Retrofitting Equipment for Efficient Use of Variable Feedstock in Metal Making Processes - REVaMP

H2020-NMBP-ST-IND-2018-2020 / H2020-NMBP-SPIRE-2019

Grant agreement no. 869882

Start Date:	January 1st, 2020
Duration:	48 months
Project Type:	Innovation Action

LCA for assessment of impact reduction (energy & resource efficiency, GHG emissions) for the different demonstration cases

Due Date:	November, 30th, 2023
Submission Date:	January 31st, 2024
Work Package:	**WP 8 – Evaluation of retrofitting solutions at industrial scale**
Lead Beneficiary:	**RWTH AACHEN**

Authors:

Partner	Name
BFI	Bernd Kleimt
SIDENOR I+D	Diana Mier Vasallo, Raquel Arias
EURECAT	Manel da Silva López
GRUPAL ART	Tomas Baldi, Francesc Peregrín
RWTH AACHEN	Felix Kaiser, Tim Reichel, Thomas Echterhof
EXIDE	Nuria Jimeno
Fraunhofer ILT	Cord Fricke-Begemann
AMB	Jan Bartel
REF	Represented by INATEC
INATEC	Greta Minelgaite, Noelia Montes
AZT	Clara Delgado, Lucia Unamunzaga, Erika Garitaonandia
CAR	Clemente Cardenas

Dissemination level

PU public ☒

CO Confidential, only for members of the consortium (incl. the Commission Services) ☐

Table of Contents

1. About REVaMP

The main objective of the project “Retrofitting Equipment for Efficient Use of Variable Feedstock in Metal Making Processes” (REVaMP) is to develop, adapt and apply innovative retrofitting technologies to cope with the increasing variability of scrap and to ensure an efficient use of the feedstock in terms of materials and energy.

For this purpose, existing metal production plants shall be retrofitted with appropriate sensors for scrap analysis and furnace operation. Furthermore, the selection of the optimal feedstock in terms of material and energy efficiency shall be improved by application of appropriate process control and decision support tools. Also, a solid scrap preheating system operated with waste derived fuel shall increase the energy efficiency of the melting processes. To monitor and control the process behaviour in an optimal way, model-based software tools will be developed and applied.

The retrofitting solutions will be exemplarily demonstrated within three different use cases from the metal making industry: electric and oxygen steelmaking, aluminium refining and lead recycling. The performance of the different technologies will be assessed, and the benefits will be evaluated in terms of economic and ecological effects, as well as cross-sectorial applicability in other process industries.

2. Introduction and Summary

This deliverable D 8.3, “LCA for assessment of impact reduction (energy & resource efficiency, GHG emissions) for the different demonstration cases”, is included in work package 8 “Evaluation of retrofitting solutions at industrial scale” of the REVaMP project.

This task is aimed at the evaluation of the environmental benefits gained by the integration of the several retrofitting solutions in the industrial processes, validated in the different use cases in WP5, WP6 and WP7. In special, fulfilment of the Topic impact reduction targets regarding GHG, fossil fuels, fossil resources, energy and resource efficiency are assessed for all use cases in steelmaking, aluminium refining and secondary lead production, by means of estimating changes in the scores of a set of selected environmental impact indicators, versus the values they reach in the baseline scenarios (environmental performance of said processes before implementing any retrofitting action). The evaluation is conducted following the approach of a life cycle assessment (LCA), which is defined by international norms ISO 14040 and 14044. The structure of the report is therefore based on the four phases of a life cycle assessment, which are shown schematically in Figure 1:

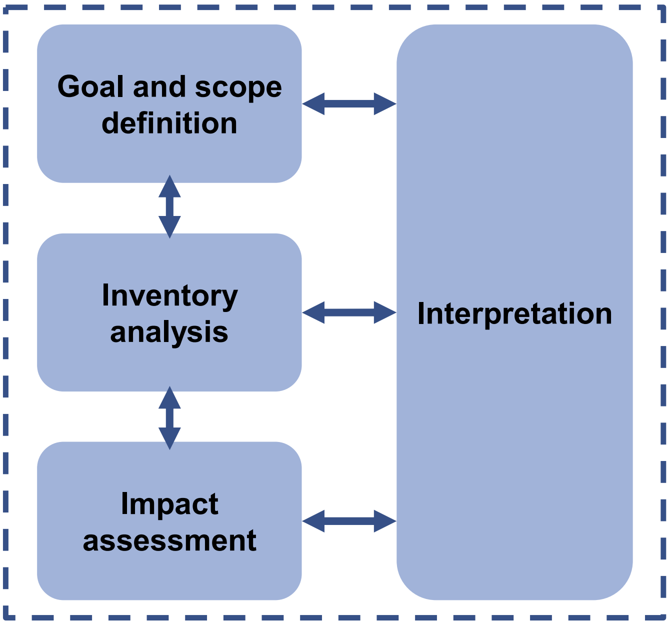


Figure 1 – Phases in the creation of a life cycle assessment in this project

Two REVaMP project beneficiaries have been in charge of performing the LCAs of the four retrofitting demo cases:

- RWTH for the use cases of steel at SIDENOR, aluminium at GRUPAL Art and lead at EXIDE;
- Azterlan for the aluminium use case at Refial.

The application of the LCA in REVaMP has consisted of four steps. First the goal and scope as well as temporal and geographical system boundaries regarding the different use cases was defined together with a functional unit (FU). This was followed by an inventory analysis where all relevant material and energy flows within the production system were identified. A material flow model was built, including data collection and allocation, calculation of material flows concerning the FU, calculation of emission and other relevant parameters. Within the impact assessment a calculation of environmental impacts was carried out. During the final phase of interpretation, the evaluation and verification of system boundaries and material flows were finalised. The LCA results have been documented, including all assumptions, action steps and visualizations (e.g. through Sankey diagrams) of the relevant results.

In the three use cases analysed by RWTH, a reduction of resource and energy use was generally achieved for the steel and aluminium production processes. These savings lead also to a favourable environmental impact assessment of the retrofitted processes compared to the respective base cases. For the lead use case, an increase in material usage was recorded, while simultaneously some parts of the energy consumption were reduced. This however led to an overall unfavourable environmental assessment of the retrofitted case compared with the base case.

The retrofitting approach followed for the REFIAL use case has differed from the other three use cases. In this case the focus has not been on optimising the process through the optimisation of the scrap feedstock by using sensor technologies and charge mix optimisation tools, but on optimising energy efficiency and reducing fossil fuel consumption in the aluminium refining process in a tilting rotary furnace (for a selected scrap mix), through implementation of a scrap pre-heating step. For the scrap pre-heating it was proposed a heat exchanger using heat from the combustion of a Waste Derived Fuel (WDF) prepared from Automotive Shredder Residue (ASR). Thus, as extensively described in Deliverable D2.3, the improvement of the melting process in the rotary furnace was sought in terms of reduced melting time and gas consumption, while equal (or improved) aluminium alloy quality and metal yield were secured and holistic environmental gains (regarding decreased utilisation of fossil resources, total GHG emissions and final waste for disposal) were achieved.

Another difference with the other three use cases in REVaMP project is that the REFIAL use case has been developed at two levels:

- industrial scale design
- validation at pilot scale in a small rotary furnace at REFIAL

As with the other demonstration cases, the environmental viability of the proposed retrofitting solution at REFIAL has been evaluated by performing a comparative LCA. The specificities of this use case are conveniently highlighted and discussed in the following sections of the report.

3. Phase 1 – Definition of goal and scope

In order to perform the following calculations, the goal and scope of the study have to be defined in the beginning. These definitions shall be consistent within the intended application and may change over the course of the LCA due to its iterative nature. In the following, the essential details of the Goal and Scope definition for the three use cases Sidenor (steel), Grupal Art (aluminium) and Exide (lead) are described. Differences or industry-specific characteristics are pointed out separately.

For the RWTH use cases, the presented contents in this chapter have been mostly covered in deliverable 1.4 already. The focus for the RWTH parts here will therefore be on the main points and any updated definitions.

For the Refial use case, the necessary definitions are given in order to conform to the norms ISO 14040 and 14044, although some of these may be identical to RWTH use cases.

3.1. Goal definition

The goal definition has been aggregated and now reflects the definitions for all use cases covered in this report. The definitions are given below.

Definition of the target

The aim of the LCA studies is to compare the environmental impact of different process routes in the respective plants of the partners. The analyses are carried out for one plant per considered branch of the steel, aluminium and lead industry. For this purpose, the current state of the art is to be compared with an alternative use case in which the innovative aspects of REVaMP are implemented: installation of a scrap analysis sensor, comparison of different feedstocks, analysis and mapping of upstream processes, evaluation of recycling rates and other plant-specific applications of further optimisation tools. The associated resource consumptions and emissions and their environmental effects will be investigated in this comparative study. Additionally, for the aluminium industry, a separate retrofitting alternative, consisting in the integration of a scrap pre-heating step based on WDF combustion is compared.

Intended application

The present LCA studies deal with the production of crude steel, secondary aluminium and lead through scrap recycling. The examined plants belong to the Spanish companies Sidenor (steel), Grupal Art (aluminium), Refial (aluminium) and Exide (lead). The product systems are to be investigated using a cradle-to-gate approach. Therefore, the analyses are carried out up to the final raw product, which means that the melting process and all upstream processes are considered. For the steel use case this includes all relevant process steps from scrap yard to EAF tapping. The aluminium use case at Grupal Art (GRU) considers the process steps chips reception and handing, separation of iron particles, cleaning process and melting to produce new ingots. The aluminium use case at Refial (REF) comprises the aluminium refining by melting a defined mix of post-consumer scrap categories and the end-of-life ASR, either as waste disposal or as recovery in WDF. And finally, the lead use case includes the following process steps: battery breaking and separation of the components, smelting and refining.

