

GREEN-MAC-LCCP®: A Tool for Assessing Life Cycle Greenhouse Emissions of Alternative Refrigerants

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ABSTRACT

The **GREEN-MAC-LCCP®** [Global Refrigerants Energy & Environmental - Mobile Air Condition - Life Cycle Climate Performance] model described here is an evolution of a previous GM model that assesses the lifecycle energy and GHG emissions associated with the production, use and disposal of alternative refrigerants and MAC components. This new model reduces the complexity of inputs and provides a consistent output analysis. This model includes Microsoft Excel Visual Basic® code to automatically make the calculations once inputs are complete. The **GREEN-MAC-LCCP®** is a comprehensive analytical tool that takes into consideration key MAC system characteristics such as Coefficient of Performance (COP), and evaporator cooling capacity data (Qe) obtained from bench tests and integrates them with other vehicle and alternative refrigerant inputs such as: annual driving time, A/C on time, weather data, vehicle lifetime, refrigerant leakage rates, MAC system mass requirements, energy requirements due to manufacturing, and end-of-life impacts of alternative refrigerants and MAC components. The model provides CO₂-equivalent emissions due to A/C installation and operation on a vehicle. The output can provide results for any proposed alternative refrigerant for:

- i) Three vehicle classes: (a) compact, (b) midsize and (c) SUV,
- ii) Fifteen cities: Boston, Houston, Miami, Phoenix, Athens, Frankfurt, Kagoshima, Tokyo, Sapporo, Bangalore, Bombay, New Delhi, Sydney, Beijing, and Shanghai
- iii) Four alternative vehicle fuels: gasoline, diesel, ethanol, and methanol
- iv) Alternative refrigerants such as: HFC-152a, R-744, Refrigerant "H", DP-1, AC-1.

This tool was developed based on input data harmonized by the industry and it is hoped that it will become the global standard for assessing the life cycle greenhouse emissions of alternative refrigerants.

INTRODUCTION

In response to concerns over the impact of man-made greenhouse gases (GHG) on climate, the European Union (EU) issued Directive 2006/40/EC (1) covering Mobile Air Conditioning (MAC) that prohibits the use of all refrigerants with Global Warming Potentials (GWP) greater than 150, with a phase-in starting from 2011. The impact of this mandate is that the current automotive refrigerant HFC-134a, which has a GWP of 1430 (2), will be banned in all new type vehicle models starting January 1st, 2011, and in all new production vehicles starting January 1st, 2017. Due to such regulations, the mobile air conditioning industry is evaluating alternative refrigerants. Selection criteria for replacement refrigerants for MAC systems include: refrigerant engineering performance, system design impact, MAC system changes to optimize the use of the new refrigerant, cost, environmental impacts including total GHG impact based on life cycle analysis, and human toxicity risks.

General Motors is leading the development of a comprehensive, robust and transparent model to harmonize the assessment of the life cycle global warming impact of mobile air conditioning systems (3). The current version of this model is called **GREEN-MAC-LCCP®** [Global Refrigerants Energy & Environmental - Mobile Air Conditioning - Life Cycle Climate Performance] and it can be downloaded from USEPA's website (6). Global harmonization of the LCCP (Life Cycle Climate Performance) is recognized as highly important by HVAC (Heating Ventilating and Air-Conditioning) engineers, SAE, VDA, JAMA and USEPA. As a result, JAMA members Honda, Nissan, and Toyota and several other European OEMs including Mercedes-Benz, Fiat, VW and Audi have worked together with GM to develop a common approach to conduct LCCP assessments for alternative refrigerants and this effort is reflected in the harmonized input data of the **GREEN-MAC-LCCP®** model. The LCCP, expressed in terms of GHG emissions, is a function of: (a) direct and (b) indirect global warming impacts. The "direct" component is due to refrigerant leaks from a variety of sources during use and in service. A refrigerant with lower GWP has lower warming impact

when it escapes into the atmosphere. The “indirect” component is associated with the energy consumption and therefore carbon dioxide (CO₂) emissions due to the A/C operation as well as due to refrigerant and MAC system manufacturing and their end-of-life (EOL) recycling. Thus, the “indirect” component is a function of the MAC system characteristics, the refrigerant heat transfer capability, and the complexity of the refrigerant chemical synthesis process.

