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Life Cycle Assessment for filling media for radiator thermostats

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1. Introduction

As agreed with Danfoss Heating Solutions, the Danish Technological Institute, Division for Building and Construction has performed a life cycle assessment (LCA) study on two alternative filling media for radiator thermostats for Danfoss A/S during June/July 2019.

2. Background

Danfoss A/S is the world's largest manufacturers of thermostatic radiator valves. Different filling media can be used inside Danfoss' radiator thermostats. The function of the filling media is to expand, depending on the surrounding temperature, inside their containing bellow capsule; by expanding, the filling media closes the radiator valve, preventing the radiator to warm up the room further.

Danfoss has traditionally used primarily two filling media in their radiator thermostats: a liquid filling medium (ethylacetate) and a mixture of two gas filling media (1-butene and N-butane). The different filling media require two different sizes and models of the containing bellow capsule and of the associated thermostat. The two thermostats are called respectively RAW and RA.

Danfoss would like to understand the overall environmental impacts associated with the two options of filling medium, and therefore of thermostat. As a first step in this direction, the Danish Technological Institute has been asked to perform a preliminary study on the environmental impacts associated with the two alternative filling media only. A full study of the whole thermostat will be considered by Danfoss as next step.

3. Objective

While the size and model of the bellow capsule and of the thermostat, as well as the filling process, change depending on the used filling media, the objective of the present study is limited to the *life cycle assessment of the filling media* itself, including its production, transportation to the Danfoss production plant in Silkeborg, Denmark, storage and internal transportation until the actual filling site, as well as its final disposal after use.

The functional unit of this LCA, i.e. *the product system studied* in this project, is the manufacture, transportation, storage and disposal of a quantity of filling media corresponding to one bellow capsule, for the following two alternative filling media:

- Ethylacetate (Scenario 1)
- Mixture of 1-butene and N-butane (Scenario 2).

4. Data and received information

Danfoss has gathered information regarding the following aspects:

- Amount and type of the studied filling media used in the two types of bellow capsules;
- Transportation of the filling media from their respective production sites to Danfoss' production site in Silkeborg, Denmark;

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- Storage and internal transportation methods of the filling media at Danfoss' production site in Silkeborg, Denmark;
- Disposal of the discarded bellow capsules during production. This information is used as a proxy for the disposal of the filling media itself after use.

It was not possible to gather information regarding the manufacturing process of the filling media. Therefore, generic processes have been used to model these steps (cf. Section 5).

5. Methods

LCA Software/Tools: The environmental impact associated with the filling media is calculated through a life cycle assessment (LCA) using the GaBi software tool (version 9.2.0.58).
LCIA (life cycle impact assessment) method: Environmental impact assessment has been performed based on the EF (Environmental Footprint) method (version 3.0), which is the EU recommended method, developed as part of the PEF (Product Environmental Footprint) and OEF (Organisation Environmental Footprint) recent initiatives. This method has recently been included in the forthcoming revised version of the EN standard for environmental product declarations on construction products, EN 15804. The method comprises the 27 environmental impact categories listed in Table 1.
For the sake of simplification, however, this report only comments in details on results for the categories climate change, ecotoxicity freshwater, ionising radiation and resource use, energy carriers. Results for the remaining categories are briefly discussed at the beginning of Section 6, and reported in Appendix 1. The four categories have been chosen in cooperation with Danfoss, and based on the following considerations: climate change has been chosen as it is a globally recognised impact, which most people, even non-LCA experts, can relate to. The remaining three categories have been chosen as the categories showing highest normalised impacts for both scenarios, therefore representing significant impacts of the studied product systems.
Results are presented as characterised results[1], which means the individual impact categories are expressed in different units and cannot be compared with each other, but they can be compared across the two scenarios. Normalised results[2] have however been used during the phase of interpretation of results, in order to identify the four most significant impact categories that will be analysed in more details in the present report (as mentioned above: climate change, ecotoxicity freshwater, ionising radiation and resource use, energy carriers). Normalised results are not shown in the present report.
Database: The required LCA datasets have been retrieved from the EcoInvent 3.5 database. A list of the utilised processes is reported in

[1] Cf. Appendix 2 for further details on Life Cycle Impact Assessment (LCIA) steps.
[2] Normalisation gives the different impact potentials in a common scale, and thus allows comparison across impact categories. Cf. Appendix 2 for further details on Life Cycle Impact Assessment (LCIA) steps.

Table 2.

Geography: The LCA has been carried out based on the actual location of Danfoss' production site in Silkeborg, Denmark.

Time horizon: The LCA has been executed with a time horizon of 100 years.

Table 1 List of environmental impact categories used in connection with LCA in this project

Impact category	Unit
Acidification terrestrial and freshwater	Mole of H+ eq.
Cancer human health effects	CTUh
Cancer human health effects (Metal)	CTUh
Cancer human health effects (Organic)	CTUh
Climate Change	kg CO2 eq.
Climate Change (biogenic)	kg CO2 eq.
Climate Change (fossil)	kg CO2 eq.
Climate Change (land use change)	kg CO2 eq.
Ecotoxicity freshwater	CTUe
Ecotoxicity freshwater (Inorganic)	CTUe
Ecotoxicity freshwater (Metals)	CTUe
Ecotoxicity freshwater (Organic)	CTUe
Eutrophication freshwater	kg P eq.
Eutrophication marine	kg N eq.
Eutrophication terrestrial	Mole of N eq.
Ionising radiation - human health	kBq U^{235} eq.
Land Use	Pt
Non-cancer human health effects	CTUh
Non-cancer human health effects (Inorganic)	CTUh
Non-cancer human health effects (Metals)	CTUh
Non-cancer human health effects (Organic)	CTUh
Ozone depletion	kg CFC-11 eq.
Photochemical ozone formation - human health	kg NMVOC eq.
Resource use, energy carriers	MJ
Resource use, mineral and metals	kg Sb eq.
Respiratory inorganics	Disease incidences
Water scarcity	m^3 world equiv.

5.1. Scenario 1: liquid filling medium – Ethylacetate (used in capsule type RAW)

Ethylacetate is manufactured by Danfoss' supplier in Hull, England, and transported by tanker truck to Danfoss production site in Silkeborg, Denmark (appr. 1500 km). Ethylacetate is typically delivered in batches every couple of months, by using large and relatively new tanker trucks. An amount corresponding to 13 $g_{ETHYLACETATE}$ is necessary to fill one bellow capsule. No wastage of ethylacetate is assumed. Once at Danfoss production site in Silkeborg, the liquid is transferred to an underground tank, where it is stored until utilisation. Internal transportation to the filling site happens through pipes, and electricity is used to pump the liquid to the final utilization place.
At the end of its use-life, the filling medium is disposed of as hazardous waste, and incinerated. Energy recovery from the incineration process is modelled assuming 22% electrical efficiency and 73% thermal efficiency, as done for Danish incineration plants in the model for LCA of waste management systems Easetech[3]. The produced electricity and heat are assumed to substitute respectively the Danish electricity grid mix and the average fuel composition for heat generation in Denmark according to the latest available IEA data[4]. Transportation of the waste to the incineration site is not explicitly considered in this study, since there is no specific information on where the filling media is used nor where the incineration plant is located. This process is however approximated by using a "market" process for the incineration of hazardous waste, which includes a generic transportation step for the waste.

