's characteristics are typical values of an 11 kW unit available in the USA. The heat pump modeled is Goodman SSZ16-0361A. The unit is a single speed compressor unit with a fixed fan speed and a resistance heater for backup heat. The heat pump performance characteristics were evaluated according to AHRI Standard 210/240 (2008) [13]. The values used are shown in Table 6.1.

Table 6.1: Residential Heat Pump Characteristics

Capacity	11 kW
Refrigerant	R-410A
Charge	6 kg
Lifetime	15 years
Unit Mass	115 kg
Annual Leakage Rate	4%
EOL Leakage Rate	15%

6.2 Direct Emissions Calculation

The residential heat pump uses the refrigerant R-410A. The GWP value of this refrigerant is found in Table 3.1. The standard assumptions for the leakage rates are found in Table 3.2. The breakdown of the calculation is shown in Table 6.2. The direct emissions remain the same for all locations evaluated. Adaptive GWP for R-410A was assumed to be zero because of the lack of available data.

Table 6.2: Direct Emissions

Annual Leakage Emissions (kg CO_{2e})	6,926
End of Life Emissions (kg CO_{2e})	1,732
Adp. GWP Emissions (kg CO_{2e})	0

6.3 Indirect Emissions Calculation

The indirect emission calculation was broken down into three parts: energy consumption calculation, material manufacturing emissions, and the end of life disposal emissions.

6.3.1 Energy Consumption Calculation

The energy consumption calculation was performed using the AHRI Standard 210/240 [13] for Residential Heat Pumps and the TMY3 data [28] for the five locations. The local conditions were evaluated using the temperature bin method. The standard temperature bins and resulting bin hours for the cities are shown in Table 6.4 on the following page. Each city was evaluated at each bin for the amount of energy required to provide cooling and heating. That value was then multiplied by the number of hours in the bin. This calculated value was multiplied by the regional energy generation emissions rate to determine the total amount of emission from energy consumption per year that the unit generates. The NERC interconnection used for each city is shown in Table 6.5. NERC Eastern and Western interconnections have emissions rates of 0.788 kg CO_{2e}/kWh and 0.594 kg CO_{2e}/kWh, respectively .

Table 6.3: AHRI Standard 210/240 Performance Data *

Cooling or Heating	Test Number	Capacity (W)	Total Power (W)
Cooling	A Test	10,140	2,550
Cooling	B Test	10,474	2,378
Heating	H1 Test	10,082	2,500
Heating	H2 Test	8,382	2,370
Heating	H3 Test	6,154	2,310

*** Single Speed unit - Fixed Fan Speed**

6.3.2 Material Manufacturing Emissions

The material manufacturing emissions are calculated using the mass of the unit and the percent composition of the unit shown in Table 4.1 and the material manufacturing emissions rates from Table 4.2. This calculation used the standard virgin manufacturing emissions for the materials and refrigerant. The results are shown in Table 6.6 for each material.

6.3.3 End of Life Disposal

The end of life disposal of the unit assumes that the unit is shredded for recycling. This is calculated using the emission rates in Table 4.5. The unit weight was taken and multiplied by the percentage of metal and plastic. This amount was then multiplied by the recycling emissions factor for the material. The results are shown in Table 6.7 for each material.

Table 6.4: Temperature Bin Hours for U.S Cities from AHRI Std 210/240 (2008)

Cooling Temperature Bins (°C)	Miami, FL	Phoenix, AZ	Atlanta, GA	Chicago, IL	Seattle, WA
18.2 < °C ≤ 21.1	778	711	944	767	505
21.1 < °C ≤ 23.8	1,327	586	977	538	285
23.8 < °C ≤ 26.6	2,511	744	879	531	155
26.6 < °C ≤ 29.3	2,312	922	703	428	72
29.3 < °C ≤ 32.1	838	817	424	160	17
32.1 < °C ≤ 34.9	54	619	127	26	0
34.9 < °C ≤ 37.7	6	614	13	1	0
Above 37.7	0	750	0	0	0
Heating Bins (°C)	**Miami, FL**	**Phoenix, AZ**	**Atlanta, GA**	**Chicago, IL**	**Seattle, WA**
15.6 < °C ≤ 18.2	480	929	1,066	848	1,001
12.7 < °C ≤ 15.6	276	730	795	677	1,479
10 < °C ≤ 12.7	146	670	751	641	1,613
7.2 < °C ≤ 10	25	329	562	528	1,352
4.4 < °C ≤ 7.2	7	268	626	567	1,296
1.6 < °C ≤ 4.4	0	71	369	773	652
(-1.2) < °C ≤ 1.6	0	0	221	759	264
(-4.0) < °C ≤ (- 1.2)	0	0	197	473	63
(-6.6) < °C ≤ (-4.0)	0	0	86	322	6
(-9.5) < °C ≤ (-6.6)	0	0	20	382	0
(-12.3) < °C ≤ (-9.5)	0	0	8	157	0
(-15.1) < °C ≤ (-12.3)	0	0	1	108	0
(-17.9) < °C ≤ (-15.1)	0	0	0	83	0
(-20.6) < °C ≤ (-17.9)	0	0	0	41	0
(-23.4) < °C ≤ (-20.7)	0	0	0	23	0
(-26.2) < °C ≤ (-23.4)	0	0	0	0	0
(-28.3) < °C ≤ (-26.2)	0	0	0	0	0
Below (-28.3)	0	0	0	0	0

