Carbon Footprint of AC-Sun

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1 Executive summary

The company AC-Sun ApS has asked FORCE Technology to perform an assessment of their air condition system, also called AC-Sun. The AC-Sun system has the feature that it is to a large extent driven by solar power and thus has a modest consumption of power in its use phase compared to conventional AC-systems. To be able to compare the carbon footprint of AC-Sun with other AC-systems it is necessary to quantitatively describe the differences.

In order to do this, life cycle assessment (LCA) has been used. This report is a documentation of such an assessment. The ISO 14040-44 standard for performing LCA's has been followed, but only the balance for emission of greenhouse gasses has been calculated and documented in this report.

AC-Sun has been compared to conventional AC-systems based on both average and best available technology. The functional unit used in the comparison was defined as the provision of 10 kW cooling capacity for 2022 hours during one year for a Spanish household. All technologies are expected to have a life time of 12 years.

The major finding is that the provision of air conditioning using AC-Sun has a carbon footprint of approximately 390 kg CO_2-equivalents per year, while the average AC-system and the BAT AC-system have carbon footprints of respectively 6680 and 2970 kg CO_2-equivalents per year.

An important element is that the weight of the AC-Sun unit is only about half of that of a conventional AC-system. However, when the weight of the solar panels, which powers the system, is included the combined weight is about four times higher. In regards to the carbon footprint, this significant higher usage of materials is more than counterbalanced by the lower use of electricity.

The main assumptions behind the results are: 12 years lifetime, power produced with Spanish grid mix, an annual leakage rate of 11.7% of the refrigerant R407C and recycling rates obtained for the WEEE fraction large household appliances in Spain.
If one or more of these precondition are changed the results will change accordingly, but changes within reasonable limits will most probably not change the overall conclusions.

On the basis of the data calculated an Excel model has been developed in order to assist in the future development of AC-Sun.

2 Introduction

There is a fast growing market for both residential and commercial air conditioning (AC) throughout the world. In 2009 it was estimated that the global turnover was $70 billion per year and in EU the rate of growth is 10 % per year, which at the moment equals the installation of 8.6 million new AC systems every year according to IEA Task 38 (Tecsol, et al. 2009). In Australia about 600,000 systems are sold annually and the growth rate is 11% per annum (Lundie et al., 2008).

In Southern Europe (Italy, Spain, Portugal, Greece and Southern France) the fast growing penetration of small residential air-conditioners is a major contributor to increases in electricity consumption and more important to electricity peak demand (Wesnæs et al., 2009). Total residential AC electricity consumption in EU-25 in year 2005 was estimated to be between 7-10 TWh per year (Wesnæs et al., 2009).

Increasing energy prices, growing request for higher energy efficiency and rising focus on environmental consequences of using AC increases the demand for new technologies, concepts and alternative sources of energy to satisfy the growing demand for AC.

One promising possibility to power the AC in the future is to exploit the energy from a temperature difference occurring between some source of heat, e.g. from a solar panel, and the ambient air, which will be warm but still have a considerable lower temperature.
This is possible with multiple technologies e.g. via an adsorption, absorption or desiccant process which all relies on chemical substances and processes. Another approach is to exploit the temperature difference by means of phase change of water in a mechanical system.
AC-Sun is a newly developed AC system which is based on this latter technology. This technology has the feature that it is able to work at lower temperature differences than the previously mentioned technologies.

The environmental impact of both AC-Sun and different conventional AC systems has been investigated by means of modelling the fate of all the relevant materials along with the energy consumption in GaBi4. Based on the differences in the accumulated amount of materials used during the entire life cycle and the energy consumed during usage, a life cycle assessment (LCA) has been performed and the results is presented in this report.

On the basis of the results from GaBi4 a rather simple model for calculating carbon footprints has been developed in Excel, with the primary purpose to facilitate further product development of AC-Sun.

It is difficult to compare the different technologies since provision of AC is a service with many variables like differences in temperatures, humidity, consumer behaviour, type and size of the technology, characteristics of the building in question etc. Another difficulty is to assess the impact of the actual electricity consumption. As mentioned above, the growing use of AC-systems has become a problem in some regions in relation to providing sufficient power in peak load hours, since AC systems tend to be operating concurrently. All assumptions and considerations should therefore be carefully considered before drawing any conclusions.