This paper documents, in detail, the latest version of the **GREEN-MAC-LCCP**[®] model. The key assumptions and the conceptual framework are similar to the older version (3,4,5); however, the input data are now based on globally harmonized assumptions and engineering data obtained from bench tests are now applied to various driving cycle engine conditions. The model uses COP (Coefficient of Performance) and evaporator cooling capacity (Q_e) data obtained from bench tests and integrates these results with other vehicle and refrigerant inputs.

MODEL OVERVIEW AND METHODOLOGY

The **GREEN-MAC-LCCP**[®] tool is a Microsoft Excel[®]-based model with multilayered-spreadsheets consisting of an instructions spreadsheet, and multiple input and output spreadsheets. A copy of it can be downloaded from USEPA's website (6). In this section we provide a detailed explanation of the direct and indirect components of the LCCP assessment and the spreadsheets that provide such analysis. The direct and indirect components of the model are explained as follows:

Direct Emissions result from the direct leaks of the refrigerant into the atmosphere and are an aggregate of the following leakage categories:

1. *Regular* emissions, which refer to the refrigerant leaks from the A/C system during operation,
2. *Irregular* emissions due to accidents, stone hits, product defects etc,
3. *Service* emissions from garages during maintenance and repair. These items are newly estimated based on the SAE Improved Mobile Air Conditioning (SAE I-MAC) study recently completed. The results are dependent on the skills and practices of the service technicians.
4. *End-of-Life emissions* from the recovery of refrigerant at the end-of-life of the vehicle,
5. *Leakage* during refrigerant production and transportation.
6. *Atmospheric reaction products* associated with the atmospheric breakdown of the refrigerants.

The direct CO₂ emissions are evaluated based on the GWP of each chemical and its mass emitted into the atmosphere over the lifetime of MAC systems. The direct emissions are expressed in terms of CO₂-equivalent (CO₂-eq.) emissions.

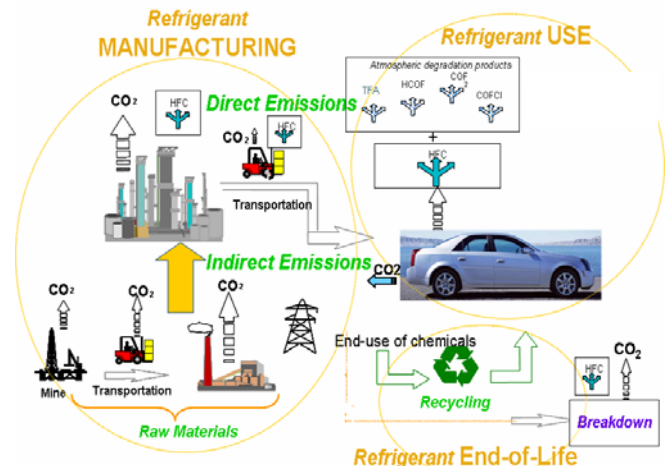
Indirect Emissions are evaluated from the energy

consumption due to MAC manufacturing, EOL, and in-use operation, and is an aggregate of the following CO₂ emissions categories:

1. Manufacturing of various alternative refrigerants and each component of the A/C system,
2. End-of-life recycling processes of various alternative refrigerants and each component of the A/C system,
3. Emissions associated energy consumption during A/C operation (such as those associated with the operation of the compressor, and engine cooling fan) during the lifetime of the vehicle,
4. Emissions associated with the additional fuel consumption due to the A/C mass transportation onboard the vehicle throughout the lifetime of the vehicle.

The Indirect component is reported in terms of CO₂ emissions, considering the carbon content of the fuel utilized in each process and during vehicle operation. Figure 1 provides a schematic diagram of the Direct and Indirect components.

