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# COMPARATIVE ENVIRONMENTAL ASSESSMENT OF NANOFLUID APPLICATION IN REFRIGERATION OF POWER ELECTRONIC TRACTION SYSTEMS*

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## Abstract

In Power Electronic Traction (PET) applications one of the central problems is the effective temperature management, since power demand and reliability requirement grow and devices become increasingly miniaturized. This paper presents a comparative Life Cycle Assessment (LCA) study among three systems: 1. Baseline Cooling System (BCS) that uses as refrigerant a mixture 50wt% of water and glycol; 2. Nanofluid Cooling System single stage ($NCS_{single}$) that uses alumina nanofluid as refrigerant produced with the single stage process; 3. Nanofluid Cooling System two stage ($NCS_{two}$) that uses alumina nanofluid produced with the two stage process. The functional unit is a liquid cooling system for Insulated Gate Bipolar Transistor (IGBT) in PET system for train with a lifetime of 30 years. The system boundary is from cradle to grave. Both $NCS_{single}$ and $NCS_{two}$ show lower potential environmental impacts than the BCS for all impact categories, due to better energy efficiency and increased lifetime of the IGBT. The latter is possible thanks to the lower service temperature. $NCS_{two}$ has lowest potential impacts for all categories, due to the less energy consumption in the alumina nanofluids two stage production. A sensitivity analysis using several IGBT lifetime shows that the longer is the lifetime the more potential environmental advantages arise for all impact categories, due to a more efficient use of materials. Anyway, nanofluid application requires further development in terms of improvements of nanofluid stability and a new design of the cooling system.

*Keywords:* cooling system, IGBT, LCA, nanoalumina

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## 1. Introduction

The transport is a critical sector in European Community. In 2010 it accounts for about 4.9% of EU-27 gross value added (GVA) and for around 5% of employment (EC statistical pocketbook, 2013). The railway plays a key role in addressing rising traffic demand, congestion, fuel security and decarbonization. The European Commission presented a comprehensive package of measures to deliver better quality and more choice in railway services in Europe (EC, 2013). The energy saving in the railway sector is increasing. The sector is in continuing devolvement, in particularly the High Speed Rail (HSR). For controlling the output power of the engine of the train, Insulated Gate Bipolar Transistor (IGBT) Modules are widely used (Gelman, 2014; Uzuka and Masada, 2014). The IGBT (Fig. 1) represents the last generation of power semiconductors. The IGBT are capable of switching high currents (~kA) and high voltages (~kV), which lead to electric powers in the MW range. The switching works very efficiently but there are still heat losses of some kW.

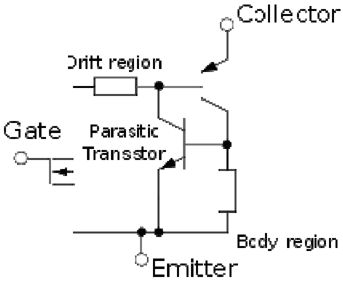


**Fig. 1.** Equivalent circuit for IGBTs

Therefore, for this power electronics traction (PET) application one of the central problems is the effective temperature management, since power demand and reliability requirement grow and devices become increasingly miniaturized. The thermal management limits the switching power of converters based on IGBT modules and it has a strong impact on converter reliability. The efficiency of thermal management is substantially defined by the cooling system. Liquid cooling systems are suitable for applications with high power (Kang, 2012; Wang et al., 2014). These cooling systems consist mainly of a cold-plate, which is directly placed on the IGBT surface, a pump to circulate the cooling fluid, a heat exchanger to remove the heat from the system, and a reservoir to fill in the fluid and to allow thermal expansion of the fluid.

Further improvements of this system are investigating by new design integrating liquid cooling structure in IGBT module for Hybrid and Electric Vehicles (Wang et al., 2014) or by adaptation of microgroove structure in the design of the internal flow passage of the cooling system (Zhang et al., 2013). Instead, NanoHex project (http://www.nanohex.org/the-project), financed by 7th Framework Program, and focussed on use of new cooling fluids to improve the thermal management limits. In particular the alumina ($Al_2O_3$) nanofluid was investigated as new refrigerant for the power electronic traction system. The production of alumina nanofluid with two different pilot lines, “single-stage” and “two-stage” was also compared.

A comparative Life Cycle Assessment (LCA) study, from cradle to grave, assessed the environmental performance of this new coolant compared with the traditional coolant, in order to better understand the main environmental aspects of the system and to derive recommendations to improve it. The paper, after a short description of the analysed system and how its functioning has been tested, describes the LCA study and its main results, providing some recommendations for the industrial implementation.

## 2. Material and methods

### *2.1. Cooling system: description and tests*

The analysed product is a liquid cooling system of the Insulated Gate Bipolar Transistor (IGBT) power semiconductor with integrated Pulse Width Modulation (PWM) inverters. The main components of liquid cooling systems of IGBT are the cold plate, the circulation pump and the heat exchanger. A mixture of water and glycol is used as coolant fluid, to have high thermal exchange performance. A demonstrator was developed to simulate the heat management for applications like electrically driven trains. All components of the Demonstrator were assembled as shown in Fig. 1.