Reasons for execution

The LCA studies will be carried out to evaluate the use of the following retrofitting solutions:

- Installation of a scrap pre-heating equipment fuelled by WDF (REFIAL case only)
- installation of a scrap analysis sensor
- comparison of different feedstocks
- analysis and mapping of upstream processes
- evaluation of recycling rates
- other plant-specific applications of further optimisation tools

This should improve the productivity and yield of the processes. While the focus of the main research work is on a purely technical evaluation, these studies will provide an ecological assessment.

Intended audience

The studies are part of an international research project. The LCA thus serve to inform the European Commission, the responsible research institutions, the participating industrial partners (especially their plant operators, technical team and R&D Department), their customers, stakeholders and shareholders as well as other interested groups from science, industry and politics.

Reporting of the results

Within the LCA studies, comparative statements will be made. The current state of the art processes will be compared with the processes after the retrofitting solutions like comparison of different feedstocks, analysis and mapping of upstream processes, evaluation of recycling rates, installation of a scrap analysis sensor and other plant-specific applications of further optimisation tools.

3.2. Scope Definition (RWTH use cases)

For RWTH use cases, the product systems to be analysed have also remained the same since the initial definition. For all use cases, a cradle-to-gate approach is used to model the processes being conducted on the production sites of each industrial partner. The upstream processes are included by means of system expansion. For the aluminium recycling use case, alloying materials have been added to the list of input materials. The details are explained in deliverable 6.5 and also later in this report in phase 2. The impact assessment methodology used is the ReCiPe-Midpoint Method combined with data from the ecoinvent® database. The modelling software used is Umberto® LCA+. The results are presented in this reported according to the international standards ISO 14040 and ISO 14044.

3.3. Scope Definition (energy feedstock use case at Refial)

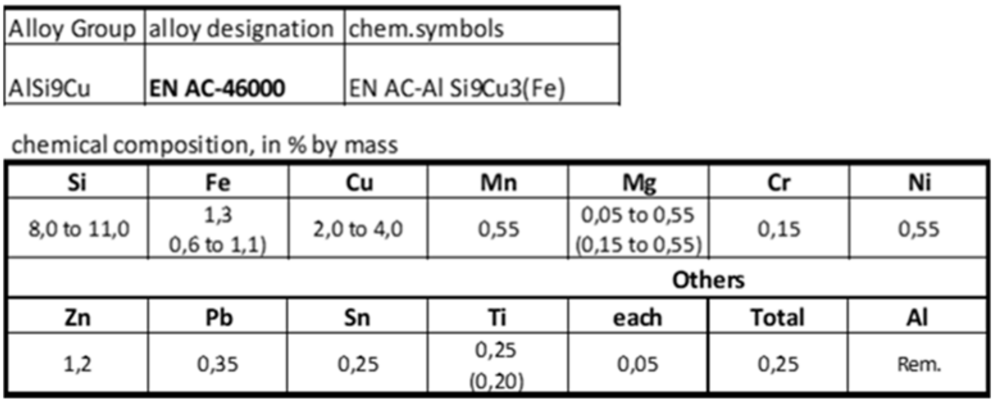
For the Refial use case, the scope of the LCA is defined in the following according to the requirements of ISO 14040 and 14044. Some contents may be similar to the RWTH use cases, but are stated here again in order for this report to conform to the norms.

Product system

The main system to be studied in the REF use case is the production of (secondary) aluminium casting alloy EN AC-46000 (see *Table 1*) by refining post-consumer scrap in a pilot tilting rotary furnace with a natural gas burner, using a mix of three scrap types (B, E, H) in a mass ratio

3:1:6 within the scrap mix and cryolite as salt flux, in a proportion of 0.450 kg of cryolite for every 10 kg of scrap charged, per heat.

Table 1 – Chemical composition of the target secondary casting alloy EN AC-46000 in REF use case (source: Standard UNE-EN 1706:2020+A1:2022)



Alloy Group	alloy designation	chem.symbols
AlSi9Cu	**EN AC-46000**	EN AC-Al Si9Cu3(Fe)

chemical composition, in % by mass

Si	Fe	Cu	Mn	Mg	Cr	Ni
8,0 to 11,0	1,3 0,6 to 1,1)	2,0 to 4,0	0,55	0,05 to 0,55 (0,15 to 0,55)	0,15	0,55
				Others		
Zn	**Pb**	**Sn**	**Ti**	**each**	**Total**	**Al**
1,2	0,35	0,25	0,25 (0,20)	0,05	0,25	Rem.

REFIAL uses the results obtained in the heats at the pilot furnace as a basis for upscaling to the refining process with fluxes in their smart industrial tilting rotary furnace with oxy-fuel burners (natural gas + air enriched with oxygen). The scrap mix to be charged for melting is defined so as to obtain a chemical composition of the secondary alloy produced in the rotary furnace as close as possible to the composition of the target alloy (EN-AC 46000 in REVaMP). Any corrections, by addition of iron, copper and silicon alloying additives are made in a later step, in a holding furnace. Once the composition of the liquid alloy is within limits, the ingots are casted. The flowchart of the system product at industrial scale is shown in Figure 2, including as grey boxes the later steps of alloy adjusting and ingot casting.

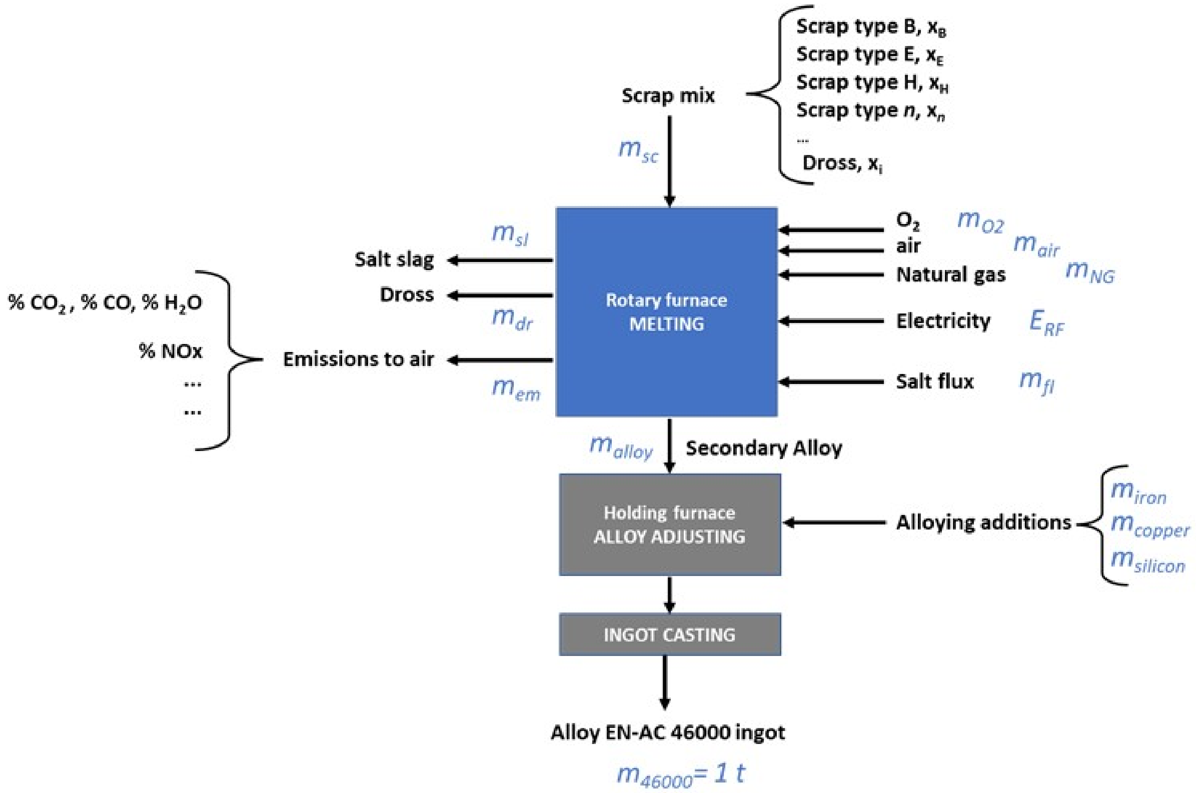


Figure 2 – Flowchart of the aluminium refining process into alloy EN-AC 46000 at industrial scale in REF use case

Since the retrofitting proposal in this industrial use case is based on the use of a waste derived fuel to pre-heat the scrap to be refined in the rotary furnace, another product system to which the flows are traced should also be incorporated somehow in the study: the processing of the heavy fraction (SHF) of automotive shredder residue (ASR). The process flow diagrams showing all the unit processes concerned and their inter-relationships are depicted next, in the description of the system boundaries.

Functions of the product system

The function of the product system is the production of aluminium alloys from scrap and additional resources.

Functional unit

The functional unit, on which all further calculations are based on, is one tonne of aluminium alloys, which are the final products of the analysed system.