It would be highly relevant to include the system's ability to work as a heat pump providing heating as well, but this application is more complicated and outside the range of this study.

3 Goal and scope

3.1 Goal

The goal of this study is to calculate the Carbon Footprint of the service provided by a proposed version of the AC system "AC-Sun" and compare it with the Carbon Footprint of the same service provided by a conventional AC-system based on both the average technology on the market and the "Best Available Technology" (BAT).

3.2 Scope

3.2.1 Functional unit

The functional unit is defined as the provision of 10 kW cooling capacity for 2022 hours during one year, including 2394 hours standby for a Spanish household. This number of hours is based on Table 3-1, which are estimates based on climate data from Alanya in Turkey collected by AC-Sun ApS. It is anticipated that the data are also valid in a Spanish context.

According to information from AC-Sun the system in question can maintain a temperature of maximum 24ºC in a domestic house of about 150 -200 m^2 by supply of air at a temperature of 17ºC through a ventilation duct system, implying an exchange of the air 4 times an hour. When the system is operating the outdoor temperature is at average 35ºC (25ºC - 40ºC). It is assumed that this is the case for the conventional system as well, but it has not been possible to thoroughly assess within the course of this study.

Table 3-1: Running, standby and off time per day and month [hours]

Month	Running time per day	Running time per month	Standby time per day	Standby time per month	Off time per day	Off time per month
January	0	0	0	0	24	744
February	0	0	0	0	24	672
March	0	0	0	0	24	744
April	0	0	0	0	24	720
May	10	310	14	434	0	0
June	12	360	12	360	0	0
July	12	372	12	372	0	0
August	12	372	12	372	0	0
September	12	360	12	360	0	0
October	8	248	16	496	0	0
November	0	0	0	0	24	720
December	0	0	0	0	24	744
Hours/ year		2022		2394		4344

3.2.2 System description

The investigated system is restricted to the basic AC-systems supplying the chilled air. It is expected that the remaining ventilation system with ventilators, thermostats, air blending unit etc. in the house is identical regardless of which AC-system is used and these are thus not included within the system boundaries of this study.

The processes of producing the raw-materials and disposing of them at end of useful life are included in the calculations, as well as electricity consumption and leakage of refrigerant during the use phase. Production and transport of the AC-systems is not included, i.e. production of parts and assembly.

Both AC-Sun and conventional AC-systems need to be lubricated and have filters cleaned or replaced about every second year. It is assumed that the need for service is identical and this is therefore left out of the assessed system.

Transport of the materials and the AC system between or within any of the lifecycle phases are excluded.

3.2.3 Geographical scope

The assessment is performed for a Spanish context. This has an implication for the numbers of hours of operation per year, the supply of electricity and the rate of reutilisation of materials at the end-of-life stage. The results should not be used for other geographical regions.

3.2.4 Temporal scope

The Economical Product Life (EPL) of conventional AC-systems is difficult to predict since the systems can vary a lot in design and quality and the circumstances of operation is a very important factor. Besides the theoretical total number of hours a system can operate, the decision of scrapping a system is also a question of consumer behaviour and depends on efficiency/energy prise, noise, growing service cost etc. Information found on the internet suggests a lifetime from 10 to 14 years for conventional systems including BAT systems[1].

Riviere et al., (2008) investigates four different systems and define lifetimes between 10.3 and 12.6 years with an average of 12 years. These figures are based on an average of data from both Japan, where the number of hours in operation limit the lifetime, and Southern Europe where other considerations are involved as well. This might be a very conservative assumption since, e.g. Lundie et al (2008) assumes a life span of 20 years in Sidney.

A characteristic feature of the AC-Sun system is that the axle with the fan blades combining the expander and compressor is the only moving part, besides the ventilator and pump, which are well known inexpensive and replaceable components. Thus it has the potential of achieving a longer EPL than conventional AC-systems. The developer of AC-Sun expects that the EPL of AC-Sun will be 15 years, but since the concept is at an early stage of development a more conservative assumption has to be considered. Thus 12 years EPL is assumed for both the conventional AC-systems and for AC-Sun.