5.2. Scenario 2: gas filling medium – N-butane + 1-butene (used in capsule type RA)

N-butane and 1-butene are delivered by Danfoss' supplier, located in Aalter, Belgium, and transported in pressurised tanks, in liquid form, by truck to Danfoss production site in Silkeborg, Denmark (appr. 1000 km). Both gasses are produced by refining of natural gas, and this typically happens at the extraction site. This is why the production process for both gasses has been modelled using a "market" process, which includes a generic transportation step for the gases from their extraction/refining site to a generically located supplier/final user. N-butane and 1-butene are typically delivered to Danfoss using medium-sized, relatively new trucks. A total amount corresponding to 0.13 $g_{GAS\ MIXTURE}$ is necessary to fill one bellow capsule. No wastage of n-butane and 1-butene is assumed. Once at Danfoss production site in Silkeborg, the gas tanks are stored in a shed, where they need to be maintained at a temperature of appr. 40˚ C in order to keep the pressure, until utilisation. This requires a relatively high energy consumption (65 Wh/bellow capsule). Danfoss is however currently optimising this step, and expects to be able to cut the energy consumption by more than 60% (to 22 Wh/bellow capsule) by better isolating the shed; the latter value of 22 Wh/bellow capsule is used as a default value in the current study. However, as it implies a very large expected improvement, this parameter is tested in a sensitivity analysis. The internal transfer of the gas to the filling equipment does not require further energy consumption, as the gas is already pressurised.

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[3] Clavreul, J., Baumeister, H., Christensen, T.H., Damgaard, A., 2014. An environmental assessment system for environmental technologies. Environ. Model. Softw. 60, 18–30. DOI: 10.1016/j.envsoft.2014.06.007
[4] International Energy Agency, Share of heat generation by fuel, Denmark 2016. Retrieved at https://www.iea.org/statistics/?country=DENMARK&year=2016&category=Heat&indicator=ShareHeatGenByFuel&mode=chart&dataTable=ELECTRICITYANDHEAT

At the end of its use-life, the filling medium is disposed of as hazardous waste, and incinerated. Energy recovery from the incineration process is modelled in the same way as in the previous scenario (i.e. assuming 22% electrical efficiency and 73% thermal efficiency), where the recovered electricity and heat are, again, assumed to substitute respectively the Danish electricity grid mix and the Danish average fuel composition for heat generation. Transportation of the waste to the incineration site is not explicitly considered in this study, since there is no specific information on where the filling media is used nor where the incineration plant is located. This process is however approximated by using a "market" process for the incineration of hazardous waste, which includes a generic transportation step for the waste.

Table 2 Data provided by Danfoss A/S and Ecoinvent dataset used to model each process

Capsule type		RAW	RA	
Filling media type		Ethylacetate	1-butene	N-butane
Production of filling media				
Amount	g/capsule	13	0.13	
Ecoinvent dataset		Ethyl acetate production, Europe	Market for butene, mixed, Europe	Market for butane, Global
Transport of filling media from producer to Danfoss				
Transport distance	km	1500	1000	
Transport type	-	Large tanker truck, relatively new	Medium truck with pressurised gas tanks, relatively new	
Transport	kg·km/capsule	19.5	0.13	
Ecoinvent dataset		Transport, freight, lorry >32 t, EURO 5, Europe	Transport, freight, lorry 7.5-16 t, EURO 5, Europe	
Storage of filling media at Danfoss				
Energy for storage	Wh/capsule	0	22	
Ecoinvent dataset		-	Market for electricity, low voltage, Denmark	
Internal transport of filling media from storage to filling site				
Energy for transport	Wh/capsule	0.028	0	
Ecoinvent dataset		Market for electricity, low voltage, Denmark	-	
Disposal of end of life filling media				
Amount	g/capsule	13	0.13	
Ecoinvent dataset		Market for hazardous waste, for incineration, Europe without Switzerland		
$LHV_{FILLING\ MEDIUM}$	MJ/kg	25.4	48.4	49.5
Energy efficiency	-	η_{EL}=22%, η_{THERM}=73%		
Ecoinvent dataset for electricity substit.		Market for hazardous waste, for incineration, Europe without Switzerland		
Ecoinvent datasets for heat substitution		Heat and power co-generation, wood chips, 6667 kw, state-of-the-art 2014, Denmark		
		Heat and power co-generation, biogas, gas engine, Denmark		
		Heat, from municipal waste incineration to generic market for heat district or industrial, Denmark		
		Heat and power co-generation, natural gas, comb. cycle powerplant, 400MW electrical, Denmark		
		Heat and power co-generation, natural gas, conventional power plant, 100MW electrical, Denmark		
		Heat and power co-generation, hard coal, Denmark		
		Heat and power co-generation, oil, Denmark		

6. Results

Based on the complete LCA results reported in Appendix 1, Tables A.1 and A.2, the following considerations can be made.
In general, good agreement can be seen across different impact categories concerning both the relative ranking of the two studied filling media (for most impact categories the liquid filling medium provides consistently higher environmental impacts than gas filling medium), and concerning the relative contribution of the single subprocesses to the overall results .
For all categories except three (climate change - biogenic; eutrophication terrestrial; land use), the gas filling medium provides lower environmental impacts than the liquid one, while for a single impact category (the under-category climate change - land use change) the two alternative filling media give the same environmental impact. For the three mentioned categories of climate change - biogenic, eutrophication terrestrial and land use, the liquid filling medium actually provides negative impacts, i.e. environmental benefits. This is due to the energy recovered during the incineration process of a much larger quantity of liquid filling medium (13 g/bellow capsule), compared to the incineration of only 0.13 g/bellow capsule of gas filing medium. For the remaining 23 impact categories, however, including the overall "climate change category" (which represents the sum of the three under-categories climate change - biogenic, climate change - fossil and climate change - land use change), the gas filling medium provides consistently lower environmental impacts.

Regarding the relative contribution of different subprocesses to the overall results, the following can be observed:

- For the liquid filling medium, the most significant contribution comes from either production of ethylacetate (between 14% and 421% in absolute value[5], however most often above 60%) or from its disposal as waste (between 1% and 555% in absolute value, however most often above 30%), depending on the actual impact category. Transportation of ethylacetate from the English supplier to Denmark gives typically a minor contribution (below 34% in absolute value, but most often below 10%), while energy consumption for internal transportation of ethylacetate is responsible for insignificant impacts (below 0,3% in absolute values).
- For the gas filling medium, by far the most significant contribution comes from energy consumption for internal storage of the gas tanks, that need to be maintained at a certain temperature (between 57 and 114% of the total impacts, depending on the individual impact category, but mostly above 95%). Disposal of the gas mixture as waste is responsible for between 1 and 41% of the total impacts in absolute value, but mostly below 5%). Production of N-butane contributes to the overall impacts with between 0,1 and 9% of the total impacts (however mostly below 2%), while transportation of the gases from the Belgian supplier to Denmark gives only a minor contribution (mostly below 1% of the total impacts), as well as production of 1-butene (below 1,1%).

[5] Contributions above 100% in absolute value, as well as negative contributions, indicate that there might be negative impacts, i.e. environmental benefits, for either single subprocesses or for the total result for the relevant impact category.

In the following sections, results are presented in detail for climate change, as well as for the three impact categories that showed highest normalised impacts: ecotoxicity freshwater, ionising radiation and resource use, energy carriers. Presentation of results is preceded by a short description of the impact category and its relevance.

6.1. Climate change

Emission of greenhouse gases (GHG) causes an increase in their atmospheric concentration. This generates in turn an increase of the radiative forcing capacity of the atmosphere, resulting in a larger part of the solar energy being retained in the atmosphere. This leads to an increase in global temperature, thus affecting human health as well as the natural ecosystems.

Quantification of the climate change impacts in the LCIA method EF 3.0 follows the reference method proposed by IPCC 2013[6] (GWP100) and is expressed in kg CO_2 eq.

Climate change impacts for the two filling media are shown in Figure 1. The gas mixture filling medium (scenario 2) has a total impact of $8,5 \cdot 10^{-3}$ kg CO_2 eq./bellow capsule, while the liquid filling medium (scenario 1) has a total impact of $6 \cdot 10^{-2}$ kg CO_2 eq./bellow capsule, i.e. approximately one order of magnitude higher.
Production of ethylacetate contributes to 59% of scenario 1 impacts, waste disposal is responsible for 38%, and delivery of ethylacetate from the English supplier contributes with 3% only. 97% of the impacts of scenario 2 are due to the electricity consumption to maintain the gas tanks at the right temperature before utilisation, while waste disposal of the smaller amount of gas mixture contributes to the total results with only 1,3%. Production of N-butane and of 1-butene are responsible for only 1 and 0,5% of the total impacts, while their shipping from Belgium provides only 0,4% of the total impacts.