In the tests it is assumed that the IGBT works at 70% of the nominal current 1200A with an average efficiency of 98%. The tests show that, using the two alumina nanofluids, the cold plate and IGBT chip temperature is 3K lower than when using water and glycol, thanks to an increase of about 20% of the thermal heat exchange performance of the nanofluid.

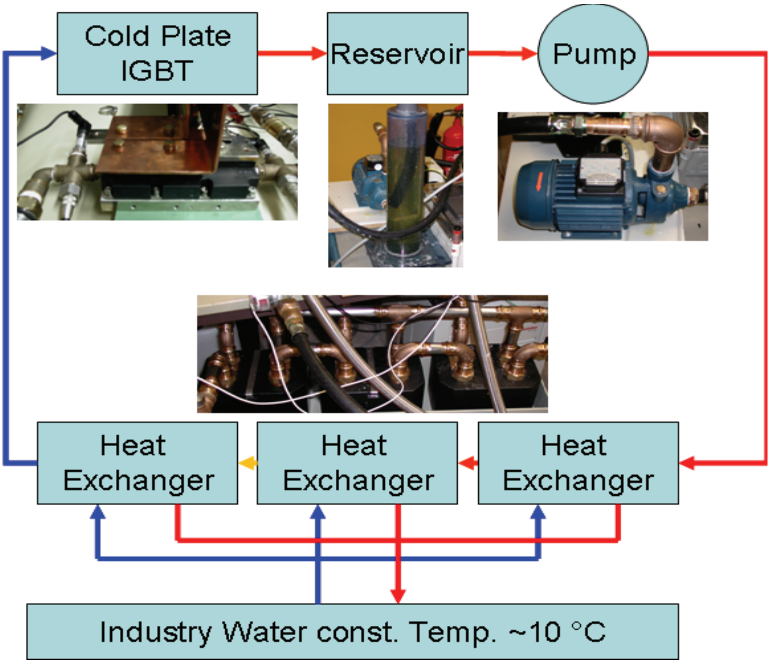


**Fig. 1.** Demonstrator Assembly (NanoHex, 2013)

The IGBT chip temperature influences the conduction and switching losses, where the reduction of temperature leads to reduced electrical losses. These losses reduction depend on the load cycle of the IGBT, in turns, depending on how the drive cycles of the train is. Anyway, a temperature reduction of about 3 K in the IGBT leads to about 2% reduction in the energy losses of the IGBT. Even though compared to the energy consumption of a train in its life time is a very small percentage, in absolute value in 30 years, a total amount of about 63 MWh could be saved in the use of a train with about 1 MW power.

Moreover, the reduction in temperature during the use increases the PET lifetime. In the study we assumed, based on expert judgement, an increase from 30 to 37 years using nanofluid coolant. The effects of this assumption have been checked in the sensitivity analysis, described in section 0.

### *2.2. Production of alumina nanofluid*

The NanoHex project developed two pilot lines to produce nanofluid of alumina, named “single-stage” and “two-stage”. The “single-stage” incorporates the complete production of the nanofluid from particle formation to stable dispersion in one production line. Depending on the formulation, this process can vary a lot already for the particle formation step. In case of alumina nanofluid (with a concentration in mass of 9wt%), an aqueous solution (50%) of $Al(OH)_nCl_{6-n}$ and alumina comes under calcination at 1000C° in oven. In this phase, the nanoparticles are produced. Ethanol is after added to produce a suspension at 20wt%, that is milled, breaking agglomerations and producing surface modification. At the end, the solution is distilled in a rotary vacuum evaporator to remove the ethanol. In the “two-stage” production line, the pre-produced nanoparticle powder is added to a carrier fluid (water). To produce alumina nanofluid (9wt%), in the first stage a suspension with carrier fluid, nanoparticle of alumina 20wt% and ethanol is prepared and in the second stage the suspension is milled, breaking agglomerations and producing surface modification. At the end, the solution is diluted to 9wt% alumina and is distilled in a rotary vacuum evaporator to remove the ethanol. The main differences in the two pilot lines are that the “single-stage” production is far more versatile, while “two-stage” production is faster and more cost effective (Barberio et al., 2014).

The end-of-life treatment of nanofluids depends on their composition. There is no general rule, however, NanoHex partners proposed some guidelines for different nanofluids:
Nanofluids with water as base fluid and particles of a material with toxic properties: measure pH value; dispose as hazardous liquid waste, after process of neutralization if pH is <7.2 or >7.9

- Nanofluids with water as base fluid and particles of a material with no toxic properties: evaporate water (at a temperature of 90°C); avoid formation of fine dust; if the composition of the nanofluid does not automatically leave large agglomerates after water removal, it is best to add a binding agent before vaporization; dispose of dried solids with normal household or industrial waste
- Nanofluids with water/ethylene glycol as base fluid:dispose as hazardous waste containing organic solvents.