Figure 1: Direct and Indirect LCCP Components
Life Cycle Greenhouse Gas Emissions of Refrigerants



The model can simultaneously analyze up to six alternative refrigerants and compare them with the HFC-134a baseline built into the model. The user is free to choose which alternative refrigerants will be compared with the baseline. For each refrigerant, fifteen cities around the world are analyzed: Boston, Houston, Miami, Phoenix, Athens, Frankfurt, Kagoshima, Tokyo, Sapporo, Bangalore, Bombay, New Delhi, Sydney, Beijing, and Shanghai. Three vehicle platforms are included into the model (compact car, midsize car, SUV) and default engine RPM data are included for each drive cycle of the region of the world analyzed, such as: FTP (USA), NEDC (EU), JC-08 (Japan), Indian cycle (India). However, the user is allowed to enter new vehicle data as needed. The model includes four different fuels (gasoline, E85, M85, and diesel) which have different carbon content and as a result contribute differently to the indirect CO₂ emissions. The model calculates the CO₂-equivalent emissions using factors available in the literature of the direct and indirect components. The indirect energy is expressed in terms of the CO₂

equivalents due to the MAC operation during vehicle driving. As a result the MAC operation has a direct impact on vehicle fuel economy. Although fuel consumption can be analyzed with this tool, such data are not reported at the present time. This is because the fuel consumed by the vehicle due to air conditioning usage is influenced by many vehicle characteristics and engine calibrations which are not considered in the LCCP models. Nevertheless, for the indirect CO₂ emissions due to A/C operation, one can convert directly to fuel use by considering 2.32 kg CO₂ emitted per liter gasoline consumed.

The CO₂-equivalent emissions of the direct and indirect component are added to provide the LCCP impact of any refrigerant evaluated. The LCCP results for each refrigerant analyzed are provided in Output spreadsheets which are automatically generated during each model run. A detailed description of each output and input spreadsheet is provided in the following sections.

OVERVIEW OF INPUT AND OUTPUT SHEETS

1. Instructions Sheet

The Instructions spreadsheet provides a brief description of the data and calculations used in each subsequent spreadsheet. For clarity, we have highlighted in purple color all cells that are entries for user's input and in light yellow all cells that are fixed values agreed to, based on the SAE harmonization effort. Currently, the purple cells are the only cells that can be modified by the user, and they reflect input parameters that are unique to each refrigerant, such as: refrigerant charges, COP, evaporator capacity data, etc. The light yellow cells provide data that are universal parameters and can be used for each refrigerant, such as weather data, vehicle parameters, driving behavior, etc. References are shown to clearly show the source of all boundary conditions and assumptions.

2. Overview of Input Spreadsheets

There are seven input spreadsheets in the model: MAC-Manufacturing-EOL-Input, Leakage-Input, CAP-INPUT, COP-INPUT, Drive Cycle-Input, Fuel-Data-Input, and Climate-Input. These spreadsheets provide manufacturing, engineering, climatic, and driving distance data. The manufacturing data provide life cycle CO₂-equivalent emissions for each component of the Mobile Air Conditioning (MAC) system. The engineering data provide the cooling performance of the MAC system expressed in terms of cooling capacities (Q_e) and coefficients of performance (COP). The climatic data provide the weather conditions, in terms of ambient temperatures and humidity, of each city analyzed. The driving distance data are based on the annual driving distance of vehicles in each of the cities. Microsoft Excel Visual Basic® code performs calculations using the input data to generate the output spreadsheets when the model is run.

An overview of each input spreadsheet is provided next.

➤ 2.1 MAC-Manufacturing-EOL-Input

The MAC-Manufacturing-EOL-Input sheet consists of three distinct sections which provide life cycle analysis data for: (a) refrigerant manufacturing, (b) MAC component manufacturing and (c) end-of-life recycling of MAC components. In particular, CO₂-equivalent emissions data are provided for:

- (a) refrigerant manufacturing, in terms of virgin refrigerant production and its EOL recycling
- (b) refrigerant fugitive emissions during manufacturing and vehicle assembly,
- (c) refrigerant leaks during its transportation from the chemical plant to the vehicle assembly,
- (d) fuel consumption during refrigerant transportation from the chemical plant to the vehicle assembly,
- (e) CO₂ equivalent emissions due to its chemical breakdown into the atmosphere into other chemical species. In this calculation we consider the GWP of the breakdown species reported in references (7,8).
- (f) End-of-Life (EOL) energy and CO₂-equivalent emissions associated with the recycling of the refrigerant and MAC components.