Table 6.5: Annual Energy Consumption

Location	Miami, FL	Phoenix, AZ	Atlanta, GA	Chicago, IL	Seattle, WA
NERC Interconnection	Eastern	Western	Eastern	Eastern	Western
Annual Cooling Energy Consumption (kWh)	8,228	8,924	3,700	1,946	559
Cooling Season Emissions (kg CO_{2e})	6,483	5,301	2,916	1,534	332
Heating Climate Region	I	II	III	IV	V
Annual Heating Energy Consumption (kWh)	211	1,162	3,352	8,265	4,075
Heating Season Emissions (kg CO_{2e})	166	691	2,641	6,513	2,420
Total Energy Consumption Emissions (kg CO_{2e})	99,745	89,868	83,358	120,699	41,289

Table 6.6: Manufacturing Emissions

Steel Manufacturing (kg CO_{2e})	95
Aluminum Manufacturing (kg CO_{2e})	174
Copper Manufacturing (kg CO_{2e})	66
Plastic Manufacturing (kg CO_{2e})	74
Total Manufacturing Emissions (kg CO_{2e})	409

Table 6.7: EOL Emissions

Metal EOL (kg CO_{2e})	6.2
Plastic EOL (kg CO_{2e})	0.4
Total EOL Emissions (kg CO_{2e})	6.6

6.4 Total Lifetime Emissions

The direct and indirect emissions are summed for the total emissions generated over the lifetime of the unit. Table 6.8 shows the total emissions generated using the LCCP equation shown in Equation 1. The most influential category for all of the locations is the energy consumption of the unit over its lifetime.

Table 6.8: Total Lifetime Emissions

Results	Miami, FL	Phoenix, AZ	Atlanta, GA	Chicago, IL	Seattle WA
Total Lifetime Emission ($kg\ CO_{2e}$)	108,819	98,941	92,431	129,772	50,362
Total Direct Emission ($kg\ CO_{2e}$)	8,658	8,658	8,658	8,658	8,658
Annual Refrigerant Leakage ($kg\ CO_{2e}$)	6,926	6,926	6,926	6,926	6,926
EOL Refrigerant Loss ($kg\ CO_{2e}$)	1,732	1,7312	1,7312	1,732	1,732
Adaptive GWP ($kg\ CO_{2e}$)	-	-	-	-	-
Total Indirect Emissions ($kg\ CO_{2e}$)	100,161	90,283	83,773	121,114	41,704
Energy Consumption ($kg\ CO_{2e}$)	99,745	89,868	83,358	120,700	41,289
Equipment Manufacturing ($kg\ CO_{2e}$)	409	409	409	409	409
Equipment EOL ($kg\ CO_{2e}$)	6.6	6.6	6.6	6.6	6.6
Refrigerant Manufacturing ($kg\ CO_{2e}$)	103	103	103	103	103

6.4.1 Specific LCCP

Specific LCCP was calculated for each location. The total emissions were divided by the amount of kWh consumed by the unit. The results are shown in Table 6.9.

Table 6.9: Specific LCCP

Results	Miami, FL	Phoenix, AZ	Atlanta, GA	Chicago, IL	Seattle WA
Specific LCCP ($kg\ CO_{2e}/kWh$)	12.9	9.8	13.1	12.7	10.9

7. LCCP Tools

There are several LCCP tools in existence. The AHRTI tool [3] and IIR tool [1] are available for residential heat pumps. The AHRTI LCCP tool is an excel based tool capable of evaluating up to 12 single speed residential heat pump systems in different locations using IP units. The IIR LCCP tool is an Excel based tool capable of evaluating a single speed residential heat pump in 5 cities in different climate zones in SI units using the AHRI Std 210/240 [13] for the energy calculation.