In literature no data on toxicity of alumina nanofluid was found. However, alumina nanopowder is less toxic than Al nanopowder. $Al_2O_3$ nanoparticles exhibited mild toxicity toward microorganisms in the environment (Sadiq et al., 2009) and showed the ability to induce genotoxicity and cytotoxicity in vitro test (Di Virgilio et al., 2010); otherwise Zhu et al. (2008) showed that $Al_2O_3$ nanoparticles produced effects on zebrafish embryos and larvae not different from the effects caused by exposing to its bulk counterparts, that is considered non toxic. These data are conflicting and too poor to identify with sufficient confidence the toxicity of nanoalumina. Indeed, adopting the precautionary approach to risk management, the study assumed as end-of-life treatment that recommended for nanofluids with water as base fluid and particles with toxic properties, without a process of neutralization because the measured pH is between 7.3 and 7.8

### *2.3. LCA goal and scope*

The goal of the study is twofold:

1) Identifying the main parameters (process, materials, energy consumption, elementary flows), that contribute more to the potential environmental impacts in the life cycle of the cooling system for power electrical traction system for a train

2) Identifying eco-design recommendations for the industrial scale up of the nanofluid cooling system.

To reach these goals, an LCA study was performed to compare the environmental performance of alumina nanofluid systems with respect to the present conventional technology. Therefore, only differences between the systems are modelled. The nanofluid refrigerant technology, developed by NanoHex, is the basis for the comparison. The three systems are:

1. Baseline Cooling System (BCS) that uses as refrigerant a mixture of water (50wt%) and glycol (50wt%);
2. Nanofluid Cooling System single stage ($NCS_{single}$) that uses as refrigerant alumina nanofluid produced with the single stage process;
3. Nanofluid Cooling System two stage ($NCS_{two}$) that uses as refrigerant alumina nanofluid produced with the two stage process.

The common function of the three systems is the heat removal from IGBT to improve performances and lifetime of trains. The functional unit is a liquid cooling system for IGBT in power electronic traction system for train with a lifetime of 30 years. The system boundary is from cradle to grave (Fig. 3)

BCS and NCSs has different expected lifetime for the power electronic traction system (30 and 37 year, respectively). That has been accounted for considering the material composition (copper, steel, aluminum, plastics etc.) of the PET (cooling system, IGBT and integrated PWM inverters) systems and the end of life of these materials. The energy for assembly and disassembly is neglected because assumed equal in both systems. In BCS we considered the production and the end of life of one system. In NCSs we considered the production and the end of life of 30/37 of the system. The main components of PET included in the analysis are:

- power electronic IGBT modules with integrated Pulse Width Modulation (PWM) inverters;
- cold plates in Aluminum;
- heat exchangers;
- electrical blowers and passive heatsinks in Aluminum;
- pumps;
- coolant (water/ethylenglycol and alumina nanofluid produced with single and two stage system);
- electrical circuit boards.

### *2.4. Life Cycle Inventory*

The data collected comprehend:

- Primary data from NanoHex partners on production, use and end of life of nanoparticle (NPs), nanofluid, cooling system and on IGBT and cold plate composition in terms of component and materials. The data were collected throughout a questionnaire and a spread-sheet, sent to NanoHex partners.
- Secondary data from commercial databases Ecoinvent 2.2 and from literature.

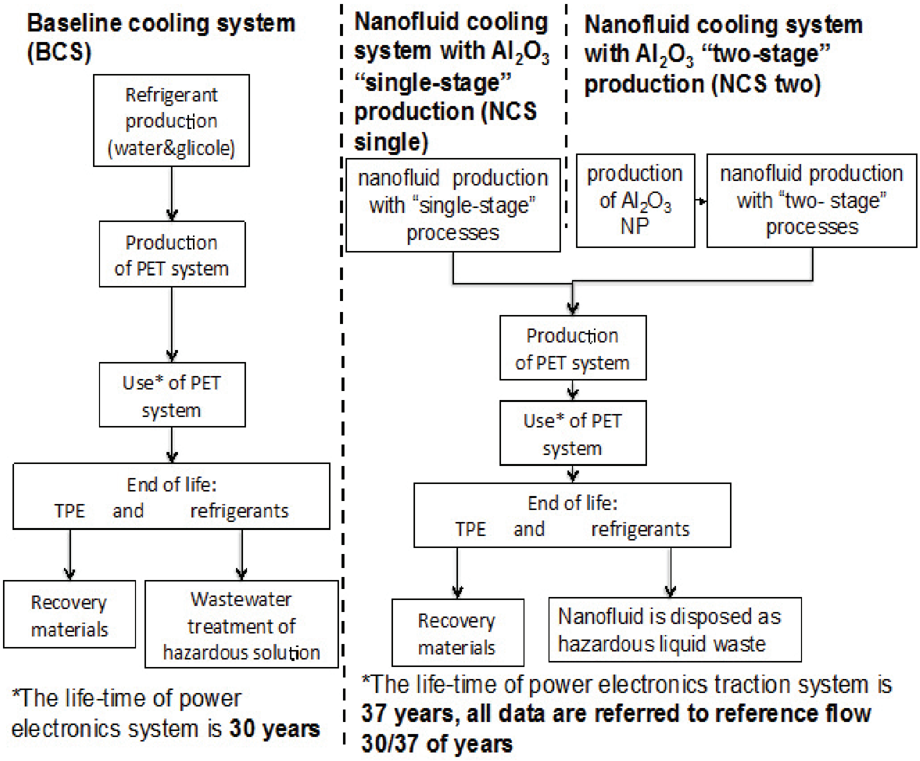


**Fig. 3.** System boundaries of BCS and NCS

### *2.4.1. BCS system*

Table 1 shows the process considered in the BCS system and their amount for all life cycle, considering a life time of 30 years.