2.2 Refrigerant Manufacturing - CO₂-Eq. Emissions

The model provides Life Cycle Analysis (LCA) CO₂-eq. emissions associated with the manufacturing of HFC-134a, HFC-152a and R-744. This is because the chemical structures of the new alternative refrigerants are not publicly disclosed and as a result the LCA manufacturing energy and GHG emissions of the alternative refrigerants are proprietary to the chemical manufacturers at the present time. For HFC-134a and HFC-152a the data are obtained from McCulloch and Lindley (9) and Krieger, et al. (10). For R-744 the data are obtained from Johnson (11). The LCA CO₂-eq. emissions of HFC-134a manufacturing are expressed as an average of the two literature values, and those of HFC-152a are from Krieger, et al. (10).

The model also offers the flexibility to use explicit CO₂-eq. emissions due to: (a) recycling of refrigerants at the chemical plant, (b) CO₂-eq. fugitive emissions of other GHG gases (i.e., methane, HFCs, etc.) which are emitted during refrigerant manufacturing, (c) and CO₂-eq. emissions due to fuel consumption from the transportation of the refrigerant to the assembly plant. In case some of these emissions are already included in one of the reported categories the model identifies them as "Included above".

The spreadsheet also provides CO₂-eq. emissions due to refrigerant leakage during transportation, assuming a 0.03% leakage rate as found in the literature (12) for liquid fuel transportation. This was accepted during harmonization.

For the CO₂-eq. emissions associated with the Atmospheric Reaction Byproducts, the model provides data only for HFC-134a and HFC-152a, because the chemical structures of the other alternative refrigerants are proprietary and CO₂ has no by-products.

Table 1a provides an example of the refrigerants manufacturing part found in this input sheet.

TABLE 1a: MAC-Manufacturing- EOL-Input Spreadsheet; HFC-134a Manufacturing Example

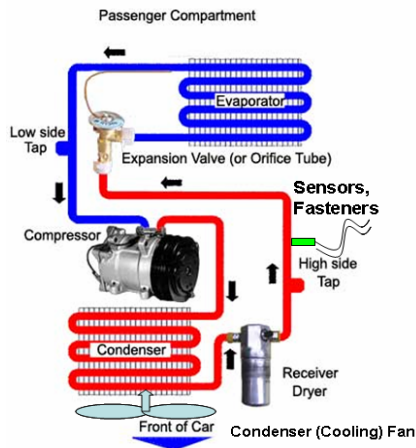
A/C Component Manufacturing - Energy Consumption & CO₂-Equivalents Emissions

Refrigerant System		CO ₂ -Eq. from Production (kg/kg)	CO ₂ -Eq. (kg/kg)	Refrigerant: HFC-134a
Refrigerant		NA	60.3	[Calculation resulting from inputs below]
		CO ₂ -Eq. emissions for virgin refrigerant	8.0	
		CO ₂ -Eq. emissions for recycled refrigerant	2.1	
		CO ₂ -Eq. fugitive emissions of other gases from manufacture		Included above in the case of R134a
		CO ₂ -Eq. due to refrigerant Leakage during transport/delivery	42.3	
		CO ₂ -Eq. due to fuel consumption during Transportation		Included above in the case of R134a
		Atmospheric Reaction Byproducts		Not considered now
		GWP	1410	

➤ 2.3 A/C Component Manufacturing - Energy Consumption & CO₂-Equivalent Emissions

The Mobile Air Conditioning (MAC) system consists of the compressor, the condenser, the evaporator, the high/low pressure lines and pressure regulating devices such as thermal expansion valve, accumulator, valves and sensors. A detailed discussion of the MAC system can be found in Hill and Papasavva (3). The model includes all MAC components, as illustrated in Figure 2.

Figure 2: MAC Components Included in the Model



For each MAC component, the mass and type of material (i.e., aluminum, steel, plastic, etc.) are provided. The manufacturing energy and related CO₂ emissions for each material are obtained from publicly available LCA databases (refs. 13, 14). The LCA energy data and GHG emissions are expressed in MJ/kg and CO₂-eq./kg respectively, for each material manufactured. These data are explicitly shown in the Manufacturing Input spreadsheet for each component of the MAC system. Table 1b provides an example of the A/C components manufacturing found in this input sheet.