[1] Even though BAT units are supposed to have a longer lifetime if they are based on frequency controlled regulation, which means that the compressor and fans will run continuously but with a load adapted to the requirement

4 Life cycle inventory

An overview of the sources of data for the different processes included in the calculations is shown in Table 4-1.

Table 4-1: Data sources for the life cycle processes

	Data sources
Aluminium	European Aluminium Association
Cast iron	GaBi Databases 2006
Copper	GaBi Databases 2006
Galvanized steel	GaBi Databases 2006
Glass	ecoinvent 2.0
Mineral wool	GaBi Databases 2006
Stainless steel	ecoinvent 2.0
Rubber	GaBi Databases 2006
Polypropylene	ELCD as in GaBi Database
Refrigerants	ecoinvent 2.0
Electricity	ELCD as in GaBi Database/ GaBi Databases 2006
Landfilling of aluminium	GaBi Databases 2006
Recycling of aluminium	European Aluminium Association
Landfilling of cast iron	GaBi Databases 2006
Recycling of cast iron	GaBi Databases 2006
Landfilling of copper	GaBi Databases 2006
Recycling of copper	GaBi Databases 2006
Landfilling of galvanized steel	GaBi Databases 2006
Recycling of galvanized steel	GaBi Databases 2006
Landfilling of glass	ELCD as in GaBi Database
Recycling of glass	Estimate
Landfilling mineral wool	GaBi Databases 2006
Landfilling of stainless steel	GaBi Databases 2006
Recycling of stainless steel	GaBi Databases 2006
Landfilling of rubber	GaBi Databases 2006
Landfilling of PP	ecoinvent 2.0
Incineration of PP	ELCD as in GaBi Database

4.1 Bill of materials - AC-Sun system

4.1.1 AC-Sun unit

The amount of materials constituting the AC-Sun unit, excluding the thermal solar collector, is based on data delivered by the manufacturer.

Table 4-2: Bill of materials for AC-Sun, excluding the solar collector

Material	Amount [kg]
Aluminium	43.0
Copper	0.2
Galvanized steel	11.0
Mineral wool	3.0
Polypropylene (PP)	0.4
Stainless steel	5.3
Total weight	62.9

4.1.2 Solar thermal collector

The major energy supply that powers the AC-Sun system comes from a solar thermal collector. Data for the weight of different solar thermal collectors are listed in Table 4-3. The choice of thermal solar collector is up to the consumer and could thus be the lightest model listed in the table. To be conservative the average figure of 432.2 kg is used in the calculations. The distribution of the weight on different materials is based on the "solar thermal collector process" from the Ecoinvent database. A cut-off rule of 1% is applied. The resulting material consumption can be seen in
Table 4-4.

Table 4-3: Weight for different solar thermal collectors on the market and from the Ecoinvent database

Area of solar collector [m^2]	Unit weight, empty [kg]	Weight of 20 m^2 solar collector, empty [kg]	Data source:
2.23	41	367.7	http://www.bosch.dk/content/language1/downloads/Solvarmebrochure_til_Installatoren.pdf
13.72	347	505.8	http://www.sunmark.dk/files/14m2-dk-140D_0.pdf
9.28	196	422.4	http://www.sonnenkraft.dk/danmark/download/090713-111201-2_9-11-IDMK-DS-D%C3%84N.pdf
12.53	250	399.0	http://www.energinet.dk/NR/rdonlyres/77AE7163-07E0-492B-81E4-800C17AFA9E4/0/Bilagsrapport280306.pdf
1[2]	23.3	466.0	Ecoinvent database, 2002
20		**432.2**	Average weight of 20 m^2 solar collector

Table 4-4: Bill of materials for solar panel

	Amount of material [kg]
Aluminium	72.9
Copper	52.3
Galvanized steel	76.8
Glass	169.2
Mineral wool	45.1
Silicone sealant and rubber	13.6
Total:	432.2

4.2 Bill of materials - Conventional AC system

The material composition of a typical domestic split system air conditioner can be seen in Table 4-5. The table comprises data from three different sources and an weighted average has been calculated. The calculation is weighted according to the number of units in the sample. In some cases the data is aggregated, like for ferrous metals, and in these cases the contribution has been distributed in the same manner as in the samples where a distinction between materials is made.