Typically an amount of 30-50 L of *refrigerant* (50wt% water and 50wt% glycol) is used for a power electronic converter, and in this study a value of 30 l is used as suggested by NanoHex partners. During maintenance the fluid level is controlled and refilled if necessary. It is assumed that only one complete refill of baseline refrigerant is necessary during the lifetime, total 60 L. Moreover, the water and glycol mixture is classified as hazardous waste (CER 07.07.04) so it is assumed that is treated in a wastewater treatment plant for hazardous waste.

### *2.4.1.1. Energy consumption*

To calculate the energy consumption in use phase of BCS, data from demonstrator tests are used. Train characteristics, in term of power, energy losses and use of train in its lifetime had been proposed by NanoHex partners. The power of the train ($P_t$ ) is equal to 1MW, the total energy losses in the IGBT are 2% and the train is used for about 60% of a year, the calculation for energy losses in 30 year gives is 3513.6 MWh (Eq.1).

$$E_{loss(30y)} = 0.02*1MW*365days*30years*0.6=3513.6\ MWh \qquad (1)$$

The *electricity* considered in the study is only the difference in the energy consumption between BCS and NCSs. Considering that the reduction of IGBT losses using nanofluid is 2%, the energy saving is 63.07 MWh (Eq. 2).

$$E_{saving(30y)} = 0.02 * E_{loss(30y)} = 63.07\ \text{MWh} \quad (2)$$

The electricity module is taken from Ecoinvent database 2.2 and includes the electricity production in Europe, the transmission network and direct SF6-emissions to air. Electricity losses during medium-voltage transmission and transformation from high-voltage are accounted for. The production energy considers 29.2% of nuclear energy, 14.4% of hydro energy, 1.1% of hydropower energy, 50.7% of fossil fuel, 3.3% of renewable energy, 1.2% of energy from waste.

**Table 1.** Inventory data for BCS system

| ***Process*** | ***Amount*** | ***Unit*** | ***Process in database*** |
|---|---|---|---|
| *BCS refrigerant:* Water (50wt%) and glycol (50wt%) | 31.6 | kg | CH: water, deionised, at plant |
| | 31.6 | kg | RER: ethylene glycol, at plant |
| *Production of IGBT-cold plate (materials only)*: | 1 | pcs | |
| Aluminium | 660 | kg | aluminium, primary, at plant |
| Copper | 870 | kg | copper, at regional storage |
| Steel | 630 | kg | steel, converter, unalloyed, at plant |
| Solder | 2 | kg | solder, bar, Sn95.5Ag3.9Cu0.6, for electronics industry, at plant |
| Ceramic | 8 | kg | ceramic tiles, at regional storage |
| Plastic | 160 | kg | polyvinylchloride, at regional storage |
| Silicon Gel | 8 | kg | silicon, solar grade, modified Siemens process, at plant |
| Printed wiring boards | 11 | kg | printed wiring board, power supply unit desktop PC, Pb containing, at plant |
| *electricity* | 63 | MWh | electricity, low voltage, production RER, at grid |
| *end of life IGBT-cold plate:* | 1 | pcs | |
| Aluminium | 660 | kg | Recycling; aluminium secondary, from old scrap, at plant |
| Copper | 870 | kg | Recycling; copper, secondary, at refinery |
| Steel | 630 | kg | Recycling; steel, electric, un- and low-alloyed, at plant |
| Aluminium | 669 | kg | Avoided product: aluminium primary, at plant |
| Copper | 641 | kg | Avoided product: copper primary, at plant |
| Steel | 573 | kg | Avoided product: steel, converter, low-alloyed, at plant |
| Solder | 2 | kg | disposal, plastics, mixture, 15.3% water, to municipal incineration |
| Ceramic | 8 | kg | disposal, inert waste, 5% water, to inert material landfill |
| Plastic | 160 | kg | disposal, plastics, mixture, 15.3% water, to municipal incineration |
| Silicon Gel | 8 | kg | disposal, plastics, mixture, 15.3% water, to municipal incineration |
| Printed wiring boards | 11 | kg | disposal, treatment of printed wiring boards |
| *end of life refrigerants* | 60 | L | treatment, heat carrier liquid, 40% $C_3H_8O_2$, to wastewater treatment, class 2 |