[6] IPCC (2013). Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang, 2013: Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

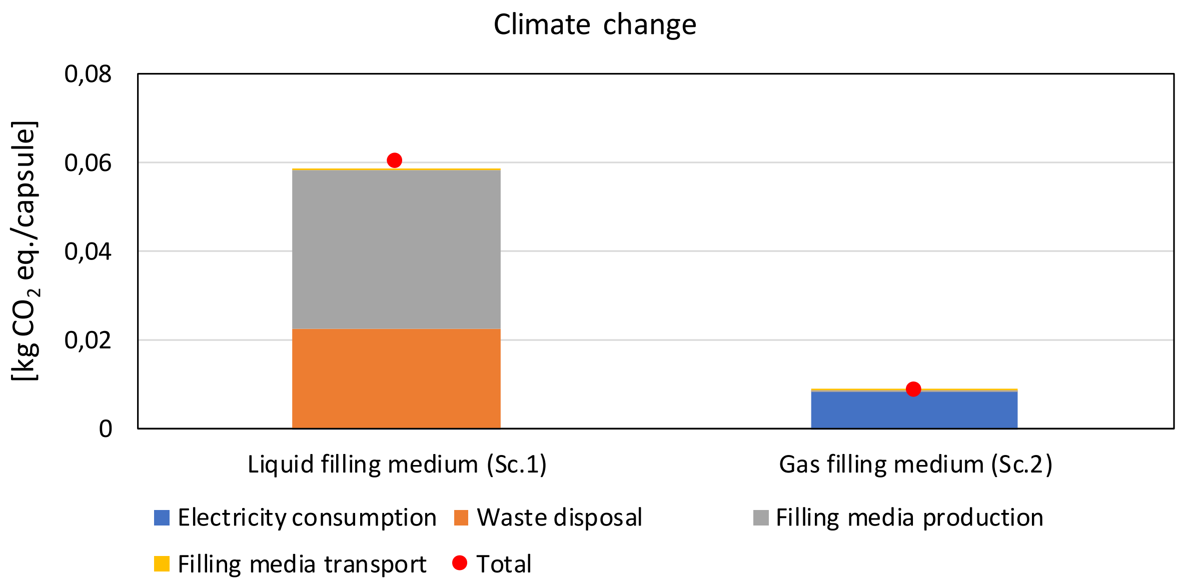

Figure 1 Characterised LCA-results for the two filling media for the impact category Climate change, including contribution of different sub-processes.

6.2. Ecotoxicity freshwater

Chemicals emitted to the environment (air, water, soil, etc.) during all life cycle stages of products, services and systems, may have the potential to cause toxic impacts on human beings and/or ecosystems – in this specific case, aquatic ecosystems. The related impact pathway of this impact category covers the environmental fate of emitted toxic chemicals, ecosystem exposure to increased environmental concentrations of these chemicals, the associated toxicity-related effects due to chemical exposure in different environmental compartments, and finally the translation of these effects into damages on ecosystem quality.

Quantification of the ecotoxicity freshwater impacts in the LCIA method EF 3.0 follows the most recent version of the USEtox® model[7] (version 2.1) and is expressed in CTUe (comparative toxic units for ecosystems). This category represents toxic effect on aquatic freshwater species in the water environment. It should be pointed out that the ecotoxic effect is not specifically related to the two studied filling media *per se* (e.g. the two filling media emitting toxic chemicals), but to all the activities modelled in the LCA study (production, transport, energy consumption, etc.).

Ecotoxicity freshwater impacts for the two filling media are shown in Figure 2. The gas mixture filling medium (scenario 2) has a total impact of 0,18 CTUe/bellow capsule, while the liquid filling medium

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[7] Rosenbaum RK, Bachmann TM, Gold LS, Huijbregts MAJ, Jolliet O, Juraske R, Koehler A, Larsen HF, MacLeod M, Margni MD, McKone TE, Payet J, Schuhmacher M, van de Meent D, Hauschild MZ (2008) USEtox - The UNEP-SETAC toxicity model: Recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. Int. J. Life Cycle Assess. 13:532-546. doi:10.1007/s11367-008-0038-4

(scenario 1) has a total impact of 1,25 CTUe/bellow capsule, i.e. approximately one order of magnitude higher.

Production of ethylacetate contributes to 54% of scenario 1 impacts, while its end-of-life disposal is responsible for 44% of the same impacts; delivery of ethylacetate from the English supplier contributes with 1,7% only. 96% of the impacts of scenario 2 are due to the electricity consumption to maintain the gas tanks at the right temperature before utilisation, while waste disposal of the smaller amount of gas mixture contributes to the total results with only 2%. Production of N-butane and of 1-butene are responsible for only 1,8 and 0,01% of the total impacts, while their shipping from Belgium provides only 0,1% of the total impacts.

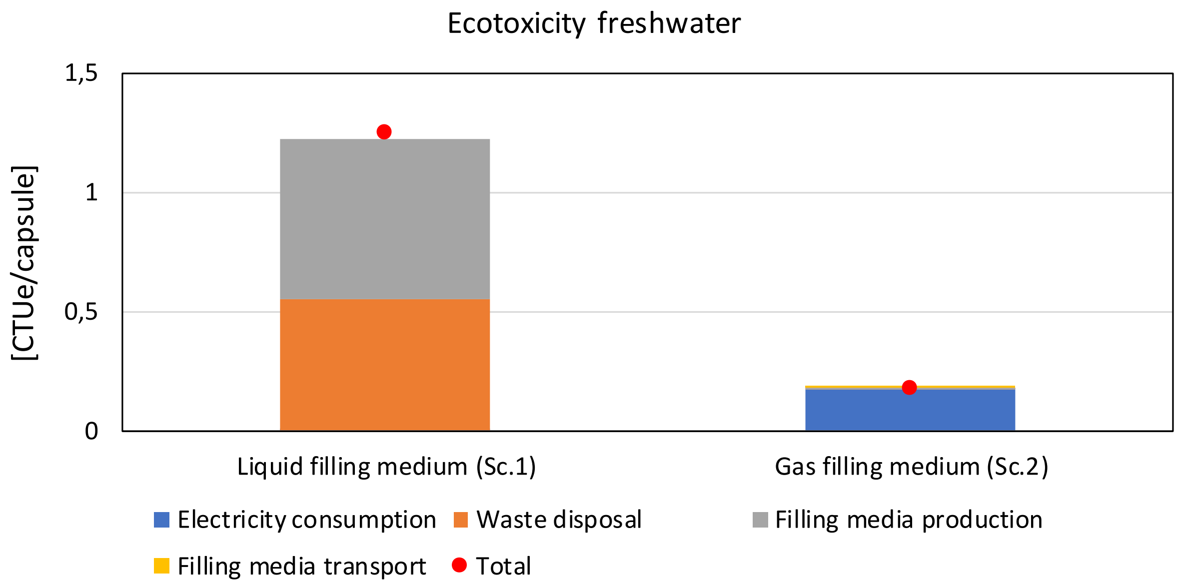

Figure 2 Characterised LCA-results for the two filling media for the impact category Ecotoxicity freshwater, including contribution of different sub-processes.

6.3. Ionising radiation, human health

Radioactive particles can be released during a number of human activities. These can be related to the nuclear fuel cycle or during more conventional energy generation such as the burning of coal. Airborne radioactive particles can be inhaled by humans, while those that end up in freshwater can be ingested during swimming, via drinking water produced from surface water or can enter the food cycle via crops. When radioactive particles decay, they release ionising radiation. Human exposure to ionising radiation causes alterations in the DNA, which in turn can lead to different types of cancer and birth defects. Similar effects must be expected in other living organisms, but damage to ecosystems is not quantified at the moment. Thus, the only area of protection covered by this category is human health.