System boundary

For assessing REF use case it is proposed a consequential cradle-to-gate LCA, which means that, apart from the unit processes included in the production of the secondary aluminium alloy at plant, the upstream production and supply of raw materials, auxiliaries, intermediate products and energy is also considered.

In the production life cycle stage, the material flows of a subsequent step to the refining of the scrap into the secondary alloy, representing the alloying needs to adjust the composition of the secondary alloy obtained in the rotary furnace within the limits established for EN AC-46000 alloys, is included in the system to be evaluated. This is done to consider the environmental implications of the quality of the secondary alloy produced in the melting step of the selected scrap mix.

Slag formed in the pilot rotary furnace is considered dross by REFIAL. It is a by-product recycled at the refinery, to recover aluminium and other metals (feedstock to the industrial rotary furnace). INATEC estimate 0.4 kg final residue/kg dross recycled. Dross-salt slag recycling process at REFIAL has not been included in the product system at pilot scale. Only the mass of the final residue (40% of dross mass) disposed of in landfill is considered. Metal yield of the scrap melting in the pilot rotary furnace has been adjusted to include the aluminium content in the dross.

In order to address the supply of energy from combustion of WDF in the retrofitted product system, the system boundaries have been expanded to include the operations at the end-of-life of a waste produced in another product system (ASR heavy fraction: SHF). Thus, two evaluation scenarios have been defined for comparing the environmental performance of the refining of scrap in REF use case, before and after retrofitting:

- Baseline scenario: the current scenario of aluminium refining and ASR disposal
    - REVaMPed scenario: retrofitted refining process, using the ASR to prepare a WDF for the combustion chamber of a scrap pre-heater.

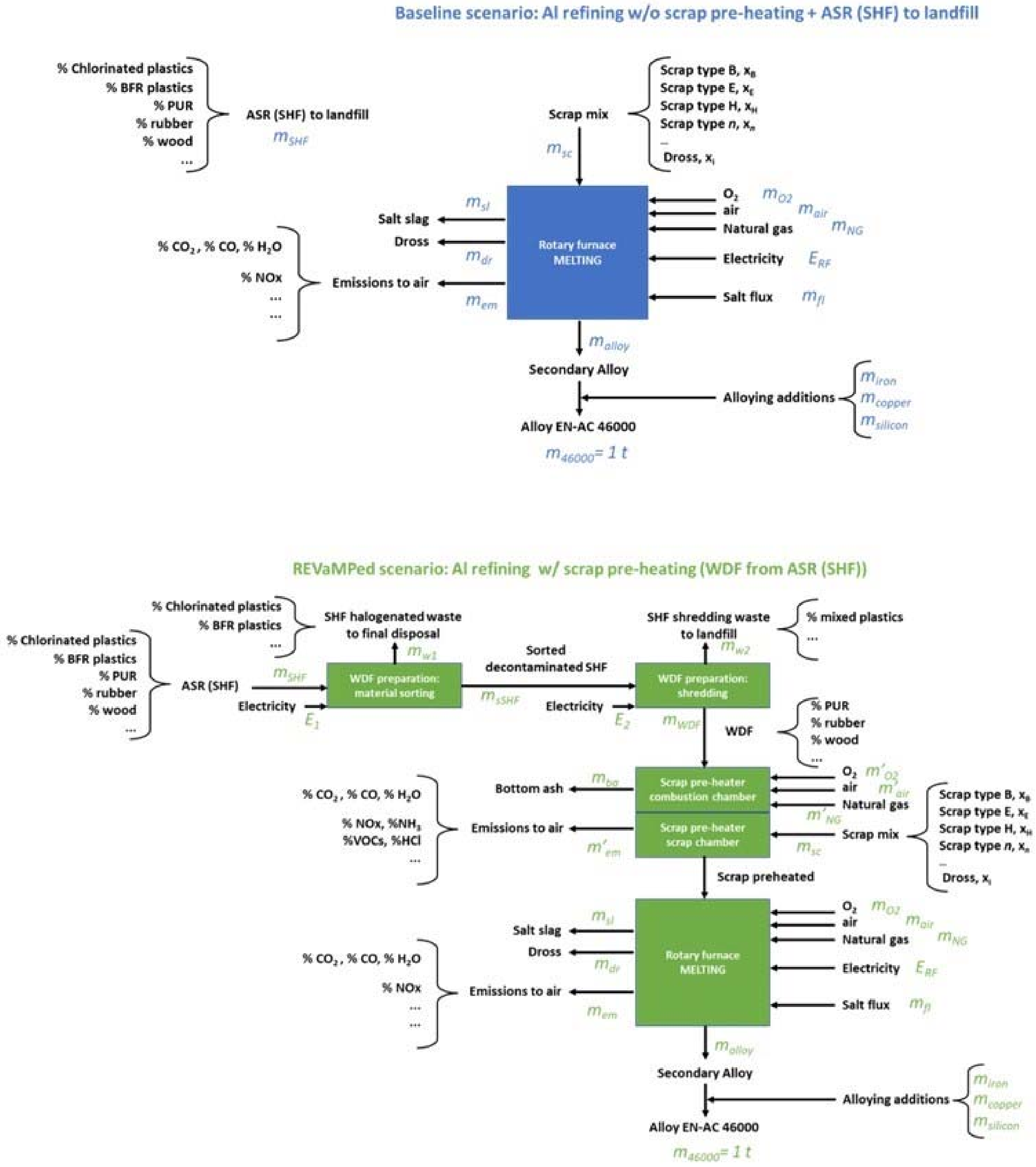


Figure 3 – Flows within the system boundaries of the REF aluminium refining system for the baseline (top) and REVaMPed (bottom) scenarios

As represented in the flowcharts of the Figure 3, the life cycle of the product system leading to the SHF output is not included in the comparative study boundaries. Only the output flow of SHF and the unit processes integrating its final management (disposal or production of WDF) are part of the study.

Allocation procedures

In the superficial product systems, no allocation procedures are used since no cyclical processes are taken into account and a holistic analysis (cradle-to-grave) is not taken.

LCIA methodology and types of impacts

For quantifying the environmental performance of the refining scenarios in REF use case, an *ad-hoc* method has been defined that aggregates several environmental indicators, which are three Life Cycle Impact Assessment (LCIA) midpoint indicators (*Characterisation*) adapted from the environmental Footprint method (EF 3.0) and one Life Cycle Inventory (LCI) indicator:

- GWP, Global Warming Potential (kg CO_2 equiv.)
- ADP-elements, Abiotic resource (minerals and metals) Depletion Potential (kg Sb equiv.)
- ADP-fossil, Abiotic resource (fossil fuels) Depletion Potential; based on lower heating value (MJ)
- W, Non- & Hazardous Waste to final disposal (kg)

Those indicators have been selected because they can be used as project's KPIs, addressing SPIRE topic impacts (30% reduced GHG emissions, 20% increased energy and resource efficiency, 20% decreased fossil resources utilisation, as well as increased productivity).

A single score summing up the weighted contributions of the four normalised impact category indicators is defined as follows, representing overall Environmental Performance (EP):

$$EP = 0.5425 \cdot GWP_N + 0.2143 \cdot ADP\text{-}fossil_N + 0.1945 \cdot ADP\text{-}elem_N + 0.0487 \cdot W_N \qquad \text{Equ. 1}$$

The normalisation rules applied in the EF 3.0 have been extended to calculate the normalization factors (NF) detailed in Table 2. The weight factors have been set so that the weight ratio between GWP, ADP-elem and ADP-fossil indicators in the EF 3.0 methodology is maintained and the weight factor for the Waste indicator is equal to ¼ of the value of the lowest weight factor of the other three categories in the EF 3.0 methodology.

Table 2 – Normalization-Weighting set in the LCIA method to calculate the Environmental Performance (EP) score

Impact category	charact. unit	Indicator	Global NF, total	Global NF, per capita*	weight factor
Climate change	kg CO_2 eq	GWP	5.55E+13	8040	0.5425
Resource use, fossils	MJ	ADP-fossil	4.48E+14	65000	0.2143
Resource use, minerals & metals	kg Sb eq	ADP-elem	4.39E+08	0.0636	0.1945
Waste to final disposal	kg	W	1.52E+13	2171,22	0.0487

**reference year: 2010 (2011 for W indicator). Global population: 6.896 billion people (Y2010) | 7 billion (Y2011)*

Interpretation

To evaluate and analyse the quality of the results, various measures can be carried out. Among others, the applicable standards ISO 14040 and ISO 14044 suggest the following:

- Identification of significant parameters
- Completeness check
- Consistency check
- Sensitivity test

Data requirements

To ensure the data requirements, the following guidelines concerning the data used should be followed:

- temporal: The primary data originates from the years 2020, 2021 and 2023. The secondary data from the database used will be collected between 2020 and 2022. The age of the data is also documented.
- geographical and technological coverage: The data used corresponds to the current state of the art in steel, aluminium and lead production / recycling, and preferentially refers to the technologies in place in the industrial cases examined and to the region of Spain.
- precision: In this study, plant-specific process data is used. If this data can’t be measured or precisely determined otherwise, estimations are made based on literature values and expert interviews.
- completeness: The industrial data provided is combined with data sets from the literature and other relevant sources. In addition, data verifications based on mass and energy balances are carried out.
- representativeness: The data reflects the defined temporal, geographical and technological coverage. Thus, the data can be considered to be representative.
- consistency: The methodology of the study is applied on the different components of the analysis uniformly.
- reproducibility: The presented information on modelling and the explanations regarding the data basis enables the results to be reproduced.
- data sources: The primary data comes from the Spanish plants of the respective industrial partners. The secondary data is taken from established databases, scientific literature or from expert estimates.
- uncertainties: Possible uncertainties related to the used primary and secondary data are estimated at a maximum of 5-15%. Uncertainties in relation to the estimations are also valued at a maximum of 5-15%.