The weight of all AC-systems has been linearly extrapolation to 10 kW cooling capacity.

[2] 1 m^2 collector is the unit for the process but the actual size of the collector in question is not known.

The weighting might lead to an average weight which is to low (in a Spanish context) since the Australian sample Lundie et al. (2008) has a significantly lower weight while being far the biggest sample.

Table 4-5: Material composition of conventional air conditioning systems

	Reversible split base case of 3.5 kW (EU)[3]	**Multi-split (EU)[4]**	**Misc. (AU)[5]**	**Weighted average distribution**	**Weight, weighted average**
Weight, 10 kW cap. [kg]	131.43	140	115.51		**119.8**
Number of units in sample	32	4	106		
Material	**%**	**%**	**%**	**%**	**kg**
Plastics, PP	18.7	13.0	10.5	12.4	**14.9**
Ferrous metals, cast iron	43.1	57.0	20.7	19.21	**23.0**
Ferrous metals, steel			42.1	39.04	**46.8**
Non-ferrous metals, Cu	16.8	23.0	11.5	12.7	**15.3**
Non-ferrous metals, Al	7.2		8.6	8.3	**9.9**
Coatings, cut off	0.1				
Electronics, cut off	3.2	2.0			
Refrigerants, cut off			5.6		
Various materials	11.0	5.0	1.0		
Various mat. and cut off	14.26	7.0	6.6	8.3	**10.0**

The dimmed cells contains information which is "cut off" and will not be used in this assessment since they have a small contribution, are poorly defined and are not available in the BOM for all the samples. Various materials are materials which are cut off at an earlier stage when the BOM for the different samples were created.

Initially the refrigerants are not accounted for since the quantity and type is unclear according to the BOM. Instead a fixed amount of 6 kg R407C has been chosen. See paragraph 4.4.

According to Riviere et al. (2008) the composition of materials does not vary much from average AC-systems to best performers and among different sources of data. However, the size of a BAT system and its total weight increases as in general the heat exchanger size increases with efficiency. It has not been possible to quantify this difference and include it in the calculations, thus the assessment is biased towards the conventional BAT.

4.3 Energy consumption

During literature search no data was found for energy consumption of an AC-system with a cooling capacity of 10kW. The power consumption for a conventional cooling only single split unit with a cooling capacity of 7.1 kW was reported to be 2.9 kW for the *Compressor on* mode, 0.066 kW for the *Thermostat off* mode, 0.006 kW for both *Stand-by* mode and *Off mode* in Riviere et al. (2008). These data are representative for average AC-systems available on the European market. Compared to a cooling only single split unit, the BAT system consumes approximately 70% less energy, i.e. ~0.9 kW for the *compressor on* mode.

As the AC-Sun system is mainly powered by solar heat the majority of the electricity consumption induced by conventional AC systems is avoided though there is still a small electricity consumption from a ventilator at the evaporator (150 W), a small water pump (5W), a pump at the solar collector (50 W) and the controller (30 W) which add up to 0.23

[3] Riviere et al. (2008)
[4] Riviere et al. (2008)
[5] Lundie et al. (2008)

kW. This is the power consumption at maximum load and it will probably be lower most of the time.

Table 4-6 shows data for power consumption of an average AC-system, a BAT AC-system and AC-Sun. For the two conventional AC systems, average and BAT, data for a systems with 7.1 kW cooling capacity is used to calculate power consumption during one year based on a base case scenario (Riviere et al., 2008, p.89). The power consumption is subsequently extrapolated to 10 kW by a factor 1.41. Data for AC-Suns operation mode is provided by the manufacturer. Standby and off mode use is assumed to be equal to a BAT system without crank case heater.