Quantification of the ionising radiation impacts in the LCIA method EF 3.0 follows the model proposed by Frischknecht et al. (2000)[8] and is expressed in kBq U^{235} eq. (bequerel relative to U^{235} equivalent, where bequerel is the SI derived unit of radioactivity, representing the number of atom nuclei that decay per second). This category represents toxic effect on human health caused by exposure to radioactive particles. It should be pointed out that the radioactive effect is not specifically related to the two studied filling media *per se* (e.g. the two filling media emitting radioactive particles), but to all the activities modelled in the LCA study (production, transport, energy consumption, etc.).

Ionising radiation impacts for the two filling media are shown in Figure 3. The gas mixture filling medium (scenario 2) has a total impact of $1{,}5 \cdot 10^{-3}$ kBq U^{235} eq./bellow capsule, while the liquid filling medium (scenario 1) has a total impact of $2{,}3 \cdot 10^{-3}$ kBq U^{235} eq./bellow capsule, i.e. approximately twice as much.
Production of ethylacetate contributes to 124% of scenario 1 impacts, waste disposal is responsible for -30% (meaning there is a negative impact, i.e. an environmental benefit, from waste disposal of ethylacetate), and delivery of ethylacetate from the English supplier contributes with 6% only. 101% of the impacts of scenario 2 are due to the electricity consumption to maintain the gas tanks at the right temperature before utilisation, while waste disposal of the smaller amount of gas mixture contributes to the total results with only -1% (i.e. there is an environmental benefit from incineration of the gas mixture). Production of N-butane and of 1-butene are responsible for only 0,3 and 0,001% of the total impacts, while their shipping from Belgium provides only 0,1% of the total impacts.

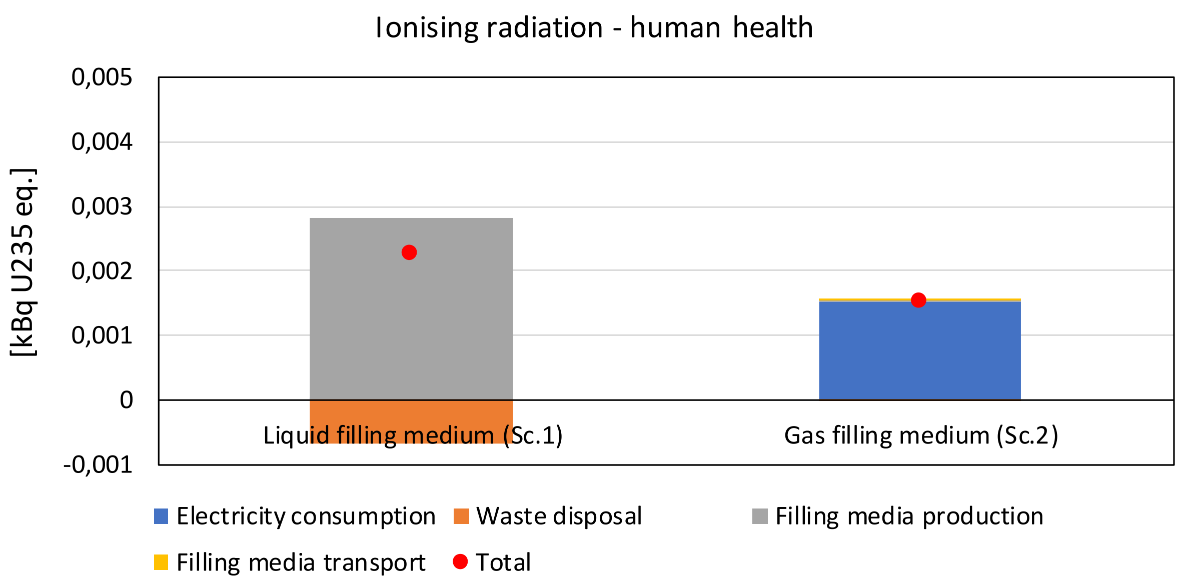

Figure 3 Characterised LCA-results for the two filling media for the impact category Ionising radiation, including contribution of different sub-processes.

[8] Frischknecht, R., Braunschweig, A., Hofstetter P., Suter P. (2000). Human health damages due to ionizing radiation in Life Cycle Impact Assessment. Environmental Impact Assessment Review, 20 (2) pp. 159-189

6.4. Resource use, energy carriers

This category represents the depletion of fossil resources. Quantification of the resource use impacts for energy carriers in the LCIA method EF 3.0 follows the reference method for abiotic resource depletion for fossil fuels (CML v. 4.8)[9] and is expressed in MJ.

Resource use, energy carriers impacts for the two filling media are shown in Figure 4. The gas mixture filling medium (scenario 2) has a total impact of 0,14 MJ/bellow capsule, while the liquid filling medium (scenario 1) has a total impact of 0,95 MJ/bellow capsule, i.e. approximately one order of magnitude higher.
Production of ethylacetate contributes to 99% of scenario 1 impacts, waste disposal is responsible for -2% (i.e. there is an environmental benefit from incineration of ethylacetate), and delivery of ethylacetate from the English supplier contributes with 3% only. 97% of the impacts of scenario 2 are due to the electricity consumption to maintain the gas tanks at the right temperature before utilisation, while waste disposal of the smaller amount of gas mixture contributes to the total results with only -1% (i.e. there is an environmental benefit from incineration of the gas mixture). Production of N-butane and of 1-butene are responsible for only 3 and 1,1% of the total impacts, while their shipping from Belgium provides only 0,3% of the total impacts.

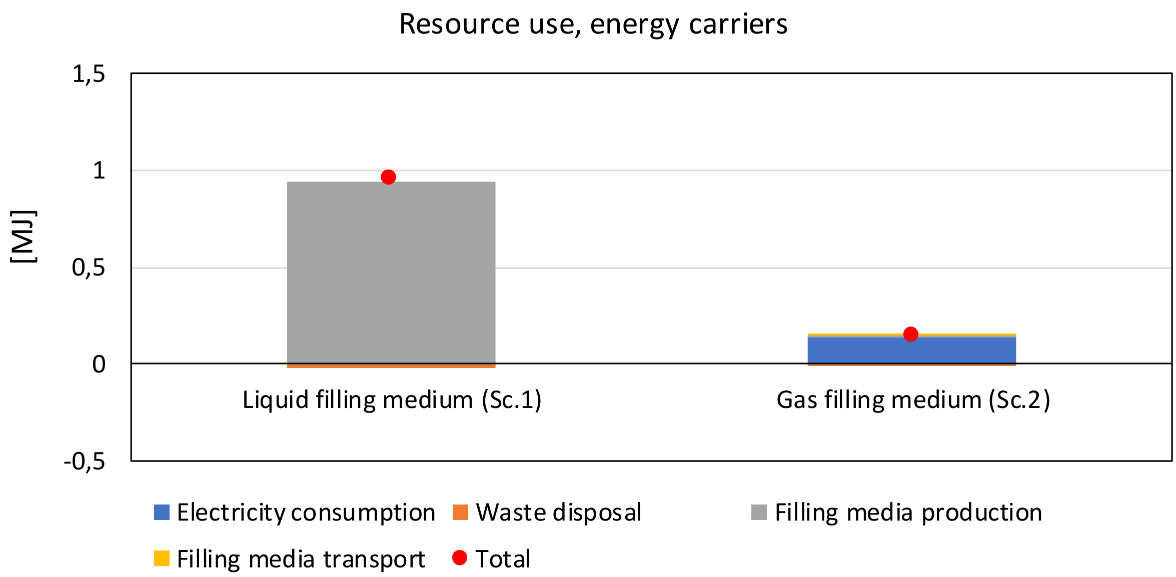

Figure 4 Characterised LCA-results for the two filling media for the impact category Resource use, energy carriers, including contribution of different sub-processes.