Assumptions

Due to the applied cradle-to-gate approach, all processes of the process route after the melting furnaces are not considered. Due to the iterative nature of LCA, this procedure is common practice.

Value choices and optional elements

Input streams that are less than 5-10 % of the mass of the desired output stream were not considered - unless these input streams or their upstream chains have a significant influence on the environmental assessment of the product system. Thus, e.g. the alloying additions, which are resource-intensive, are not to be neglected. Overall, the sum of the neglected quantities of substances should not be more than 5-10 % of the total output. None of the optional elements mentioned in the international standards ISO 14040 and ISO 14044 are necessary to apply in this study.

Limitations

The analysed recycling plant is reduced to their essential processes. Only the most relevant mass, volume and energy flows are considered. In order to enable the execution of the study, these restrictions have to be made. However, if these flows make a major contribution to one of the selected impact categories, they are still considered (as can be the case i.e. with off gases). These decisions are made in close consultation with the project partners. This procedure is in line with current common practice in LCA.

Critical review

A critical review is not necessary in the context of this study and won’t be carried out.

Type and format of the report

The report presented is based on the international standards ISO 14040 and ISO 14044. In addition, the notes from the standard ISO 14025 are considered. The focus is on the methodical procedure and transparent operation.

4. Phase 2 – Inventory analysis

In this phase, the inventory analysis results for the individual use cases are presented. These results are partly based on the material flow analysis, of which the results were presented in deliverable 2.5. As in earlier reports as well, no specific production parameters are shown due to this report being public.

4.1. Inventory analysis of RWTH use cases

Here, the updated KPI values are only demonstrated as percentual changes. It is worth mentioning, that the retrofitting solutions were initially examined and evaluated in test campaigns. In order to improve the validity of the results, long-term test series with more data would be useful.

Steel use case

All relevant input and output streams of the analysed process system with the respective values have been initially recorded in deliverables 2.5 and 5.2. During the work for deliverable 8.2 and the data preparation for the updated steel use case with the retrofit solutions installed, inaccuracies were found in the base case data, which led to further refinement. Also, more data from a longer time frame was introduced for the base case definition, which led to a change in the values. Most notably, the lime inputs have been adapted to a higher share of limestone and a larger lime input overall. Other values were only slightly adapted.

The modelling assumptions for the upstream processes of this use case described in deliverable 2.5 still remain unchanged. They are also not altered for the retrofitted case.

In the Sidenor use case, two retrofit solutions were installed: the dynamic process model (DPM) and the scrap mix optimisation system (SMO) (see work packages 2, 4 and 5). The two retrofit solutions in this case affect two different sets of process parameters. Due to the data analysis from Sidenor, it was possible to evaluate the effect of the DPM and SMO separately, which leads to a better understanding of each solution itself. Therefore, in the following the results for the steel use case are always presented separately for the two solutions. The DPM mainly suggested different amounts of lime and coke injection, whereas the SMO on the other hand affected the amounts of scrap needed and the amount of slag produced. As a special case, the electric energy demand was affected by both retrofit solutions.

Table 3 below shows the suggested change in value from the DPM as well as the new process data following the implementation of the SMO, both in comparison to the base line data. It has to be noted, that some of the other values also show changes compared to the base case. These variations could be traced back to natural variations in the process and are not related to the retrofit solutions. Therefore, these changes are omitted in the new data sets, so that the impact of the retrofit solutions in the impact assessment can be highlighted more clearly. The impact of some of these variations is evaluated later in the form of a sensitivity analysis.

It can be seen, that the DPM mainly suggests a significant lower usage of coal and lime. The electric energy usage that results from these suggestions is lower than that of the base case. However, it has to be noted that the data that the DPM was trained with deviates from the recorded base case data in their medium values of energy and resource usage. Compared to the training data of the DPM, the models' suggestions result in a 0.7 % higher use of electric energy. Compared to the base case data, and the electric energy usage value resulting from the SMO, this change represents a relatively small variation and is not more significant than natural parameter variations in everyday industrial practice. The environmental impact of these variations will again be investigated more in form of a sensitivity analysis later.

Table 3 – Parameters and percentage deviation of the steel use case

	Process modules	Parameter	Base case [%]	Retrofit, DPM [%]	Retrofit, SOM [%]	Unit
Input	**Electric arc furnace (and scrapyard)**	Electric energy	100.00	98.12	97.47	kWh/t_{Steel}
		Natural gas	100.00	-	-	Nm^3/t_{Steel}
		Scrap	100.00	-	101.75	t/t_{Steel}
		Coal	100.00	71.11	-	kg/t_{Steel}
		Oxygen	100.00	-	-	Nm^3/t_{Steel}
		Limestone	100.00	-	-	kg/t_{Steel}
		Lime (injected)	100.00	5.71	-	kg/t_{Steel}
		Electrode consumption	100.00	-	-	kg/t_{Steel}
Output	**Electric arc furnace (and scrapyard)**	Tapped steel	100.00	-	-	t/t_{Steel}
		Slag	100.00	-	89.49	kg/t_{Steel}
		Dust	100.00	-	-	kg/t_{Steel}
		CO_2	100.00	-	-	kg/t_{Steel}

The SMO leads to an overall higher usage of steel scrap and to a lower usage of electric energy. The slag formation is significantly reduced to the base case data. However, this is only the result of comparing to medium values with one another, where one sample group (SMO based charges) is significantly smaller than the other one. If two recipes (one SMO optimised and one conventional recipe) used for the production of similar types of steel are compared, it can be seen that the slag formation is increased by 3.9 %. This distinction also leads to a different assessment of the change regarding the use of electric energy. Here, the difference when comparing two recipes with a similar purpose with one another is only -0.45 %.

The output parameters concerning off-gas (Dust and CO_2) were taken as constant. If longer tests were run, it is possible that a change in these parameters (following from reduced resource usage) could be recorded as well, which would further impact the environmental evaluation.

The modelling and calculation are carried out with the software Umberto® LCA+ together with the ecoinvent® database. As an example, the model of the steel use case within the software is shown in Figure 4 below.

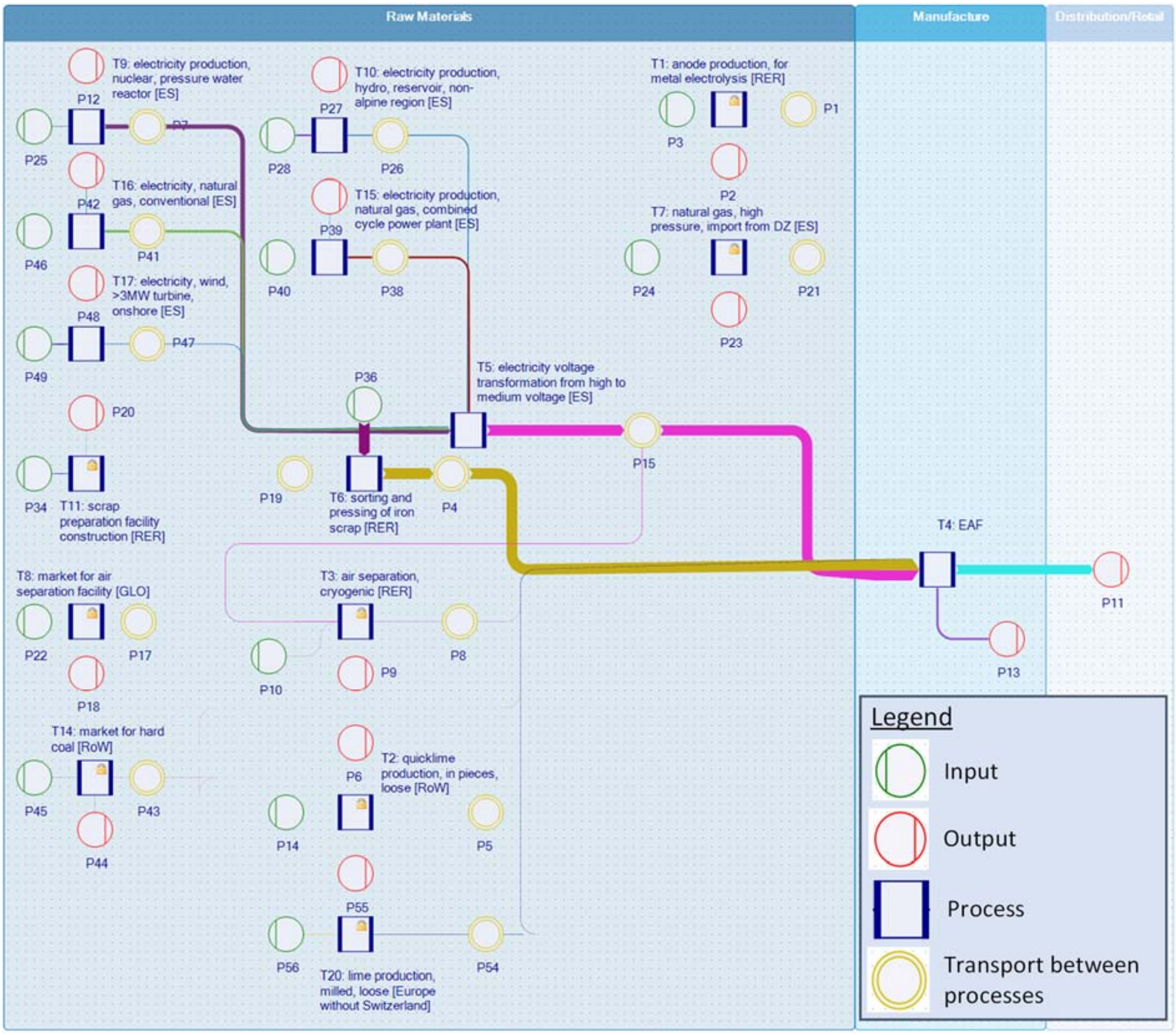


Figure 4 – Modelling of the steel use case in Umberto® LCA+

Aluminium use case

Below in *Table 4*, the updated process data following the installation of the retrofitting solutions at Grupal Art are shown as a percentual change to the base case data. The baseline corresponds to the initial values from deliverable 2.5.