The ORNL LCCP tool [8, 14] is available as both web based open source tool and a desktop application for all air conditioning and refrigeration applications. The tool includes 14 refrigerants and 47 cities built in with the option to add additional refrigerants and locations. The tool is highly customizable and can be used with any system simulation software, load calculation tool, and weather and emissions data types.

The GREEN-MAC-LCCP [5, 6] tool is for mobile air conditioning units only. The tool is an Excel based. It evaluates different types of vehicles in various locations. This tool is the automotive industry standard.

Table 7.1: LCCP Tools

Tool	Program Type	Application	Units
AHRTI LCCP	Excel Based	Single Speed Compressor Residential Heat Pumps	Mixed
ORNL LCCP	Open Source (Web and Desktop versions)	All Types	Mixed
GREEN-MAC-LCCP	Excel Based	Mobile Air Conditioning	SI
IIR LCCP	Excel Based	Single Speed Compressor Residential Heat Pumps	SI

8. LCCP Working Group

Chair: Dr. Yunho Hwang, yhhwang@umd.edu
Vice Chair: Dr. Carlos Infante Ferreira
Vice Chair: Dr. Chun-Cheng Piao
Secretary: Dr. Vikrant Aute
Researcher: Sarah Troch, stroch@umd.edu
Website: http://www.iifiir.org/medias/medias.aspx?INSTANCE=EXPLOITATION&PORTAL_ ID=portal_model_instance__WP_LCCP_Evaluation.xml&SETLANGUAGE=EN

9. References

[1] International Institute of Refrigeration Working Group on LCCP Evaluation. http://www.iifiir.org/medias/medias.aspx?INSTANCE=EXPLOITATION&PORT AL _ID = portal_model_instance__WP_LCCP_Evaluation.xml.

[2] ADL (A.D. Little, Inc), 1999: Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant, and Fire Protection Applications. Final Report to the Alliance for Responsible Atmospheric Policy, August 23, 1999, Acorn Park, Cambridge, Massachusetts, USA.

[3] Zhang, M., Muehlbauer, J., Aute, V. and Radermacher, R., 2011, Life Cycle Climate Performance Model for Residential Heat Pump System, Air-Conditioning, Heating and Refrigeration Technology Institute, Inc. (AHRTI).

[4] Sand, J.R., S.K. Fischer and V.D. Baxter, 1997: Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies, U.S. Department of Energy and AFEAS, Arlington, Va, USA.

[5] Papasavva, S., Hill, W. R. and Andersen, S. O., 2010. GREEN-MAC-LCCP: A Tool for Assessing the Life Cycle Climate Performance of MAC Systems. Environmental Science & Technology, 44(19), pp. 7666-7672.

[6] GREEN-MAC-LCCP program, version 3b (http://www.epa.gov/cppd/mac/compare.htm). Accessed October 2014.

[7] Abdelaziz, O., Fricke, B. and Vineyard, E., 2012, Development of Low Global Warming Potential Refrigerant Solutions for Commercial Refrigeration Systems using a Life Cycle Climate Performance Design Tool. 14th International Refrigeration and Air Conditioning Conference, Purdue University, West Lafayette, Indiana.

[8] Oak Ridge National Laboratory (ORNL), and the University of Maryland College Park (UMCP), 2013. LCCP Desktop Application v1 Engineering Reference. (http://info.ornl.gov/sites/publications/Files/Pub49128.pdf).

[9] "Methods of Calculating Total Equivalent Warming Impact (TEWI) 2012." Australian Institute of Refrigeration, Air Conditioning and Heating (AIRAH), 2012.

[10] Kyoto Protocol to the United Nations Framework Convention on Climate Change, 1997.

[11] U.S. Energy Information Administration, "Annual Energy Outlook 2015 with Projections to 2040." April 2015.

[12] UNEP/TEAP report, 1999. "The Implications to the Montreal Protocol of the Inclusion of HFCs and PFCs in the Kyoto Protocol".

[13] ANSI/AHRI Standard 210/240 with Addenda 1 and 2 Standard for Performance Rating of Unitary Air-Conditioning & Air-Source Heat Pump Equipment, 2008.

[14] Beshr, M., ORNL Life Cycle Climate Performance—V1.0, http://lccp.umd.edu/ornllccp/, 2014.

[15] Beshr, M., Aute, V., Fricke B., and Radermacher, R. "An Evaluation of the Environmental Impact of Commercial Refrigeration Systems Using Alternative Refrigerants." 3rd IIR International Conference on Sustainability and the Cold Chain, London, 2014.

[16] Pac Calc Pro, http://en.ipu.dk/Indhold/refrigeration-and-energy-technology/Pack%20Calculation%20Pro/Pack%20Calculation%20Pro.aspx.