[9] Guinée et al., 2002: Guinée, J.B. (Ed.), Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., Van Oers, L., Wegener Sleeswijk, A., Suh, S.,. Udo de Haes, H.A, De Bruijn, J.A., Van Duin R., Huijbregts, M.A.J. (2002). Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Series: Eco-efficiency in industry and science. Kluwer Academic Publishers. Dordrecht (Hardbound, ISBN 1-4020-0228-9; Paperback, ISBN 1-4020-0557-1).
Van Oers et al., 2002: Van Oers L, de Koning A, Guinee JB, Huppes G (2002): Abiotic Resource Depletion in LCA. Road and Hydraulic Engineering Institute, Ministry of Transport and Water, Amsterdam.

6.5. Sensitivity analysis

Due to the relatively high uncertainty of the value for electricity consumption related to storage of the gas tanks at Danfoss production site (which is quantified as 65 Wh/bellow capsule but expected to be reduced to 22 Wh/bellow capsule thanks to better insulation of the storage shelter for the gas tanks), and due to the extremely high importance that this parameter has on the overall results (for the gas filling media, it contributes to at least 57% of the total impacts, depending on the individual impact category, however mostly above 95%), it is considered necessary to perform a sensitivity analysis on this critical parameter.

The first analysis investigates the effect of a higher consumption, corresponding to the previously measured value of 65 Wh/bellow capsule (i.e. no improvement with respect to the poorly insulated shed). Results are summarised in Figure 5 for the four impact categories under detailed study. While for the categories climate change, eco-toxicity freshwater, and resource use, energy carriers the ranking between the two scenarios is unchanged (the gas filling medium still performs better than the liquid one), for the category of ionising radiation the situation is now inverted: the liquid filling medium provides lower environmental impacts than the gas one. Regarding the other categories, acidification terrestrial and freshwater, climate change (biogenic), climate change (land use change), eutrophication terrestrial, land use and water scarcity also show higher impacts in scenario 2, gas filling medium, compared to scenario 1, liquid filling medium (results not shown).

A second analysis is also performed, in which the electricity consumption is assumed to be further lowered to 5 Wh/bellow capsule[10], e.g. by radically changing the storage conditions or location. This can be considered by Danfoss as a stimulus for further improvement. Results are summarised in Figure 6 for the four impact categories under detailed study. Results show that the difference between the two scenarios becomes significantly more marked, with results that are one order of magnitude lower for the gas filling medium for the category of ionising radiation, and two orders of magnitude lower for the gas filling medium for the remaining categories.

Another option, which has however not been tested in this study, could be to switch to renewable electricity sources, since impacts from electricity consumption seems to have a very significant role in the overall environmental performance of the filling medium used in Danfoss' thermostats.

[10] It should be pointed out that the value of 5 Wh/bellow capsule has been chosen merely as an example and is not based on any consideration regarding the realistic possibilities for its achievement.

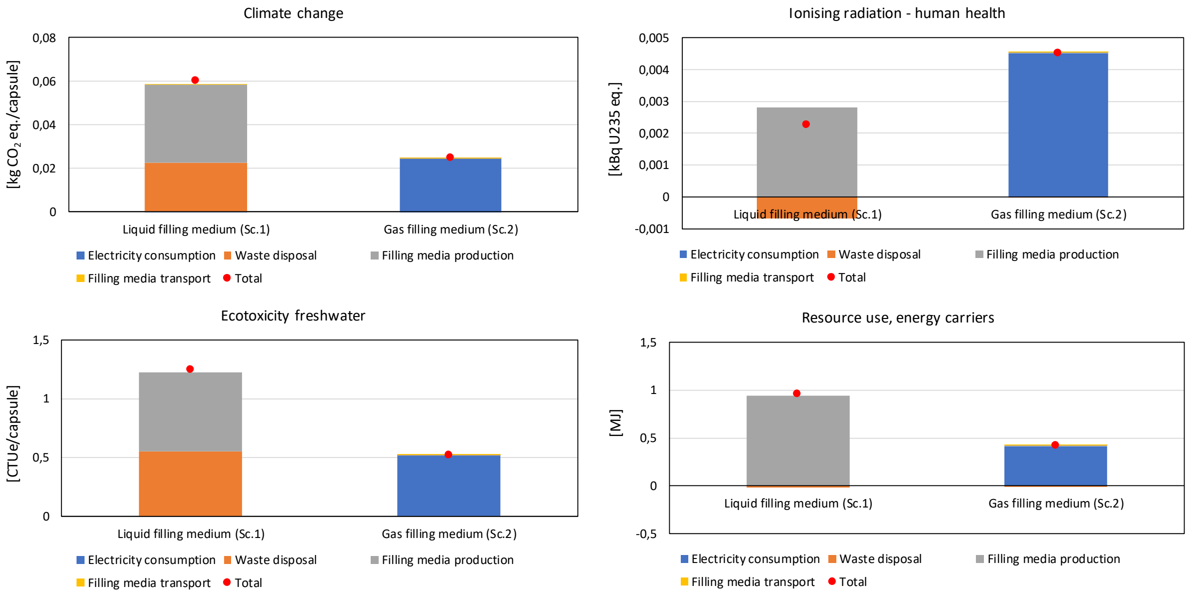

Figure 5 Characterised LCA-results for the two filling media for the four impact categories climate change, eco-toxicity freshwater, ionising radiation and resource use, energy carriers, including contribution of different sub-processes, for the sensitivity analysis scenario in which a higher energy consumption of 65 Wh/bellow capsule is assumed for the storage of the gas tanks at Danfoss.

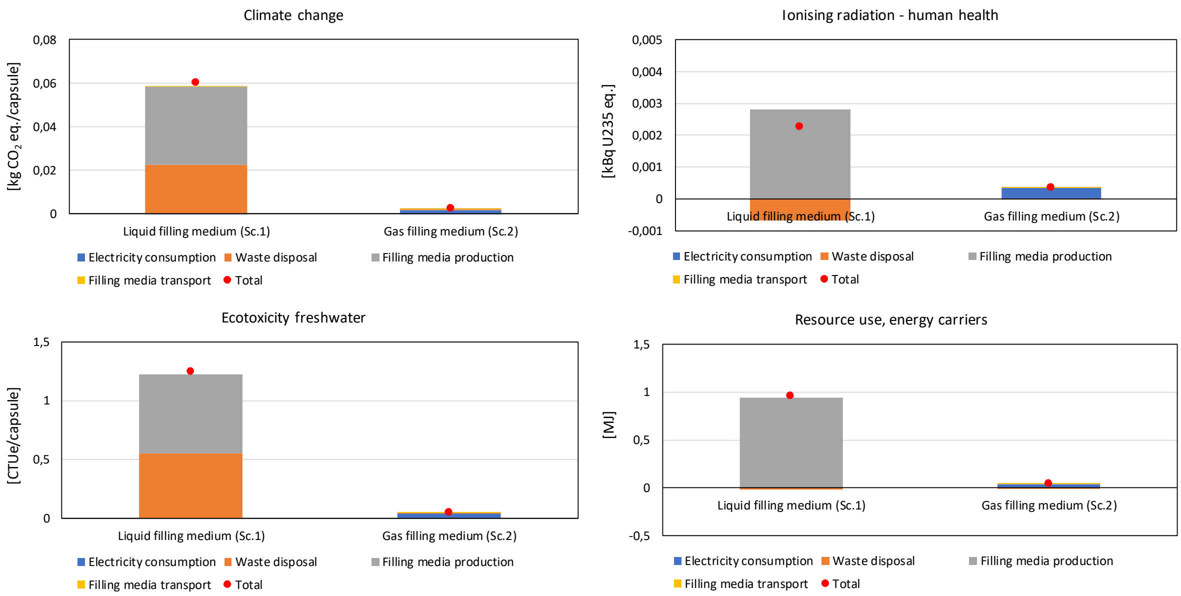

Figure 6 Characterised LCA-results for the two filling media for the four impact categories climate change, eco-toxicity freshwater, ionising radiation and resource use, energy carriers, including contribution of different sub-processes, for the sensitivity analysis scenario in which a lower energy consumption of 5 Wh/bellow capsule is assumed for the storage of the gas tanks at Danfoss.