Table 4 – Parameters and percentage deviation of the aluminium use case

	Process modules	Parameter	Base case [%]	Retrofit [%]	Unit
Input	**Heating & filling up of the furnace**	Aluminium solid scrap	100.00%	71.29%	t/t_{Al}
		Oxygen	100.00%	37.35%	m^3/t_{Al}
		Aluminium chips	100.00%	70.72%	t/t_{Al}
		Natural gas	100.00%	84.68%	m^3/t_{Al}
	Dross removal	Electric energy	100.00%	-	kWh/t_{Al}
	Dross recovery process	Dross (input)	100.00%	78.67%	t/t_{Al}
	Refilling of the furnace	Scrap	100.00%	45.13%	t/t_{Al}
		Liquid aluminium	100.00%	69.60%	t/t_{Al}
		Alloy elements	100.00%	93.87%	t/t_{Al}
		Oxygen	100.00%	93.48%	m^3/t_{Al}
		Recovered metals from dross	100.00%	92.97%	t/t_{Al}
Output	**Heating up & filling up of the furnace**	Liquid aluminium	100.00%	69.60%	t/t_{Al}
		CO_2	100.00%	84.68%	kg/t_{Al}
	Dross removal	Dross	100.00%	78.67%	t/t_{Al}
	Dross recovery process	Inorganic parts	100.00%	64.37%	t/t_{Al}
		Aluminium metallic parts	100.00%	92.97%	t/t_{Al}
	Refilling of the furnace	Aluminium (to casting)	100.00%	-	t/t_{Al}

The data was then further refined in deliverable 6.5. There, the modelling of the alloying materials in the model was updated, since they showed a higher influence on the environmental evaluation than initially expected. The updated process data was collected after the implementation of all retrofitting solutions. Therefore, their impact is measured as a whole.

Also, modifications were made to some parameter values following the work for deliverable 8.2 and the data preparation for the LCA evaluation. This mainly affected the usage of oxygen, natural gas and electricity. Modeling assumptions for the upstream processes of this use case from deliverable 2.5 remain unchanged both for the base and for the retrofitted case.

It can be seen, that after the installation of the retrofitting solutions, almost all process KPIs showed an improvement compared to the base case. Energy and resource efficiency could be improved in most categories by 8 % to 30 %. Especially significant is the change in oxygen usage, which was decreased by over 60 %. Only the usage of electrical energy for the removal of the dross has remained unchanged. The new electrical energy demand for the retrofitted case could not yet be recorded. Therefore, it is assumed to have stayed constant. Although, as lower amounts of dross are being produced in the retrofitted case, it can be assumed that this value would most likely be lower compared to the base case as well. Again, insight on this matter will be provided in the sensitivity analysis later.

Lead use case

The updated process parameters following the retrofit installations at Exide are shown below in *Table 5*. Again, the updated data is shown as a percentual change compared to the base case. The initial definition of all relevant input and output streams have been initially recorded in deliverable 2.5, and were further refined in deliverable 7.4. During the data refinement process it was discovered, that the impact of the externally sourced resources was especially high in this use case. Therefore, the modelling of the upstream processes was analysed in-depth and modelled to fit the use case of Exide as close as possible. The process data of the base model deviates in some cases slightly from data presented in deliverable 8.2. This is due to the fact, that for the base case definition of the LCA more recent data could be used confidentially. The base case data is therefore consistent with the state described in deliverable 2.5.

The updated process data was recorded after all of the retrofit installations were implemented. Their impact is therefore again measured as a whole. In the updated process data, it can be seen that several process KPIs accounting for the amount of resources used have increased following the retrofit installation. Most notably, the amount of external lead bullion has increased by almost 70 %. Consequently, most of the output parameters have increased as well, especially the amount of slag which increased by ca. 50 %. On the other hand, the energy usage through natural gas and electrical energy could be improved by ca. 10 %.

Table 5 – Parameters and percentage deviation of the lead use case

	Process modules	Parameter	Base case [%]	Retrofit [%]	Unit
Input	**Breaking and separation**	Batteries	100.00%	138.46%	t/t_{Lead}
		Electric energy	100.00%	90.43%	kWh/t_{Lead}
	Smelting	Oxygen	100.00%	98.89%	Nm^3/t_{Lead}
		Natural gas	100.00%	89.82%	Nm^3/t_{Lead}
		Fluxes (soda, coke, iron)	100.00%	-	t/t_{Lead}
		External raw lead material	100.00%	103.75%	t/t_{Lead}
		Internal raw lead material	100.00%	143.24%	t/t_{Lead}
		Dross	100.00%	70.00%	t/t_{Lead}
		Dust	100.00%	-	t/t_{Lead}
	Refining	Electricity	100.00%	102.44%	kWh/t_{Lead}
		External lead bullion	100.00%	168.97%	t/t_{Lead}
		Internal lead bullion	100.00%	98.48%	t/t_{Lead}
Output	**Breaking and separation**	Sulfuric acid	100.00%	116.67%	t/t_{Lead}
		Polypropylen	100.00%	60.71%	t/t_{Lead}
		Metals	100.00%	126.92%	t/t_{Lead}
		Paste	100.00%	109.09%	t/t_{Lead}
	Smelting	Off-gas	100.00%	84.81%	Nm^3/t_{Lead}
		Dust	100.00%	-	t/t_{Lead}
		Lead bullion	100.00%	98.48%	t/t_{Lead}
		Slag	100.00%	152.38%	t/t_{Lead}
	Refining	Dross	100.00%	70.00%	t/t_{Lead}
		Lead Ingot	100.00%	-	t/t_{Lead}

4.2. Inventory analysis in Refial aluminium refining use case (energy feedstock use case)

The life cycle inventory (LCI) for REF use case, at the baseline and REVaMPed scenarios, has been collected during melting trials at pilot scale (replicated melting trials). Data were logged online by the sensors of the pilot rotary furnace and the scrap pre-heating system (e.g. natural gas consumption) and recorded manually onsite (mass of: scrap, cryolite, slag, unmelted scrap, secondary alloy, WDF loaded, solid residue from WDF combustion) and offsite (chemical composition of the secondary alloy tapped, chemical and material composition of the WDF, hazardousness of slag and bottom ash residues). During the production of the WDF the mass and composition of the starting SHF and the mass of the solid waste from shredding and sorting operations have been measured. The electric consumption for WDF preparation has been calculated from the electrical characteristics of the equipment and the measured processing times.

With regards to the industrial flowcharts of *Figure 3*, the full list of identified input/output flows needs being shortlisted, to be adapted to the simpler equipment and operation at pilot scale and to the measurable and controllable parameters in the pilot equipment. For instance:

- combustion conditions in the burner of the pilot furnace: no oxygen flow;
- charge to the pilot furnace: no recycled dross, no salt fluxes;
- output of the pilot furnace: slag = dross;

Limitations and lack of data. Assumptions done:

- Due to the failure of the data capture of the pilot furnace, the electric consumption of the motor has not been measured. Estimated consumption, from the equipment specifications, is about 0.0018 kWh/t aluminium. As the electric energy consumption is assumed to be negligible in comparison to energy from fuel combustion in the burner and minor variation in electric consumption between the baseline and the REVaMPed scenarios is expected, it is excluded from the inventory.

- No data available about the non-channelled emissions from the pilot furnace and its burner.
    - Emissions to air from the melting process are excluded from the inventory, both in the baseline and in the REVaMPed scenario. Negligible marginal impacts are expected in the comparative LCIA due to the variation in melting emissions caused by the preheating step.
    - The combustion emissions from the burner of natural gas will be modelled by the process for heat production from natural gas combustion at industrial furnace available in the ecoinvent database.

- Combustion emissions from WDF in the scrap pre-heating equipment: off-gas flows after the post-combustion chamber and the heat exchanger are channelled into the industrial exhaust system at Refial. Depending on the set-up during the trials to be executed with WDF burning in the scrap pre-heater, emissions to air from WDF combustion with assistant fuel (NG) will be:

- calculated from measured data (pollutants concentration with the pre-heater on and off, flows of the exhaust gas from the preheater and from the industrial system);
- or estimated (if emissions sampling and analysing is not feasible and there are no data about actual flue gas flows): WDF combustion emissions has been modelled using the DOKA OpenBurning Excel tool (v2020) for generating LCI of waste-specific processes and the WDF composition data.