[17] U.S. Energy Information Administration, "Glossary", http://www.eia.gov/tools/glossary/index.cfm?id=G, 2015.

[18] Intergovernmental Panel on Climate Change (IPCC), 2014, Fifth Assessment Report: Climate Change, Geneva, Switzerland.

[19] Baral, A, Minjares, R., and Urban, R., Upstream Climate Impacts from Production of R-134a and R-1234yf refrigerants used in Mobile Air Conditioning Systems. International Council on Clean Transportation, Aug. 2013.

[20] Intergovernmental Panel on Climate Change (IPCC), 2007, Fourth Assessment Report: Climate Change, Geneva, Switzerland.

[21] UNEP, 2003c: 2002 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee – 2002 Assessment. [L. Kuijpers (ed.)]. UNEP Ozone Secretariat, Nairobi, Kenya.

[22] International Organization for Standardization (ISO), www.iso.org/home.htm.

[23] American Society of Heating, Refrigerating and Air-Conditioning Engineers, https://www.ashrae.org/home.

[24] EN 14825, Air conditioners, liquid chilling packages and heat pumps, with electrically driven compressors, for space heating and cooling. Testing and rating at part load conditions and calculation of seasonal performance. 2013.

[25] ASHRAE Standard 169, Climatic Data for Building Design Standards. 2013.

[26] International Energy Agency, http://data.iea.org/ieastore/product.asp?dept_id=101&pf_id=305.

References Continued

[27] NREL - National Solar Radiation Data Base - TMY3 Data, January 2011 (http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/).

[28] Wilcox, S. and W. Marion. 2008. User's Manual for TMY3 Data Sets, NREL/TP-581-43156. April 2008. Golden, Colorado: [National Renewable Energy Laboratory.

[29] Energy Data Sources, U. S. Department of Energy, Feb. 2014 http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_sources.cfm.

[30] Deru, M. and Torcellini, P., 2007, Source Energy and Emission Factors for Energy Use in Buildings, Technical Report NREL/TP-550-38617.

[31] Ecometrica (2011). Electricity-specific emission factors for grid electricity.

[32] Steel's Contribution to a Low Carbon Future: WorldSteel Position Paper. 2014 World Steel Association.

[33] U.S. Energy Requirements for Aluminum Production BCS Report prepared for DOE, Feb 2007.

[34] International Aluminum Institute, "Global Life Cycle Inventory Data for the Primary Aluminum Industry: 2010 Data. World Aluminum, August 2013.

[35] "Aluminum the Element of Sustainability: A North American Aluminum Industry Sustainability Report.." The Aluminum Association, September 2011.

[36] "The Environmental Profile of Copper Products: A Cradle to Gate Life-Cycle Assessment for Copper Tube, Sheet and Wire Produced in Europe.", European Copper Institute Copper Alliance, 2012.

[37] Franklin Associates report prepared for the American Chemistry Council , July 2014, "Cradle-To-Gate Life Cycle Inventory of Nine Plastic Resins and Four Polyurethane Precursors".

[38] EPA "Plastics" U. S. Environmental Protection Agency, Waste Reduction Model Version 13. June 2014.

[39] PlasticsEurope. Eco-profiles of the European Plastics Industry: HDPE bottles. March 2005 http://lca.plasticseurope.org/main2.htm.

[40] EPA, "Metals." U. S. Environmental Protection Agency, Waste Reduction Model Version 13. June 2014.

[41] Johnson, E., "Air-Source Heat Pump Carbon Footprints: HFC Impacts and Comparison to Other Heat Sources." Energy Policy 39 (2011) 1369-1381.

[42] Banks, R. and Sharratt, P., "Environmental Impacts of the Manufacture of HFC-134a." 07 Nov. 1996.

[43] Spatz, M.W., Motta, S.F.Y., 2004. "An evaluation of options for replacing HCFC-22 in medium temperature refrigeration systems". International Journal of Refrigeration, Volume 27, Issue 5, pp. 475-483.

[44] Hill, W., Papasavva, S., 2005. "Life Cycle Analysis Framework; a Comparison of HFC-134a, HFC-134a Enhanced, HFC-152a, R744, R744 Enhanced, and R290 Automotive Refrigerant Systems". SAE Technical Series Paper, 2005-01-1511, Society of Automotive Engineers, Warrendale, PA.

[45] "IIR-LCCP-EmissionsDatabase_Version1.exp", EEHP Consortium, Center for Environmental Energy Engineering, Department of Mechanical Engineering, University of Maryland, 2014.

[46] EPA, "Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012." U. S. Environmental Protection Agency. 2012.

[47] EN 378 European Standard "Refrigerating systems and heat pumps-Safety and environmental requirements". 2012.