7. Conclusion

The environmental impacts related to two alternative filling media for radiator thermostats (respectively a liquid medium, ethylacetate, and a mixture of two gases, 1-butene and N-butane) have been investigated through a life cycle assessment (LCA). The functional unit of the LCA is the manufacture, transportation, storage and disposal of a quantity of filling media corresponding to one bellow capsule.

For most of the investigated impact categories, the LCA results show that the gas-based filling medium provides consistently lower environmental impacts than the liquid one. For four impact categories, environmental impacts from the liquid filling medium are lower or equal to the ones from the gas filling medium.
A common pattern across the different impact categories can be observed also regarding the relative contribution of the single subprocesses to the overall results:

- For the liquid filling medium, the most significant contribution comes from either production of ethylacetate or from its disposal as waste, while its transportation does not provide any significant impacts.
- For the gas filling medium, energy consumption for internal storage of the gas tanks accounts for the almost entirety of environmental impacts (most often above 90%). Disposal of the gas mixture as waste provides much lower impacts, as well as production of the gases; shipping of the gases gives a negligible contribution.

Specifically regarding climate change, the gas mixture filling medium has a total impact of 8,5 g CO_2 eq./bellow capsule, while the liquid filling medium has a total impact of 60 g CO_2 eq./bellow capsule. This equals a factor 7 between the two filling media.

The results show therefore that there is a significant potential for gas filling media, however the energy consumption related to its storage is responsible for a very significant share of environmental impact. At the same time, this is a parameter that Danfoss has influence on, and that can potentially be further optimised. If the energy consumption itself cannot be further optimised, Danfoss could consider switching to renewable sources, e.g. choosing a different supplier for their electricity or installing systems for renewable energy production in-situ.

A final conclusion on the overall choice of the most environmentally friendly type of radiators thermostats cannot be based only on an analysis of the filling media. Such a conclusion needs to be supported by an LCA investigating the whole thermostat, including the materials and processes related to the bellow capsules and thermostats, the filling process and the use phase of the thermostats.

8. Appendix 1: Complete list of LCA results

Table A.1 Complete LCA results for scenario 1, Liquid filling medium.

Impact category	Unit	Total results	Electricity consumption	Waste disposal	Recovered heat	Recovered electricity	Ethylacetate production	Ethylacetate transport
Acidification terrestrial and freshwater	Mole of H+ eq.	1,23E-04	5,94E-08	1,20E-04	-1,34E-04	-4,28E-05	1,73E-04	7,44E-06
Cancer human health effects	CTUh	3,06E-11	3,97E-15	2,03E-11	-1,03E-12	-2,86E-12	1,37E-11	5,10E-13
Cancer human health effects (Metal)	CTUh	2,20E-11	2,83E-15	1,54E-11	-5,59E-13	-2,04E-12	8,92E-12	2,35E-13
Cancer human health effects (Organic)	CTUh	8,59E-12	1,14E-15	4,86E-12	-4,76E-13	-8,18E-13	4,75E-12	2,75E-13
Climate Change	kg CO2 eq.	6,01E-02	1,05E-05	3,45E-02	-4,43E-03	-7,53E-03	3,57E-02	1,77E-03
Climate Change (biogenic)	kg CO2 eq.	-2,36E-04	6,80E-08	1,18E-04	-3,52E-04	-4,90E-05	4,66E-05	5,89E-07
Climate Change (fossil)	kg CO2 eq.	6,03E-02	1,04E-05	3,44E-02	-4,07E-03	-7,47E-03	3,57E-02	1,77E-03
Climate Change (land use change)	kg CO2 eq.	1,25E-05	1,60E-08	6,59E-06	-1,94E-06	-1,16E-05	1,89E-05	4,44E-07
Ecotoxicity freshwater	CTUe	1,25E+00	2,22E-04	8,09E-01	-9,47E-02	-1,60E-01	6,72E-01	2,01E-02
Ecotoxicity freshwater (Inorganic)	CTUe	5,30E-01	1,27E-05	4,43E-01	-4,29E-03	-9,12E-03	9,54E-02	4,59E-03
Ecotoxicity freshwater (Metals)	CTUe	6,08E-01	2,09E-04	3,64E-01	-9,02E-02	-1,50E-01	4,70E-01	1,42E-02
Ecotoxicity freshwater (Organic)	CTUe	1,09E-01	5,50E-07	1,98E-03	-2,71E-04	-3,96E-04	1,06E-01	1,34E-03
Eutrophication freshwater	kg P eq.	1,92E-05	6,91E-09	1,20E-05	-1,29E-06	-4,98E-06	1,34E-05	1,39E-07
Eutrophication marine	kg N eq.	3,07E-05	8,91E-09	1,47E-05	-7,15E-06	-6,42E-06	2,73E-05	2,20E-06
Eutrophication terrestrial	Mole of N eq.	-7,22E-05	1,77E-07	2,94E-04	-5,67E-04	-1,27E-04	3,04E-04	2,42E-05
Ionising radiation	kBq U^{235} eq.	2,26E-03	1,95E-06	7,70E-04	-4,85E-05	-1,41E-03	2,80E-03	1,39E-04
Land Use	Pt	-1,13E-01	1,98E-04	4,38E-02	-1,94E-01	-1,43E-01	1,48E-01	3,12E-02
Non-cancer human health effects	CTUh	1,17E-09	1,31E-13	8,29E-10	-4,76E-11	-9,42E-11	4,63E-10	2,10E-11
Non-cancer human health effects (Inorganic)	CTUh	7,63E-10	1,13E-14	6,73E-10	-1,25E-11	-8,11E-12	1,06E-10	4,97E-12
Non-cancer human health effects (Metals)	CTUh	3,24E-10	1,16E-13	1,52E-10	-3,45E-11	-8,38E-11	2,76E-10	1,52E-11
Non-cancer human health effects (Organic)	kg CFC-11 eq.	8,39E-11	3,07E-15	4,39E-12	-5,57E-13	-2,21E-12	8,14E-11	8,63E-13

Ozone depletion	kg NMVOC eq.	8,14E-09	3,41E-13	2,68E-09	-1,66E-10	-2,46E-10	5,44E-09	4,23E-10
Photochemical ozone formation - human health	MJ	1,88E-04	2,11E-08	6,16E-05	-1,06E-05	-1,52E-05	1,44E-04	7,74E-06
Resource use, energy carriers	kg Sb eq.	9,53E-01	1,77E-04	1,72E-01	-6,11E-02	-1,27E-01	9,41E-01	2,82E-02
Resource use, mineral and metals	Disease incidences	1,73E-07	1,92E-11	2,14E-08	-8,55E-10	-1,38E-08	1,63E-07	3,28E-09
Respiratory inorganics	m³ world equiv.	1,30E-09	3,11E-13	9,92E-10	-9,20E-10	-2,24E-10	1,29E-09	1,59E-10
Water scarcity	kg CFC-11 eq.	1,30E-02	1,68E-05	5,04E-03	-4,27E-03	-1,21E-02	2,41E-02	2,40E-04

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Table A.2 Complete LCA results for scenario 2, Gas filling medium.