Specific conditions were established in order to define the baseline scenario, to compare its performance with the one obtained after implementing the scrap preheating step. The pilot rotary furnace shall operate in batches in which fixed values of scrap mix and type of target casting alloy are set. However, due to variability of scrap, elemental chemical composition can vary within a range. The fixed conditions for the charge and the melting protocol, at the baseline and REVaMPed scenarios, were the following:

- **Target alloy**: EN AC-46000, that is the most commonly alloy produced in REFIAL.
- **Scrap mix composition**: three scrap types (B, E, H) and their individual masses within the scrap mix (3:1:6) were selected, for a **total quantity of 10 kg of scrap charge**, in order to produce an alloy EN AC-46000.

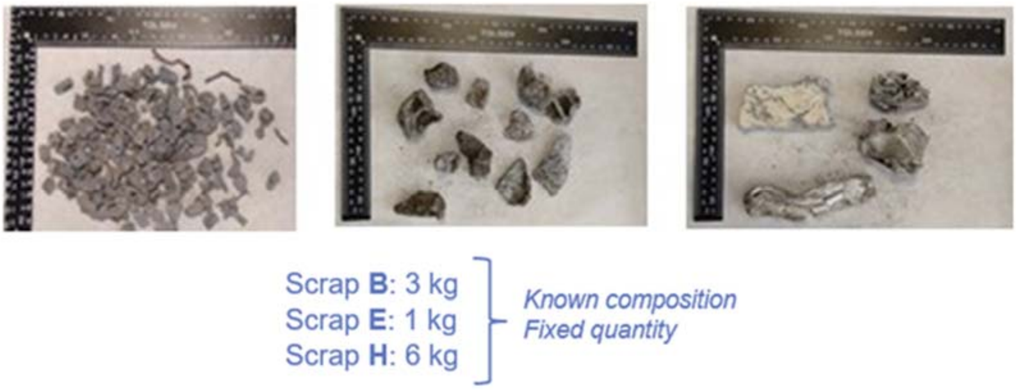


Figure 5. Fixed scrap mix composition selected for scrap charge of melting runs in the Baseline and REVaMPed Scenarios

- Use of fluxes: **no salts used, except for cryolite** to improve coalescence. Based on the quantity of scrap added in the pilot furnace, the nominal mass of required cryolite was defined as **450 g**. Its use in this case is to enhance the heating of the slag, in order to be able to compare the performance in the rotary pilot furnace and in the industrial furnace.
- **Furnace pre-heating**: in order to ensure similar steady conditions of the furnace at the time of starting the melting trials, the furnace was preheated, empty, for at least one hour before each melting experiment. The trials were scheduled at the same hour in the morning for the testing days.

Five replicated melting trials were performed in 2021 at those designed conditions on five different days, and the mean value and standard deviation of the measured and calculated parameters were estimated (WP2 activities). An additional trial, as control experiment, was run under the same baseline conditions during the retrofitting campaign in the year 2023 (WP6 activities). Three heats were run in Nov'2023, maintaining the melting protocol and charge composition, but with the scrap mix pre-heated at 300 °C in an electric muffle oven (due to technical unavailability of the pre-heater equipment fuelled with WDF). Those heats have been used to generate proxy data of the scrap refining after retrofitting the pilot refining process with a scrap pre-heating step (REVaMPed scenario). The mean values of the inputs and outputs flows recorded for the melting process at the baseline and REVaMPed scenarios are itemised in the Table 6.

Table 6 – LCI for the melting process in the rotary furnace to refine scrap into secondary alloy of EN AC-46000 quality, without and with scrap preheating.

	variable	unit	Mean BASELINE	Mean REVAMPED
RAW MATERIAL	scrap E mass	kg	1.00	1.01
	scrap H mass	kg	6.00	6.03
	scrap B mass	kg	3.02	3.01
	scrap mix mass	*kg*	10.03	10.05
	cryolite (Na_3AlF_6) mass	kg	0.453	0.450
	total mass of charge loaded	*kg*	10.48	10.50
MELTING	Melt temperature	°C	777.5	NA
	melting time	min	10:40	09:13
	electricity consumption	kWh	NA	NA
	natural gas consumption	*Nm^3*	1.702	0.7833
OUTPUTS	mass of unmelted materials (ferrous scrap)	kg	0.2854	0.1197
	mass of slag(/dross)	kg	1.2765	1.0279
	total mass of aluminium alloy produced	kg	8.5546	9.3871
	metal yield (adjusted)	*%*	*85.29*	93.44
alloying needs to adjust to EN AC-46000	Fe addition, mass	g	10.2	4.7
	Cu addition, mass	g	56.9	49.3
	Si addition, mass	g	248.2	274.7

The data inventoried for modelling the treatment alternatives of the Heavy Fraction of ASR (SHF) at the Baseline and REVaMPed scenarios are presented below:

A) Baseline Scenario

About 120 000 t of Heavy fraction of ASR is estimated to be generated annually in Otua Group, after the removal of the metallic content. Less than 1% of this quantity is destined to WDF in cement kilns, after performing processing steps to reduce size and chlorine content. The rest is destined directly to landfill. That unrecovered SHF is the potential input for the WDF production. The average composition (% by weight) of the SHF landfilled is given in Table 7 below. The mean value of the chlorine content in the SHF samples analysed was 12817 ppm.

Table 7 – Average material composition (wt%) of the Heavy Shredder Fraction

Textile	Foams	Plastics	Wood	Wires/ Metals	Stones, Glass	Fines & Others	**TOTAL**
3.56%	3.99%	40.73%	10.94%	3.28%	11.61%	25.88%	100.00%

B) REVaMPed Scenario

In the REVaMPed scenario, the Heavy fraction of ASR (SHF) is processed in the facilities of Otua Group to be used as WDF. First, the material is crushed in a knife mill and sieved (mesh size: 25 mm). At this stage, metals, stones and dense materials are separated. The next step is the elimination of pieces with high halogen content (brominated and chlorinated polymers) using X-Ray Transmission technology, in order to obtain the WDF ready to be used in the tests. Nearly 40 wt.% of the SHF is rejected in this process. The rejects, material with halogens content higher than 1% (mainly PVC), are sent to landfill. The rest, around 60% of the SHF input, is the Waste Derived Fuel to be used to generate thermal energy in the scrap preheater.

The average material composition of the prepared WDF is as follows in Table 8. The Low Heating Value (dry basis) of the WDF is 26.26 MJ/kg and its chlorine content 0.77 wt.%

Table 8 – Material composition of WDF prepared from Heavy Shredder Fraction

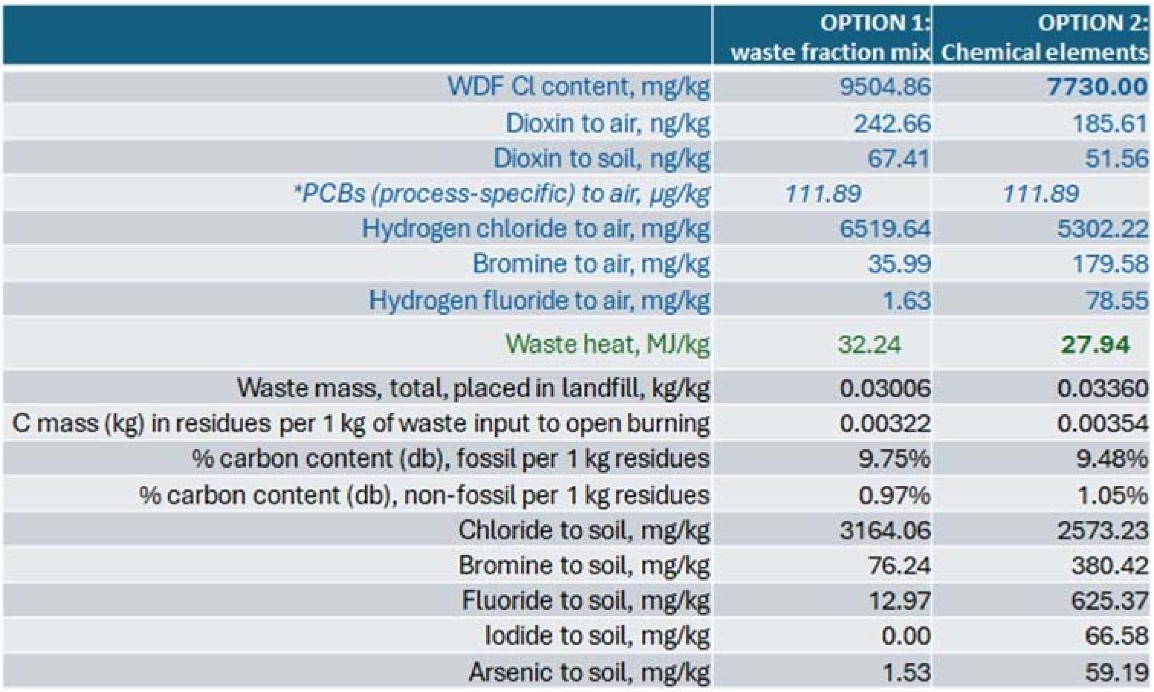
material	**wt%**		
wood	14.52		
cables	0.60		
plastics	73.93	*ABS*	*10.10%*
		fibres	*0.10%*
		PMMA	*1.80%*
		PE	*13.70%*
		PET	*7.50%*
		PS	*1.40%*
		acrylonitrile (ABS)	*0.30%*
		PA	*15.70%*
		PP	*22.20%*
		PPE	*4.20%*
		non-identified plastics	*23.0%*
foams	3.21		
others (commingled materials)	7.72		
TOTAL	100.00		

Total energy (electricity) consumption of the WDF preparation process amounts to 45.31 kWh/t and productive capacity is estimated at 1.79 t/h.