Table 4-6: Power consumption for conventional AC-system

	Operation mode	**Standby mode**	**Off mode**	**Total**
Hours/year, in Spain	*2022*	*2394*	*4344*	
Power consumption, average [W]	2900	6	6	
Power consumption [kWh/year] *7.1 kW cooling capacity, average*	5864	14.4	26.1	
Power consumption [kWh/year] *10 kW, cooling capacity, average*	8259	20.2	36.7	**8316**
Power consumption, BAT [W]	870	1.8	0	
Power consumption [kWh/year] *7.1 kW cooling capacity, BAT*	1759	4.3	0	
Power consumption [kWh/year] *10 kW cooling capacity, BAT*	2478	6.1	0	**2484**
Power consumption AC-Sun [W]	230	0.7	0	
Power consumption [kWh/year] *10 kW cooling capacity, AC-Sun*	465	1.7	0	**467**

4.4 Refrigerant consumption

The choice of refrigerant can affect the Carbon Footprint of an air condition system extensively. Different refrigerants will lead to different energy consumption as their cooling capacity differs, but the most significant difference on global warming impact is due to the leakage of the refrigerant. Due to higher pressure when R410A is used, compared to R22 and R407C, a higher leakage ratio occurs (Lundie et al., 2008).

The constituents, the global warming potential for the refrigerants if emitted to air and the leakage rate can be seen in Table 4-7. To be conservative R407C is chosen as the refrigerant in the conventional AC system. According to the Excel-model AirCon LCA , based on Lundie et al. (2008) a domestic air conditioner with 10 kW cooling capacity requires an initial refrigerant charge of 6 kg (regardless of the chosen refrigerant).

The AC-Sun system uses only water (H_2O = R718) as refrigerant.

Table 4-7: Global warming potential for common domestic refrigerants

Refrigerant	**R22**	**R407C**	**R410A**
Constituents[6]	n/a	23% R32; 25% R125; 52% R134a	50% R32; 50% R125;
Global warming potentials (kg CO_2-equivalents per kg) [7]	1810	1774	2088
Leakage rate (% per annum)	12.0	11.7	15.4

[6] Lundie et al., 2008

[7] Solomon et al., 2007

4.5 End-of-life treatment

As the life time of the air condition systems are many years, it is uncertain how the end-of-life treatment of the AC-system will be. According to the European directive on Waste Electrical and Electronic Equipment Directive (WEEE), "air conditioner appliances" are all classified as "large household appliances" (WEEE directive, 2002). As a rough estimate it is here assumed that the air condition system is disposed of as large household appliances. Statistics from EUROSTAT for WEEE treatment in Spain in 2006 is used for the end-of-life treatment distribution (EUROSTAT, 2009). According to this 69% of large household appliances were recycled in 2006, and this is also the fraction assumed to be recycled for most of the materials included in the air condition system. The fraction of the materials which is not recycled is assumed to be landfilled, i.e. 31%. Plastics, mineral wool and rubber are assumed to be 100% landfilled.

It is assumed that there is a material loss of 10% for all materials during production. The metal waste arising during production is assumed to be recycled, the plastic waste, mineral wool and rubber assumed to be landfilled.

It is assumed that the remaining refrigerant from the conventional AC-systems is collected 100 % and decomposed to harmless matter. According to Lundie et al. (2008) the refrigerants can be destroyed with "in-flight plasma arc technology to pyrolyse refrigerants at over 3000 degrees Celsius". The data for this process is not available and has thus been left out of the assessment.

5 Results & discussion

The results for the AC-Sun system, as well as a comparison to a conventional average AC-system and a conventional BAT AC-system are presented below.

5.1 AC-Sun

The carbon footprint for the service provided by the AC-Sun system is approximately 390 kg CO_2-equivalents per year, when the previously listed assumptions and data are used. The distribution of the carbon footprint for the AC-Sun system on different materials and electricity use is shown in Figure 5-1.