Impact category	Unit	Total results	Electricity consumption	Waste disposal	Recovered heat	Recovered electricity	N-butane production	1-butene production	N-butane transport	1-butene transport
Acidification terrestrial and freshwater	Mole of H+ eq.	4,52E-05	4,67E-05	1,20E-06	-2,62E-06	-8,25E-07	5,01E-07	1,22E-07	8,97E-08	2,24E-08
Cancer human health effects	CTUh	3,30E-12	3,12E-12	2,03E-13	-2,02E-14	-5,51E-14	3,78E-14	1,92E-15	8,16E-15	2,04E-15
Cancer human health effects (Metal)	CTUh	2,35E-12	2,23E-12	1,54E-13	-1,09E-14	-3,94E-14	1,68E-14	1,87E-15	3,56E-15	8,90E-16
Cancer human health effects (Organic)	CTUh	9,43E-13	8,93E-13	4,86E-14	-9,28E-15	-1,58E-14	2,10E-14	5,18E-17	4,60E-15	1,15E-15
Climate Change	kg CO2 eq.	8,50E-03	8,22E-03	3,45E-04	-8,63E-05	-1,45E-04	9,09E-05	4,44E-05	2,23E-05	5,58E-06
Climate Change (biogenic)	kg CO2 eq.	4,69E-05	5,34E-05	1,18E-06	-6,87E-06	-9,44E-07	8,49E-08	5,65E-08	7,42E-09	1,85E-09
Climate Change (fossil)	kg CO2 eq.	8,44E-03	8,15E-03	3,44E-04	-7,94E-05	-1,44E-04	9,08E-05	4,43E-05	2,23E-05	5,58E-06
Climate Change (land use change)	kg CO2 eq.	1,25E-05	1,26E-05	6,59E-08	-3,78E-08	-2,23E-07	4,75E-08	5,38E-11	7,85E-09	1,96E-09
Ecotoxicity freshwater	CTUe	1,81E-01	1,74E-01	8,09E-03	-1,85E-03	-3,08E-03	3,20E-03	1,98E-05	2,50E-04	6,24E-05
Ecotoxicity freshwater (Inorganic)	CTUe	1,53E-02	9,95E-03	4,43E-03	-8,37E-05	-1,76E-04	1,13E-03	3,05E-06	5,47E-05	1,37E-05
Ecotoxicity freshwater (Metals)	CTUe	1,65E-01	1,64E-01	3,64E-03	-1,76E-03	-2,90E-03	2,06E-03	1,51E-05	1,79E-04	4,49E-05
Ecotoxicity freshwater (Organic)	CTUe	4,73E-04	4,33E-04	1,98E-05	-5,28E-06	-7,65E-06	1,19E-05	1,66E-06	1,56E-05	3,91E-06
Eutrophication freshwater	kg P eq.	5,45E-06	5,43E-06	1,20E-07	-2,51E-08	-9,60E-08	2,02E-08	3,41E-10	2,04E-09	5,11E-10
Eutrophication marine	kg N eq.	7,01E-06	7,00E-06	1,47E-07	-1,39E-07	-1,24E-07	7,88E-08	2,19E-08	2,53E-08	6,33E-09
Eutrophication terrestrial	Mole of N eq.	1,30E-04	1,39E-04	2,94E-06	-1,11E-05	-2,45E-06	8,49E-07	2,39E-07	2,79E-07	6,98E-08
Ionising radiation	kBq U^{235} eq.	1,52E-03	1,53E-03	7,70E-06	-9,46E-07	-2,71E-05	4,59E-06	1,14E-08	1,62E-06	4,05E-07
Land Use	Pt	1,50E-01	1,55E-01	4,38E-04	-3,78E-03	-2,75E-03	2,66E-04	1,28E-06	1,93E-04	4,83E-05
Non-cancer human health effects	CTUh	1,10E-10	1,03E-10	8,29E-12	-9,28E-13	-1,82E-12	1,05E-12	9,99E-14	2,52E-13	6,31E-14
Non-cancer human health effects (Inorganic)	CTUh	1,56E-11	8,85E-12	6,73E-12	-2,45E-13	-1,56E-13	2,90E-13	6,15E-14	6,33E-14	1,58E-14
Non-cancer human health effects (Metals)	CTUh	9,16E-11	9,15E-11	1,52E-12	-6,73E-13	-1,62E-12	7,04E-13	1,70E-14	1,78E-13	4,45E-14
Non-cancer human health effects (Organic)	kg CFC-11 eq.	2,49E-12	2,41E-12	4,39E-14	-1,09E-14	-4,27E-14	5,08E-14	2,14E-14	1,12E-14	2,80E-15
Ozone depletion	kg NMVOC eq.	3,22E-10	2,68E-10	2,68E-11	-3,24E-12	-4,74E-12	2,91E-11	2,73E-14	4,96E-12	1,24E-12

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Photochemical ozone formation - human health	MJ	1,73E-05	1,66E-05	6,16E-07	-2,08E-07	-2,93E-07	3,43E-07	1,17E-07	8,49E-08	2,12E-08
Resource use, energy carriers	kg Sb eq.	1,44E-01	1,39E-01	1,72E-03	-1,19E-03	-2,46E-03	4,45E-03	1,60E-03	3,37E-04	8,44E-05
Resource use, mineral and metals	Disease inci-dences	1,51E-08	1,51E-08	2,14E-10	-1,67E-11	-2,66E-10	3,35E-11	5,54E-13	8,79E-11	2,20E-11
Respiratory inorganics	m³ world equiv.	2,39E-10	2,44E-10	9,92E-12	-1,79E-11	-4,32E-12	4,00E-12	1,26E-12	1,38E-12	3,44E-13
Water scarcity	kg CFC-11 eq.	1,30E-02	1,32E-02	5,04E-05	-8,33E-05	-2,34E-04	1,10E-05	1,73E-05	2,68E-06	6,69E-07

Table A.3 Complete LCA results for scenarios 1 and 2, sensitivity analysis assuming higher electricity consumption for storage of gas tanks (65 Wh/bellow capsule).

		Liquid filling medium	Gas filling medium	
Impact category	Unit	Total results	Total results	Electricity consumption
Acidification terrestrial and freshwater	Mole of H+ eq.	1,23E-04	1,36E-04	1,38E-04
Cancer human health effects	CTUh	3,06E-11	9,40E-12	9,22E-12
Cancer human health effects (Metal)	CTUh	2,20E-11	6,72E-12	6,59E-12
Cancer human health effects (Organic)	CTUh	8,59E-12	2,69E-12	2,64E-12
Climate Change	kg CO2 eq.	6,01E-02	2,46E-02	2,43E-02
Climate Change (biogenic)	kg CO2 eq.	-2,36E-04	1,51E-04	1,58E-04
Climate Change (fossil)	kg CO2 eq.	6,03E-02	2,44E-02	2,41E-02
Climate Change (land use change)	kg CO2 eq.	1,25E-05	3,71E-05	3,72E-05
Ecotoxicity freshwater	CTUe	1,25E+00	5,21E-01	5,14E-01
Ecotoxicity freshwater (Inorganic)	CTUe	5,30E-01	3,48E-02	2,94E-02
Ecotoxicity freshwater (Metals)	CTUe	6,08E-01	4,86E-01	4,85E-01
Ecotoxicity freshwater (Organic)	CTUe	1,09E-01	1,32E-03	1,28E-03
Eutrophication freshwater	kg P eq.	1,92E-05	1,61E-05	1,60E-05
Eutrophication marine	kg N eq.	3,07E-05	2,07E-05	2,07E-05
Eutrophication terrestrial	Mole of N eq.	-7,22E-05	4,02E-04	4,11E-04
Ionising radiation	kBq U^{235} eq.	2,26E-03	4,51E-03	4,52E-03
Land Use	Pt	-1,13E-01	4,52E-01	4,58E-01
Non-cancer human health effects	CTUh	1,17E-09	3,11E-10	3,04E-10
Non-cancer human health effects (Inorganic)	CTUh	7,63E-10	3,29E-11	2,61E-11
Non-cancer human health effects (Metals)	CTUh	3,24E-10	2,71E-10	2,70E-10
Non-cancer human health effects (Organic)	kg CFC-11 eq.	8,39E-11	7,20E-12	7,12E-12
Ozone depletion	kg NMVOC eq.	8,14E-09	8,46E-10	7,92E-10
Photochemical ozone formation - human health	MJ	1,88E-04	4,97E-05	4,90E-05
Resource use, energy carriers	kg Sb eq.	9,53E-01	4,15E-01	4,11E-01
Resource use, mineral and metals	Disease incidences	1,73E-07	4,47E-08	4,46E-08
Respiratory inorganics	m^3 world equiv.	1,30E-09	7,16E-10	7,21E-10
Water scarcity	kg CFC-11 eq.	1,30E-02	3,88E-02	3,90E-02

Table A.4 Complete LCA results for scenarios 1 and 2, sensitivity analysis assuming lower electricity consumption for storage of gas tanks (5 Wh/bellow capsule).