Regarding the ‘theoretical’ WDF consumption for scrap pre-heating, the design parameters defined by GHI for constructing the pre-heater equipment are used: 5 kg of WDF to be incinerated for heating up to 200 °C 100 kg of (heterogeneous) aluminium scrap at a heating rate ≥2 kg/min. The installed power of the pre-heater equipment constructed is 15 kW. The conclusions of the study executed by Inatec, about the performance of the exchanger of pre-heater, to pre-heat batches of 10 kg of different scrap types and of the mix used in the melting tests, suggest a minimum residence time of 30 minutes, on average, for the scrap in the chamber to reach a stabilised temperature of 160 °C.

The emissions and residues originated in the combustion have been predicted with the DOKA OpenBurning Excel tool, which can be used to produce an inventory for burning of solid waste. Predictions are based on Municipal Waste Incineration technology without any pollution control: i.e., no flue gas treatment (unlike the preheater equipment, which integrates a post-combustor chamber). The said tool allows two alternative modelling of the waste combusted, which have been compared: In Option 1 the waste is entered as a mix of waste materials; for that, the material composition of the WDF has been used. Under Option 2, the chemical elements composition, together with the fuel, ultimate and proximate analyses are inventoried. Results of the chemical and fuel characterisation of WDF (WP1) were used as inputs for the tool in that case. Under both options the tool outputs comprise CO, CO_2, SO_2, NO_x, HCl, HF, methane and other incomplete combustion products, PAHs, dioxins, PCBs, metals and particulates emissions to air, as well as elements emitted to soil. The assumed share of thermal NO_x to total NO_x in average waste burning process is 30%. Contribution from thermal NO_x is 810 mg per kg waste. In option 1, values for Cl content and waste heat are calculated based on the polymeric mix entered. For comparison purposes, the halogenated emissions and residues originated in the combustion, as predicted using the two calculation options of the DOKA Excel tool are presented in the Table 9 below.

Table 9 – Halogenated emissions to air and soil and mass of final solid waste from WDF combustion, modelled using DOKA OpenBurning Excel tool (v2020)



	OPTION 1: waste fraction mix	OPTION 2: Chemical elements
WDF Cl content, mg/kg	9504.86	**7730.00**
Dioxin to air, ng/kg	242.66	185.61
Dioxin to soil, ng/kg	67.41	51.56
**PCBs (process-specific) to air, µg/kg*	*111.89*	*111.89*
Hydrogen chloride to air, mg/kg	6519.64	5302.22
Bromine to air, mg/kg	35.99	179.58
Hydrogen fluoride to air, mg/kg	1.63	78.55
Waste heat, MJ/kg	32.24	**27.94**
Waste mass, total, placed in landfill, kg/kg	0.03006	0.03360
C mass (kg) in residues per 1 kg of waste input to open burning	0.00322	0.00354
% carbon content (db), fossil per 1 kg residues	9.75%	9.48%
% carbon content (db), non-fossil per 1 kg residues	0.97%	1.05%
Chloride to soil, mg/kg	3164.06	2573.23
Bromine to soil, mg/kg	76.24	380.42
Fluoride to soil, mg/kg	12.97	625.37
Iodide to soil, mg/kg	0.00	66.58
Arsenic to soil, mg/kg	1.53	59.19

* Model results of process-specific emissions such as incomplete combustion products to be corrected with available experimental data, e.g. 0.565 mg/kg PCBs instead of 0.112

The predicted CO_2 emissions by the tool, using transfer coefficients for the carbon content in the burnable fraction of the waste to air (volatile part), are 2.3-2.5 kg/kg_{WDF}, broken down as shown in Table 10.

Table 10 – CO2 emissions to air from WDF combustion, modelled using DOKA OpenBurning Excel tool (v2020)

predicted CO_2 emissions to air, kg/kg WDF	OPTION 1: waste fraction mix	OPTION 2: Chemical elements
Carbon dioxide, biogenic	0.2057	0.2499
Carbon dioxide, fossil	2.0626	2.2489

5. Phase 3 – Impact assessment

5.1. Impact assessment of retrofitting at RWTH use cases

Based on the results of the inventory analysis, an impact assessment will now be carried out for the individual use cases and retrofitted variants. The following set of environmental impact indicators has been defined in deliverable 1.4 to be used for the impact assessment:

- Global warming potential, GWP
- Fossil depletion potential, FDP
- Freshwater eutrophication potential, FEP
- Metal depletion potential, MDP
- Natural land transformation, NLTP
- Ozone depletion potential, ODP
- Photochemical oxidant formation potential, POFP
- Terrestrial acidification; TAP
- Human toxicity potential, HTP
- Water depletion potential, WDP

These indicators cover all major impact categories according to ISO 14040 and 14044 and are also commonly used for LCA studies in metal working industries. The values of the respective indicators are determined using LCA software. The indicator values are calculated first for the base case inventory data, and then again for the updated inventory data, after the retrofit solutions have been installed. For all indicators, a negative environmental impact is measured, meaning that a change to a lower value represents an improvement.

The impact assessment itself is carried out using the ReCiPe midpoint method without considering long-term effects. The exact allocation of the life cycle inventory results to the individual impact categories can be found in the database or in the description of the evaluation method.

Steel use case

The results for the steel use case are again presented separately for the DPM and the SOM. In *Table 11*, the relative changes for the individual impact categories are shown. In *Figure 6* and Figure 7 below, these results for the different impact indicators are illustrated in a net diagram.

For almost all indicators, an improvement could be achieved by 1 % up to 6 %. The combined improvement of both solutions together lies in the range of up to ca. 8 % or almost 16 % for the FEP. Here, the impact of the reduction of coal usage is especially visible. In the GWP, the reduced usage of lime and the reduced formation of slag has a particularly large impact on the overall reduction. The reduced slag formation has a high impact in general on eight of the ten impact categories.

Table 11 – Parameters and percentage deviation of all impact categories in the steel use case model

Impact indicator	Base case	Retrofit DPM	Retrofit SMO	Unit
GWP	100.00%	97.35%	96.76%	$kg_{CO2\text{-}eq.}$
FDP	100.00%	94.87%	97.30%	$kg_{Oil\text{-}eq.}$
FEP	100.00%	86.20%	98.17%	$kg_{P\text{-}eq.}$
HTP	100.00%	99.82%	94.01%	$kg_{1,4\text{-}DCB\text{-}eq.}$
MDP	100.00%	99.27%	100.00%	$kg_{Fe\text{-}eq.}$
NLTP	100.00%	96.55%	102.47%	m^2
ODP	100.00%	97.78%	96.91%	$kg_{CFC\text{-}11\text{-}eq.}$
POFP	100.00%	96.50%	95.82%	kg_{NMVOC}
TAP	100.00%	95.56%	97.00%	$kg_{SO2\text{-}eq.}$
WDP	100.00%	97.36%	97.59%	m^3

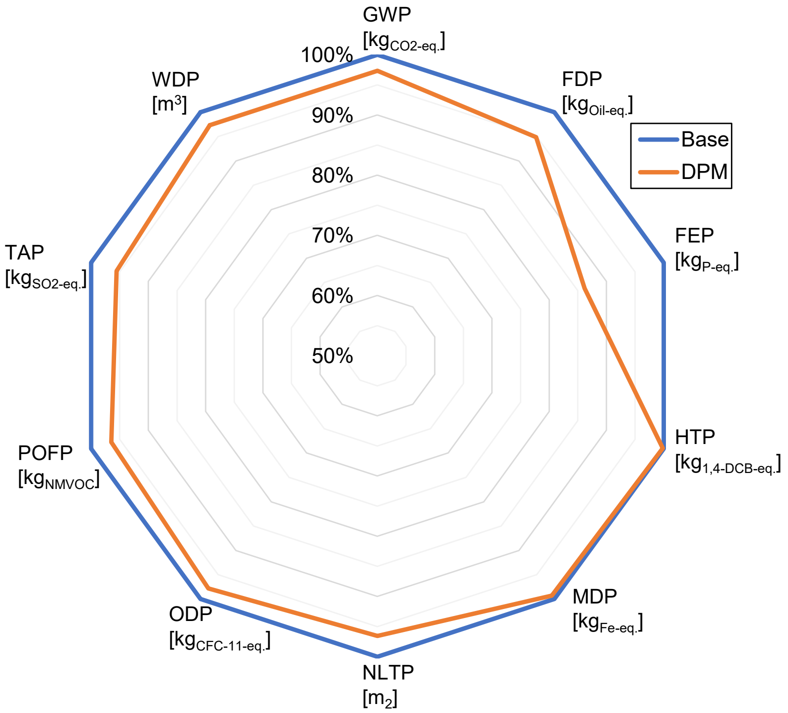


Figure 6 – Relative changes for all impact categories following the DPM installation in the steel use case model

The only impact category, where a slightly worse indicator result was achieved is the NLTP for the process data following the implementation of the SMO. This is an effect of more scrap being necessary than before to produce one tonne of steel. This impact is however counteracted by the DPM effect, where the NLTP was decreased.