Next to these data we provide the allocations of different materials to each component. In most cases, the total component mass is input and the allocations of each material (i.e., %aluminum, %plastic, etc) are defaults in this model, but they can change based on the system being evaluated and user inputs.

TABLE 1b: MAC-Manufacturing-EOL-Input Spreadsheet; Components Manufacturing Example

A/C Component Manufacturing - Energy Consumption & CO₂-Equivalents Emissions

MAC Components	Energy of Production (MJ/kg)	CO ₂ -Eq (kg/kg)	% of each component	(kg)	(MJ)	Total CO ₂ -Eq (kg)
Refrigerant				0.55		27.67
Additional Refrigerant Charge				0.20		0.42
Lubricant	54.50	1.3		0.20	10.90	0.26
Compressor			100%	6.40	238.50	12.43
Aluminum Castings	35.95	1.6	40%	2.56	92.03	4.01
Aluminum Forgings	36.00	1.64	20%	1.28	46.08	2.10
Elastomers	103.00	3.1	5%	0.32	32.96	0.99
Steel Forging	18.90	2.3	15%	0.96	18.14	2.21
Copper Alloys	55.00	3.3	8%	0.51	28.16	1.69
Steel Castings	17.00	1.6	10%	0.64	10.88	1.02
Plastics	80.00	3.0	2%	0.13	10.24	0.38
Assembly					1.00	0.02

A/C Component End-of-Life (EOL) - Energy Consumption & CO₂-Equivalents Emissions

	CO2-Eq	Energy of Recycling**	Refrigerant: R-134a		Total EOL Energy for Bulk Transport, Dismantling and Shredding of METALS & Landfilling Plastics (MJ)	TOTAL CO2-Eq (kg)
	(kg/MJ)	(MJ/kg)	Total Mass (kg)	Percent Recycling		
Refrigerant			0.45	90%	10.0	0.7
Lubricant			0.20	0%		
Compressor						
Metals	0.10	1.7	5.95	100%	10.1	1.0
Plastics	0.10	0.15	0.45	0%	0.067	0.0067
Piping/Hoses						
Metals	0.10	1.7	2.10	100%	3.6	0.4
Plastics	0.10	0.15	0.90	0%	0.135	0.0135
Sensors						
Metals	0.10	1.7	0.20	100%	0.3	0.0
Plastics	0.10	0.15	0.00	0%	0.0	0.0
Ceramics (total mass)			0.60	0%	0.1	0.0

➤ 2.4 A/C Component End-of-Life (EOL) - Energy Consumption & CO₂-Equivalent Emissions

For each component of the MAC system we estimate the energy to recycle it at its End-of-Life (EOL) using data obtained from (15). All metallic components are 100% recycled and they can go back to the manufacturing of new vehicles. The plastic components are not recyclable and after dismantling they become part of the Automotive Shredding Residue (ASR) which is disposed in landfills. As a result the energy required to recycle one kilogram of metals takes into consideration the dismantling and shredding energy requirements and this is on average 1.7MJ/kg. For plastics, ref. (15) provides the energy required for disposing one kilogram of ASR to a landfill, and this is found to be 0.15MJ/kg. The associated CO₂-eq. emissions are estimated to be 0.1kg/MJ for either metals or plastics.

We estimate the EOL energy for the metallic materials using equation (1a), and equation (1b) for the plastic components.

$$\text{EOL Energy}_{\text{metals}} = \text{Avg. Energy [Dismantling + Shredding]}/\text{kg} * [\text{Metal Mass}] \quad (1a)$$

$$\text{EOL Energy}_{\text{plastics}} = [\text{Energy for Auto Shredder Residue Landfilling}]/\text{kg} * [\text{Plastic Mass}] \quad (1b)$$

➤ 2.5 Leakage Input

This sheet provides refrigerant leakage rates that consist of: *Regular* emissions, *Irregular* emissions, *Service* emissions, *End-of-Life* emissions, and emissions during vehicle assembly, as defined in the Model Input sheet.