### *2.4.1.2. End of life power electronic traction system*

The end of life of these components is regulated by the European Directive 2012/19/EU on waste electrical and electronic equipment (WEEE) (EC Directive, 2012). The end of life scenario takes in to account the separation of metals and their recovery. The IGBT and the cold plate are removed manually. Table 1 and Table 2 show the end of life treatment of each component and material for BCs and NCSs respectively. The substitution approach has been applied. This approach considers that the materials derived from the recycling process are accounted as credit, avoiding the production of the same quantity of primary metals. This approach is particularly efficient for the metals as reported in the Declaration by the Metals Industry on Recycling Principles (Atherton, 2007) and suggested by the PE International (2014) and WSA (2011). The yield of recycling is different for each material. The yield of secondary metals depends on the phase of disassembly, the recyclability of each metals and the rate of production for the secondary production.

After the disassembly, all metals used in the production of the system are assumed to be recycled. Copper (CDA, 2014), aluminum (EAA, 2013) and steel (WSA, 2011) are 100% recyclable. The amount of secondary metals production is calculate considering that:

- Copper: to produce 1 kg of the secondary copper, the Ecoinvent process uses 1.3kg of scrap, so from 870kg of recovery copper about 669kg (870kg/1.3kg) of secondary copper from old scraps are produced. This avoids the production of the same amount of primary copper;
- Aluminum: to produce 1kg of secondary aluminum, Ecoinvent process uses 1.03 scraps of aluminum, so from 660 of recovered aluminum about 641kg (660kg/1.03kg) of secondary aluminum from old scraps (ingots) are produced. This avoids the production of the same amount of primary aluminum;
- Steel: to produce 1 kg of steel, electric, un- and low-alloyed, the Ecoinvent process uses 1.1 kg of steel scrap, so from 630kg of recovered steel, 573kg (630/1.1kg) of steel, electric, un- and low-alloyed are produced. This avoids the production of the same amount of steel.

### *2.4.2. The NCSs systems*

The main differences are the refrigerant, the energy saving and the lifetime of the PET, 37 years instead of 30 years (Table 2). In $NCS_{single}$ and $NCS_{two}$ the refrigerant is alumina nanofluid and it is assumed that is totally refilled every 5 years. In total 210 L are used in the all life of PET system.

The production and refrigerant end of life are described in section 0. For material recycling, please refer to section 2.4.1.

## 3. Results

The characterization method adopted to evaluate the environmental impacts is IMPACT 2002 + (Jolliet et al., 2003). It is important to highlight that the scientist community is developing the standards test and metric to measure the humans and eco toxicity of nanomaterials (OECD 2013; SCENIHR, 2007), but the present information on nanoalumina is not sufficient, as mentioned in the chapter 2.2, to develop characterization factors for LCA impact categories, so all information on aquatic and terrestrial ecotoxicity, presented in the results, are referred at the bulk chemicals.

The NCSs show lower potential environmental impacts than the BCS for all impact categories. In particular, results show that $NCS_{two}$ has lowest potential impacts for all categories, due to the less energy consumption in the alumina nanofluid two stage production. $NCS_{two}$ shows impacts ranging between 13% (Nonrenewable energy) and 77% (Mineral extractions) of those of BCS (Table 3).

**Table 2**. System descriptions and data for NCS single and two systems

| ***Process*** | ***Amount*** | ***Unit*** | ***Process in database/Reference*** |
|---|---|---|---|
| *refrigerant consumed:* alumina nanofluid 9 wt% | 210 | L | Barberio et al., 2014 |
| *Production of IGBT-cold plate (materials only)* | 0.81 | pcs | |
| Aluminium | 534.6 | kg | aluminium, primary, at plant |
| Copper | 704.7 | kg | copper, at regional storage |
| Steel | 510.3 | kg | steel, converter, unalloyed, at plant |
| Solder | 1.6 | kg | solder, bar, Sn95.5Ag3.9Cu0.6, for electronics industry, at plant |
| Ceramic | 6.5 | kg | ceramic tiles, at regional storage |
| Plastic | 129.6 | kg | polyvinylchloride, at regional storage |
| Silicon Gel | 6.5 | kg | RER: silicon, solar grade, modified Siemens process, at plant |
| Printed wiring boards | 8.9 | kg | GLO: printed wiring board, power supply unit desktop PC, Pb containing, at plant |
| *electricity* | 63 | MWh | "RER: electricity, low voltage, production RER, at grid |
| *end of life IGBT-cold plate:* | 0.81 | pcs | |
| Aluminium | 534.6 | kg | Recycling; aluminium secondary, from old scrap, at plant |
| Copper | 704.7 | kg | Recycling; copper, secondary, at refinery |
| Steel | 510.3 | kg | Recycling; steel, electric, un- and low-alloyed, at plant |
| Aluminium | 519.0 | kg | Avoided product: aluminium primary, at plant |
| Copper | 542.1 | kg | Avoided product: copper primary, at plant |
| Steel | 463.9 | kg | Avoided product: steel, converter, low-alloyed, at plant |
| Solder | 2 | kg | disposal, plastics, mixture, 15.3% water, to municipal incineration |
| Ceramic | 8 | kg | disposal, inert waste, 5% water, to inert material landfill |
| Plastic | 160 | kg | disposal, plastics, mixture, 15.3% water, to municipal incineration |
| Silicon Gel | 8 | kg | disposal, plastics, mixture, 15.3% water, to municipal incineration |
| Printed wiring boards | 11 | kg | disposal, treatment of printed wiring boards |
| *end of life refrigerants* | 60 | L | CH: treatment, heat carrier liquid, 40% $C_3H_8O_2$, to wastewater treatment, class 2 |