Impact category	Unit	Liquid filling medium	Gas filling medium	
		Total results	Total results	Electricity consumption
Acidification terrestrial and freshwater	Mole of H+ eq.	1,23E-04	9,10E-06	1,06E-05
Cancer human health effects	CTUh	3,06E-11	8,87E-13	7,09E-13
Cancer human health effects (Metal)	CTUh	2,20E-11	6,34E-13	5,07E-13
Cancer human health effects (Organic)	CTUh	8,59E-12	2,53E-13	2,03E-13
Climate Change	kg CO2 eq.	6,01E-02	2,15E-03	1,87E-03
Climate Change (biogenic)	kg CO2 eq.	-2,36E-04	5,65E-06	1,21E-05
Climate Change (fossil)	kg CO2 eq.	6,03E-02	2,14E-03	1,85E-03
Climate Change (land use change)	kg CO2 eq.	1,25E-05	2,73E-06	2,86E-06
Ecotoxicity freshwater	CTUe	1,25E+00	4,62E-02	3,95E-02
Ecotoxicity freshwater (Inorganic)	CTUe	5,30E-01	7,63E-03	2,26E-03
Ecotoxicity freshwater (Metals)	CTUe	6,08E-01	3,86E-02	3,73E-02
Ecotoxicity freshwater (Organic)	CTUe	1,09E-01	1,38E-04	9,84E-05
Eutrophication freshwater	kg P eq.	1,92E-05	1,26E-06	1,23E-06
Eutrophication marine	kg N eq.	3,07E-05	1,61E-06	1,59E-06
Eutrophication terrestrial	Mole of N eq.	-7,22E-05	2,24E-05	3,16E-05
Ionising radiation	kBq U^{235} eq.	2,26E-03	3,34E-04	3,48E-04
Land Use	Pt	-1,13E-01	2,96E-02	3,52E-02
Non-cancer human health effects	CTUh	1,17E-09	3,04E-11	2,34E-11
Non-cancer human health effects (Inorganic)	CTUh	7,63E-10	8,77E-12	2,01E-12
Non-cancer human health effects (Metals)	CTUh	3,24E-10	2,10E-11	2,08E-11
Non-cancer human health effects (Organic)	kg CFC-11 eq.	8,39E-11	6,24E-13	5,48E-13
Ozone depletion	kg NMVOC eq.	8,14E-09	1,15E-10	6,09E-11
Photochemical ozone formation - human health	MJ	1,88E-04	4,45E-06	3,77E-06
Resource use, energy carriers	kg Sb eq.	9,53E-01	3,61E-02	3,16E-02
Resource use, mineral and metals	Disease incidences	1,73E-07	3,51E-09	3,43E-09
Respiratory inorganics	m^3 world equiv.	1,30E-09	5,01E-11	5,55E-11
Water scarcity	kg CFC-11 eq.	1,30E-02	2,76E-03	3,00E-03

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9. Appendix 2: Steps in Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment (LCIA) phase consists of four consecutive steps.

1. *Classification*. All substances emitted or consumed during the modelled process are sorted into classes according to the effect they have on the environment. A cause-effect pathway shows the causal relationship between the environmental intervention (for instance, the emission of carbon dioxide, CO_2, or methane, CH_4) and its potential effects (in this case climate change). Substances can have an effect on only one or on multiple environmental impact(s). E.g. methane has an effect on both Climate change, Ecotoxicity freshwater, Human toxicity non-cancer effects, and Photochemical ozone formation - human health. Carbon dioxide has an effect on only Climate change.

2. *Characterisation*. All substances are multiplied by a factor (called characterisation factor, CF) which reflects their relative contribution to the environmental impact, quantifying how much impact a product or service has in each impact category. For example, carbon dioxide, CO_2 has a characterisation factor for climate change equal to 1, while methane, CH_4, has a characterisation factor for climate change equal to 36,8; dinitrogen monoxide, N_2O, has on the other hand a characterisation factor for climate change equal to 298. This means an emission of 1 kg CH_4 has the same impact on climate change as emission of 36,8 kg CO_2, and an emission of 1 kg N_2O has the same impact on climate change as emission of 298 kg CO_2. Characterised results are expressed in different units for each individual impact category (e.g. kg CO_2 eq., MJ, …) and cannot be compared with each other, but they can be compared across different scenarios.

3. *Normalisation*. The quantified impact (i.e. characterised impact) is divided by a certain reference value (called normalisation factor, NF), representing the average environmental impact of a European/world citizen in one year. For the Environmental Footprint (EF) 3.0 method, due to the international nature of supply chains, the use of global normalisation factors is recommended as opposed to EU-based normalisation factors.
By dividing the characterised impact (e.g. 16,08 t CO_2 eq. for climate change) by the NF for climate change (8,04 t CO_2 eq./PE), a number of person equivalents (PE) can be obtained (in this case 2 PE, meaning that the studied functional unit has an impact on climate change equivalent to the impact of 2 world citizens in 1 year). Normalisation gives the impact potentials for the different impact categories in a common scale, and thus allows comparison across impact categories. According to ISO 14044, normalisation is an optional step of LCIA.

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Table 3 Global normalisation factors (NF) for Environmental Footprint (EF) 3.0 LCIA method. The global NF represents the average environmental impact of a world citizen in one year (called person equivalent, PE) for each impact category (e.g. the average world citizen is responsible for 8,04 t CO_2 eq./PE). Source: EU Commission, https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml.

Impact category	Unit	Global NF, per capita
Acidification	mol H+ eq	5,56E+01
Climate change	kg CO2 eq	8,04E+03
Ecotoxicity, freshwater	CTUe	4,27E+04
Eutrophication, freshwater	kg P eq	1,61E+00
Eutrophication, marine	kg N eq	1,95E+01
Eutrophication, terrestrial	mol N eq	1,77E+02
Human toxicity, cancer	CTUh	1,86E-05
Human toxicity, non-cancer	CTUh	2,30E-04
Ionising radiation	kBq U^{235} eq	1,38E+02
Land use	pt	2,23E+06
Ozone depletion	kg CFC-11 eq	4,84E-02
Particulate matter	disease incidences	5,95E-04
Photochemical ozone formation - human health	kg NMVOC eq	4,07E+01
Resource use, fossils	MJ	6,50E+04
Resource use, minerals and metals	kg Sb eq	6,36E-02
Water use	m3 water eq of deprived water	1,15E+04

4. *Weighting*. Each impact category is assigned an importance value, and the resulting figures are used to generate a single score. According to ISO 14044, weighting is an optional step of LCIA.
Any weighting scheme is a subjective set of value, which inherently involves value choices that will depend on policy, cultural and other preferences and value systems. However, weighting can be essential to improve the practical utility of environmental assessments in complex decision situations.

Table 4 Weighting factors (WF) for Environmental Footprint (EF) 3.0 LCIA method. Source: Sala S, Cerutti AK, Pant R. (2018). Development of a weighting approach for Environmental Footprint. European Commission, Joint Research Centre, Publication Office of the European Union, Luxembourg. ISBN 978-92-79-68041-0.

Impact category	Weighting factors
Acidification	6,20
Climate change	21,06
Ecotoxicity, freshwater	1,92
Eutrophication, freshwater	2,80
Eutrophication, marine	2,96
Eutrophication, terrestrial	3,71
Human toxicity, cancer	2,13
Human toxicity, non-cancer	1,84
Ionising radiation	5,01
Land use	7,94
Ozone depletion	6,31
Particulate matter	8,96
Photochemical ozone formation - human health	4,78
Resource use, fossils	8,32
Resource use, minerals and metals	7,55
Water use	8,51