The result of the assessment shows that approximately 75% of the emissions are related to the electricity consumption. The impact from material consumption is relatively low, as this is distributed over the lifetime of the AC-system, i.e. the 12 years assumed here. The largest contributions from the material use stem from the aluminium in the AC-system (approximately 5%) and material use in the solar panel (approximately 20%). The distribution of the carbon footprint for the materials used in the solar panel is shown in Figure 5-2. This shows that aluminium is the dominant contributor in the solar panel as well.

This means that the largest potential for improvement that AC-Sun can influence is the consumption of electricity and aluminium. In addition the choice of solar panel is of some importance, and thus it should be considered to provide the customers with guidance regarding the best choice of solar collector.

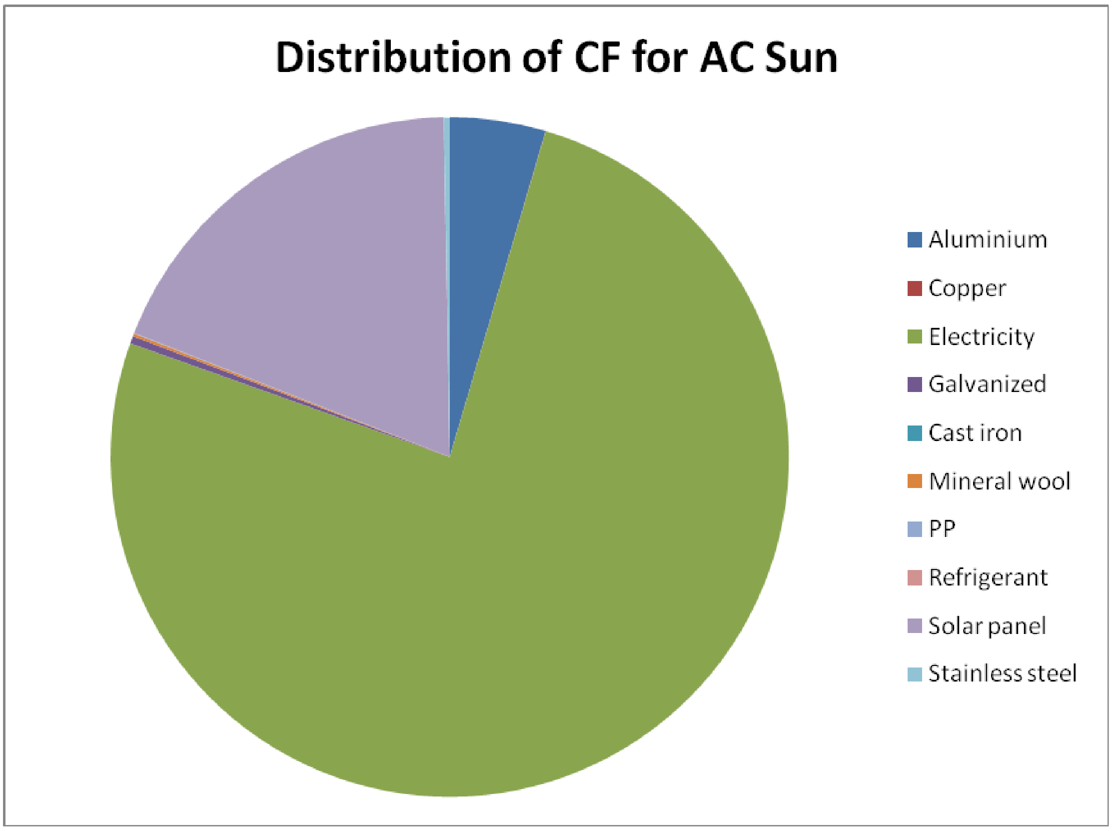

Figure 5-1: Distribution of carbon footprint for the AC-Sun system

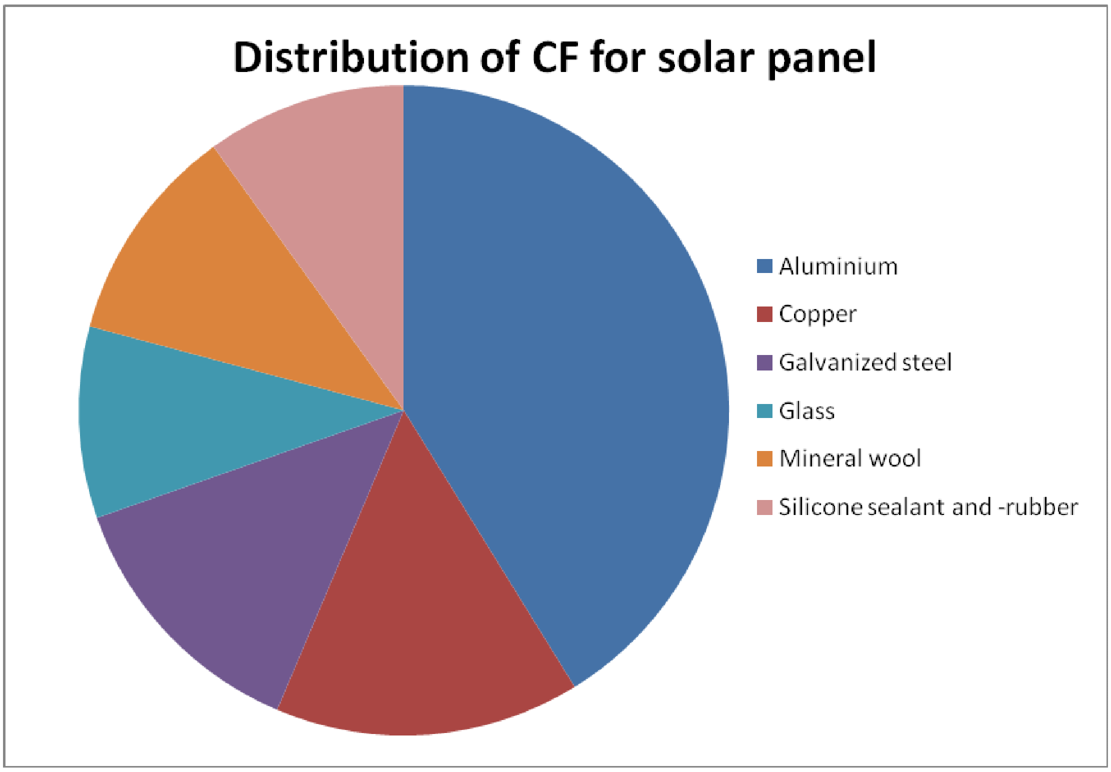

Figure 5-2: Distribution of carbon footprint for the solar panel

5.2 Comparison of AC-Sun and conventional AC-systems

The carbon footprint of the AC-Sun system is compared to the carbon footprints of an average AC-system and a BAT AC-system. The carbon footprints for the three AC-systems are shown in Figure 5-3.

The figure shows that AC-Sun has a significantly lower carbon footprint than the conventional AC-systems. Compared to the 390 kg CO_2-equivalents per year for AC-Sun, the average AC-system and the BAT AC-system have carbon footprint of respectively 6680 and 2970 kg CO_2-equivalents per year.

The reasons for this significant difference in carbon footprints is mainly AC-Sun's much lower electricity consumption (which is approximately 6% compared to average and approximately 20% compared to BAT) and that there is no use or loss of artificial refrigerant.

For the average AC-system, the electricity consumption is responsible for approximately 79% of the impact while the refrigerant (incl. leakage) is responsible for approximately 21%. The impacts from the material use are together responsible for <1% of the impact.

For the BAT AC-system, the electricity comprises 53% of the impact, the refrigerant comprises 46% of the impact and together the materials comprise approximately 1% of the impact.