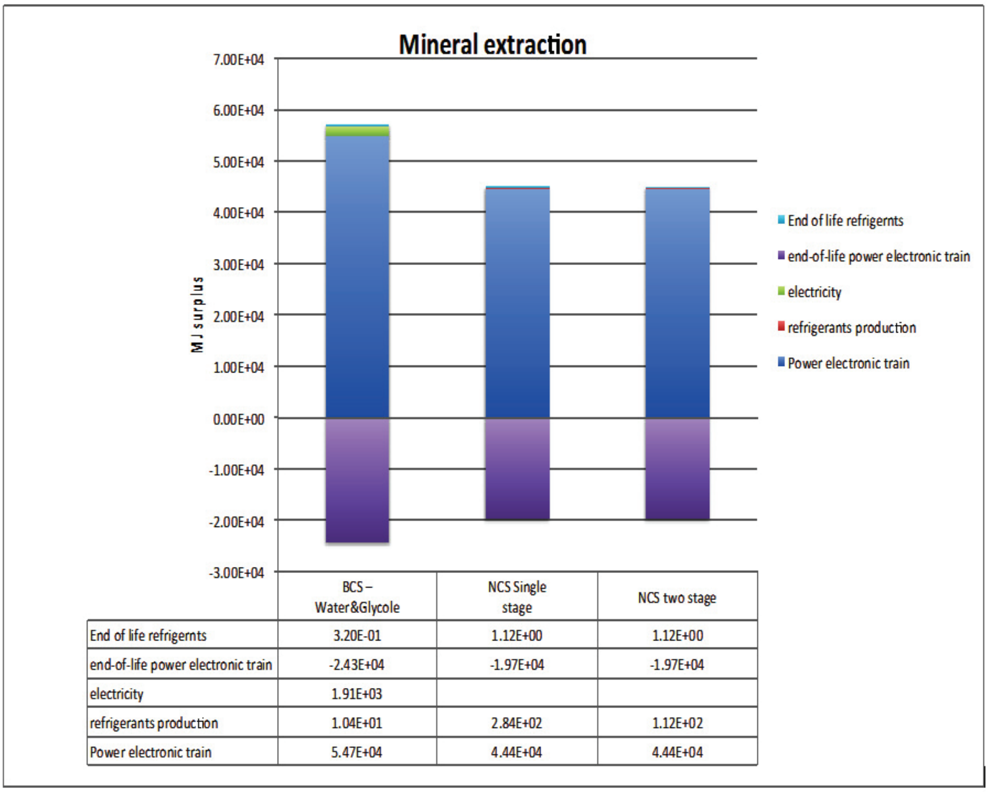
### *3.1. Contribution analysis*

In order to identify the main parameters (process, materials, energy consumption, elementary flows), that contribute more to the potential environmental impacts in the life cycle of PET, a deep analysis was performed for the categories of the mineral extraction, which refer to the depletion of metals ores (e.g. copper and bauxite) and the global warming potential, in line with the strategy of Europe 2020 a resource-efficient Europe - Flagship initiative of the Europe 2020 Strategy (EC, 2011) and the "European Climate Change Program" (EU, 2003).

As regards of mineral extraction category, the characterization analysis shows that production of power electronic gives the main contribute, these for all systems (Fig. 4). This impact is due to the use of metal in the construction of PET system. In particular the main impact is due to depletion of copper for about 88% in the BCS and 89% in $NCS_{single}$ and $NCS_{two}$, followed by nickel with the contribute of 6% (BCS), 4% ($NCS_{single}$ and $NCS_{two}$) respectively.

**Table 3.** Impact characterization (in absolute value and in percentage respect to BCS)

| ***Impact categories*** | ***Unit*** | ***BCS*** | | ***NCS$_{single}$*** | | ***NCS$_{two}$*** | |
|---|---|---|---|---|---|---|---|
| Aquatic acidification | kg $SO_2$-eq | 4.5E+02 | 100% | 2.8E+02 | 63% | 2.7E+02 | 61% |
| Aquatic ecotoxicity | kg TEG-EQ | 1.6E+08 | 100% | 4.1E+07 | 26% | 3.0E+07 | 19% |
| Aquatic eutrophication | kg $PO_4$ eq | 1.0E+00 | 100% | 5.4E-01 | 52% | 4.6E-01 | 45% |
| Carcinogens | kg $C_2H_3Cl$ eq to air | 1.1E+03 | 100% | 8.2E+02 | 76% | 8.2E+02 | 76% |
| Global warming 500yr | kg $CO_2$ eq | 4.0E+04 | 100% | 8.5E+03 | 21% | 6.3E+03 | 16% |
| Ionizing radiation | Bq-C14 | 3.9E+06 | 100% | 1.0E+06 | 27% | 8.5E+05 | 22% |
| Mineral extraction | MJ surplus | 3.2E+04 | 100% | 2.5E+04 | 77% | 2.5E+04 | 77% |
| Non Carcinogens | kg $C_2H_3Cl$ eq to air | 1.0E+04 | 100% | 7.8E+03 | 77% | 7.8E+03 | 76% |
| Non-renewable energy | MJ surplus | 8.5E+05 | 100% | 1.6E+05 | 19% | 1.1E+05 | 13% |
| Ozone layer depletion | kg CFC-11 eq | 2.1E-03 | 100% | 5.1E-04 | 25% | 4.0E-04 | 19% |
| Photochemical oxidation | kg $C_2H_4$ eq | 9.1E+00 | 100% | 5.0E+00 | 55% | 4.8E+00 | 52% |
| Respiratory effects | PM2.5 eq | 8.6E+01 | 100% | 5.1E+01 | 60% | 5.0E+01 | 58% |
| Terrestrial acidification/nitrification | kg $SO_2$-eq | 1.1E+03 | 100% | 5.6E+02 | 52% | 5.3E+02 | 49% |
| Terrestrial ecotoxicity | kg TEG- EQ soil | 5.2E+06 | 100% | 3.8E+06 | 74% | 3.8E+06 | 74% |

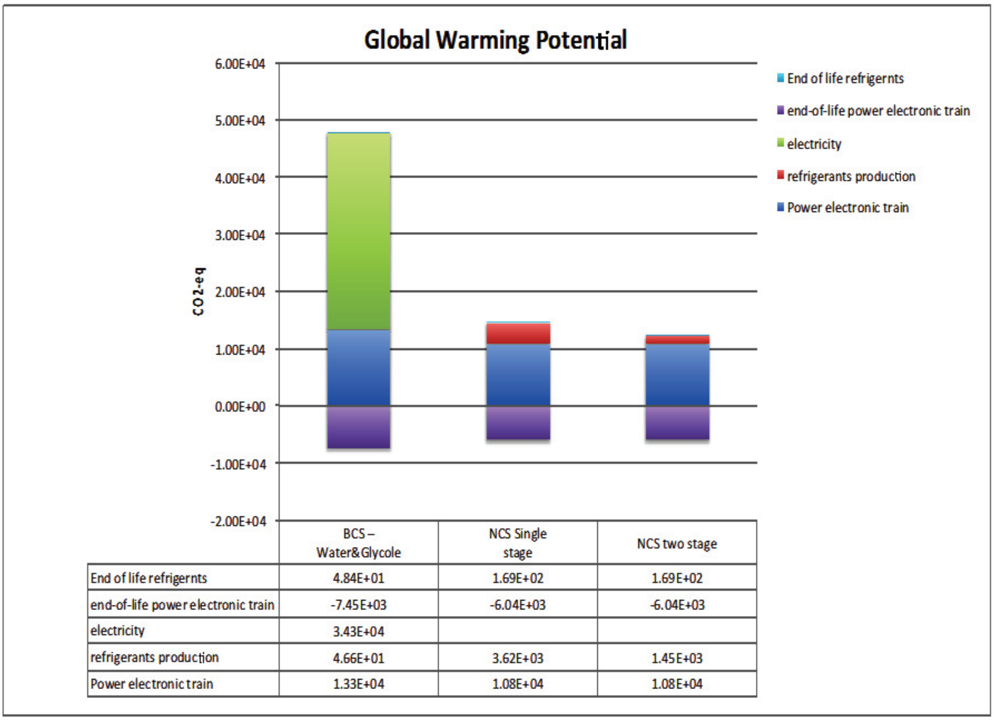


| | BCS – Water&Glycole | NCS Single stage | NCS two stage |
|---|---|---|---|
| End of life refrigernts | 3.20E-01 | 1.12E+00 | 1.12E+00 |
| end-of-life power electronic train | -2.43E+04 | -1.97E+04 | -1.97E+04 |
| electricity | 1.91E+03 | | |
| refrigerants production | 1.04E+01 | 2.84E+02 | 1.12E+02 |
| Power electronic train | 5.47E+04 | 4.44E+04 | 4.44E+04 |

**Fig. 4.** Mineral extraction potential results for each system and for each process

The recovery of metals at the end of life of IGBT is considered as “avoided product”. These impacts are represented as negative contribution to the overall impacts of the systems and reduce the total positive impacts for about 42% (BCS) and 44% for ($NCS_{single}$ and $NCS_{two}$ ).