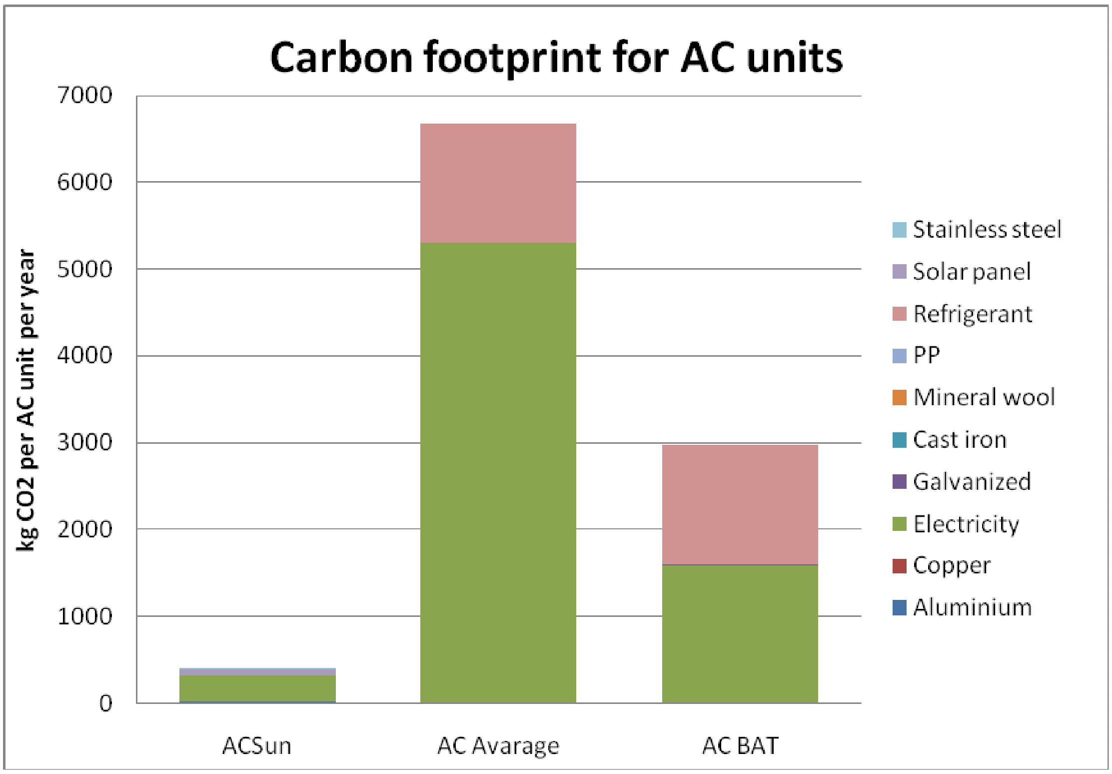

Figure 5-3: Carbon footprints for AC-Sun, an average AC-system and a BAT AC-system

It should be kept in mind that it is the refrigerant with the lowest global warming potential that is modelled, and the impact from refrigerant use could thus be higher if one of the other refrigertants were chosen. The main impact from the refrigerant use is connected to the annual leakage. A fairly high leakage rate is used (11.7%) and this means that the impact could be lowered if the leakage rates are smaller. However, even if the impact from refrigerants were completely removed from the results the AC-Sun system would still perform significantly better than the other two AC-systems.

As for any energy consuming product, the choice of energy supply is of importance. In this case data for avarage electricity production is used in the model. However, as AC-systems often influence the electricty demand in peak hours it is relevant to consider what the marginal electricity is during peak load. If the marginal electricty stem from a fossile based source, such as electricty from lignite, the impact could be of a larger magnitude. A calculation with Spanish lignite based power, resulted in AC-Sun having a carbon footprint of approximately 600 kg CO_2-equivalents per year, the average AC-system a carbon footprint of approximately 10300 kg CO_2-equivalents per year and the BAT AC-system a carbon footprint of 4100 kg CO_2-equivalents per year. This would naturally not change the conclusion that AC-Sun performs better than the other two AC-systems, as the electricity consumption is still significantly lower.

6 Conclusion

It can be concluded from the results that the AC-Sun system has a significantly lower carbon footprint than the average AC-system and the BAT system modelled here.

The main contributor to the carbon footprint for all three AC-systems is the emissions related to production of the electricity consumed. For the AC-Sun system, the material in the solar panel and the consumption of aluminium are the second and third largest contributors. For the conventional AC-systems, refrigerant use and leakage is the other major contributor to the carbon footprint.

7 Literature

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