The most relevant elementary flows for the GWP 500 years are the emissions into air of $CO_2$, contributing for 97% in BCS, 96 % in the $NCS_{two}$ and 95% in $NCS_{single}$. The $CO_2$ emissions are due to the large contribution of fossil fuels to the production of electricity and metals. The recovery of metals in the end of life of power electronic traction system reduces the total impacts of each system for about 16% in BCS, 42% in $NCS_{single}$ and 49% for $NCS_{two}$ (Fig. 5).



| | BCS – Water&Glycole | NCS Single stage | NCS two stage |
|---|---|---|---|
| End of life refrigernts | 4.84E+01 | 1.69E+02 | 1.69E+02 |
| end-of-life power electronic train | -7.45E+03 | -6.04E+03 | -6.04E+03 |
| electricity | 3.43E+04 | | |
| refrigerants production | 4.66E+01 | 3.62E+03 | 1.45E+03 |
| Power electronic train | 1.33E+04 | 1.08E+04 | 1.08E+04 |

**Fig. 5.** Global Worming Potential results for each system and for each process

### *3.2. Sensitivity analysis*

A sensitivity analysis was performed with the aim to verify the influence on results of key data and assumptions in modelling. In the study, the main assumption is the increase of lifetime of electronic traction power system from 30 to 37 years when using nanofluid coolant, justified by the lower working temperature. Three additional life time hypotheses are checked for $NCS_{single}$, selected being the worse case between the two NCS systems: 1) The life time doesn’t increase and remains 30 years, ($NCS_{single}30$); 2) The life time increases to 34 years, ($NCS_{single}$ 34); 3) The life time increases to 41 years, ($NCS_{single}$ 41).

The results show that the Nanofluid cooling systems have less potential impact than BCS for all lifetime scenarios. The potential environmental advantages of NCSs systems are due to less use of materials and this increases with longer lifetime (Table 4).

**Table 4.** Potential impacts for the several lifetime scenarios in percentage respect to BSC (set equal to 100%), in grey the best scenario

| | *BSC, %* | *NCS<sub>single</sub> 37, %* | *NCS<sub>single</sub> 30, %* | *NCS<sub>single</sub> 34, %* | *NCS<sub>single</sub> 41, %* |
|---|---|---|---|---|---|
| Aquatic acidification | 100 | 63 | 68 | 77 | 57 |
| Aquatic ecotoxicity | 100 | 26 | 27 | 30 | 24 |
| Aquatic eutrophication | 100 | 52 | 55 | 59 | 48 |
| Carcinogens | 100 | 77 | 83 | 94 | 69 |
| Global warming 500yr | 100 | 21 | 22 | 23 | 20 |
| Ionizing radiation | 100 | 27 | 28 | 31 | 25 |
| Mineral extraction | 100 | 77 | 84 | 95 | 70 |
| Non Carcinogens | 100 | 77 | 84 | 95 | 70 |
| Non-renewable energy | 100 | 19 | 19 | 21 | 18 |
| Ozone layer depletion | 100 | 25 | 26 | 28 | 23 |
| Photochemical oxidation | 100 | 55 | 59 | 66 | 50 |
| Respiratory effects | 100 | 60 | 65 | 73 | 54 |
| Terrestrial acidification/ nutrification | 100 | 52 | 56 | 63 | 47 |
| Terrestrial ecotoxicity | 100 | 74 | 81 | 91 | 67 |

## 4. Conclusions and recommendations

The analysis was based on differences existing among the three analysed PET systems. Common parts and processes were not modelled. This approach allows for highlighting the differences in environmental performances, otherwise overwhelmed by the energy consumption in train use. The results show that nanofluid-based cooling systems could have environmental advantages in applications of power electronics traction. The detailed analysis of the life cycle of the cooling system shows how the abiotic depletion and the substitution of scarce resources are important issues. Mineral extraction is a relevant impact and it is mainly originated by the use of copper in construction of power electronic traction system, followed by nickel.

Moreover, the contribution analysis shows that production of alumina nanofluid has negligible contribution (less of 1%) for the abiotic depletion but about 25% in $\mathrm{NCS_{single}}$ and 12% in $\mathrm{NCS_{two}}$ for the Global worming potential. This impact is due to the need of replacing the nanofluid during the lifetime of the train. Further efforts should be devoted to increase the stability of the nanofluids, reducing the need of replacement. The alumina nanofluid end of life, precautionally considered as hazardous waste, has a negligible effect on all impact categories. Anyway, it is necessary to stress again that these results do not include the toxicity of nanofluid and nanoalumina, because the characterization factors of nanomaterials for toxic categories are not available, so all information on Eco-toxicity are referred at the bulk chemicals.

Recommendations for the industrial scale up should take into account the possibility to use less material and substitute copper and nickel with more abundant resources. The energy saving is another key issue. It deserves further development: the results of experimental tests in Nanohex project have shown that the SiC nanofluid has better conductive performance than alumina nanofluid. However, it produces problems of corrosion and erosion on the cold plate. So a re-design of the cold plate with different materials is necessary in order to use SiC nanofluids. Moreover, the use of nanofluid could be very interesting if they increase the lifetime of the PET, as shown in the sensitivity analysis.

Therefore, more technical tests are recommended.

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