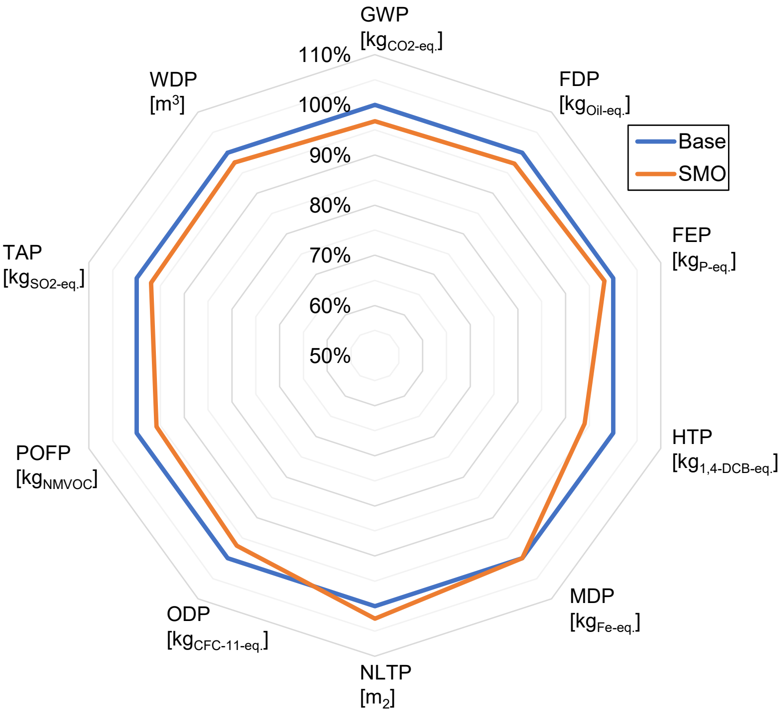


Figure 7 – Relative changes for all impact categories following the SOM installation in the steel use case model

These results are examined in more detail below. For this purpose, the allocation of the respective impact category to the upstream chains of the process considered in the modeling was determined. In the following *Figure 8* and *Figure 9*, the impact of the different flows on the individual impact categories is shown, again separately for the retrofitted cases with DPM and SOM. To better highlight the differences between *Figure 8* and *Figure 9*, the percentual change between these two cases is shown again as a value table below in*Table 12*.

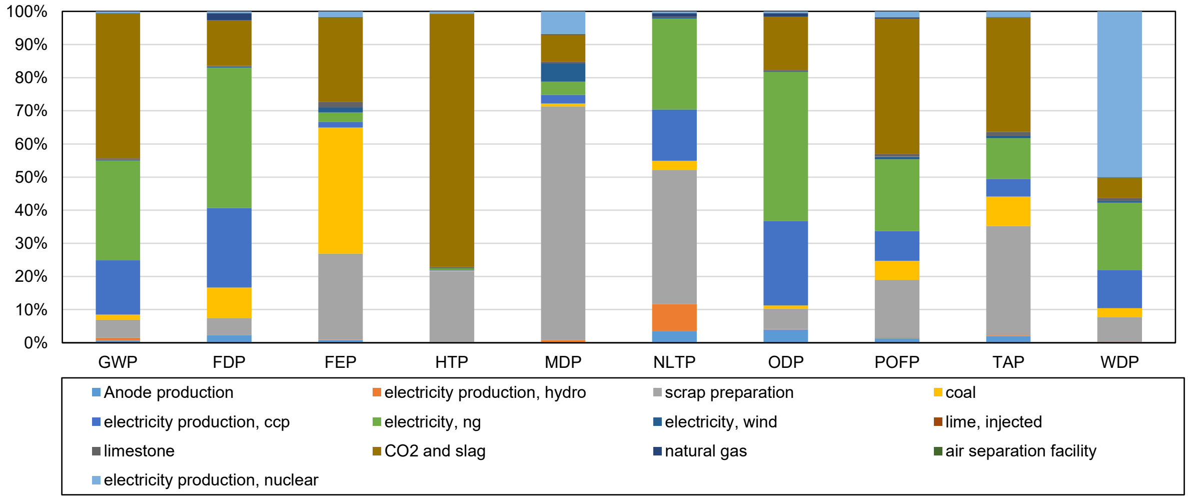


Figure 8 – Impact of different flows on impact categories for DPM retrofitted steel use case

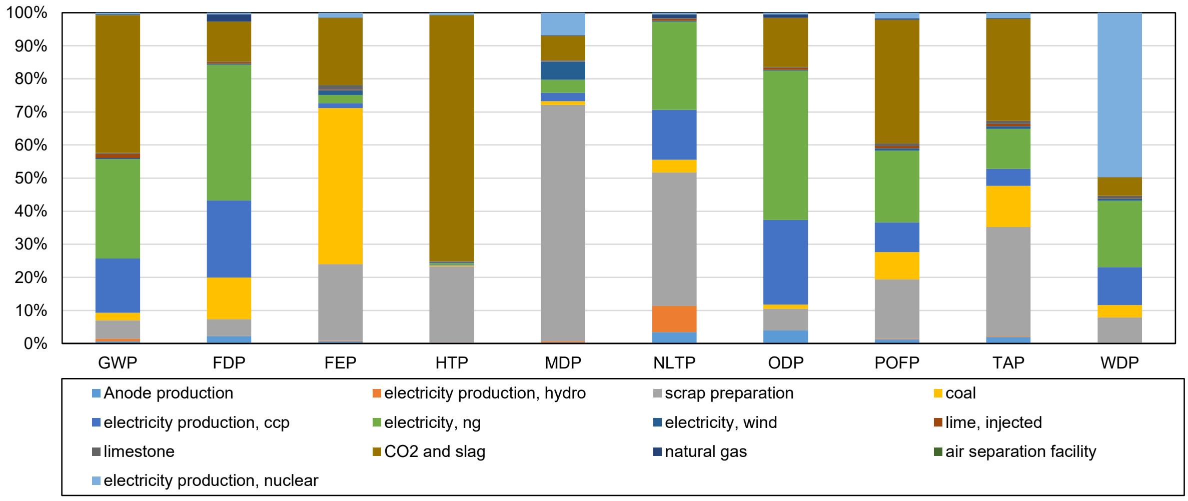


Figure 9 – Impact of different flows on impact categories for SOM retrofitted steel use case

It should also be considered that the separate forms of electricity generation in the electricity mix of Sidenor are listed separately. This is due to the fact, that the electricity demand showed a large impact on the environmental assessment early on. To accurately present the use case, the specific electricity mix of Sidenor was built up within the model.

Table 12 – Change of indicator impact for each flow from SOM to DPM results

	GWP	FDP	FEP	HTP	MDP	NLTP	ODP	POFP	TAP	WDP
Anode production	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Electricity production, hydro	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%
Scrap preparation	98.28%	98.28%	98.28%	98.28%	98.28%	98.28%	98.28%	98.28%	98.28%	98.28%
Coal	70.79%	70.79%	70.79%	70.79%	70.79%	70.79%	70.79%	70.79%	70.79%	70.79%
Electricity production, ccp	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%
Electricity, ng	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%
Electricity, wind	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%
Lime, injected	5.71%	5.71%	5.71%	5.71%	5.71%	5.71%	5.71%	5.71%	5.71%	5.71%
Limestone	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
CO_2 and slag	105.41%	110.30%	110.35%	109.03%	110.30%	100.00%	110.30%	110.30%	110.31%	110.31%
Natural gas	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Air separation facility	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Electricity production, nuclear	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%	100.64%

The impact of the emissions of the electric arc furnace (off-gas and slag) is visible, as it is the largest contributor to four out of ten impact categories. For the GWP, this portion mostly consists of the CO_2 impact, whereas in all other categories this share is made up entirely from the slag. Comparing both graphs with one another, although the percentages are quite similar, the different impacts of the two retrofitting solutions become visible (e.g. comparing both FEP bars). It can also be seen, that the scrap usage has the second most prominent influence on most impact categories. Only then comes the impact of the electric energy being used by the EAF. This is due to the fact, that the electric energy used at Sidenor has a comparatively low emission factor, as it was explained in deliverable 2.5.

Aluminium use case

The results for the aluminium use case are presented in *Table 13* as relative changes for the individual impact categories. *Figure 10* below illustrates these results as a net diagram. As commented before, in this case the impact of the retrofitting solutions is evaluated as a whole.

Table 13 – Parameters and percentage deviation of all impact categories in the aluminium use case

Impact indicator	Base case	Retrofit	Unit
GWP	100.00%	86.98%	$kg_{CO2\text{-}eq.}$
FDP	100.00%	86.67%	$kg_{Oil\text{-}eq.}$
FEP	100.00%	88.31%	$kg_{P\text{-}eq.}$
HTP	100.00%	88.32%	$kg_{1,4\text{-}DCB\text{-}eq.}$
MDP	100.00%	88.35%	$kg_{Fe\text{-}eq.}$
NLTP	100.00%	87.45%	m^2
ODP	100.00%	87.07%	$kg_{CFC\text{-}11\text{-}eq.}$
POFP	100.00%	87.89%	kg_{NMVOC}
TAP	100.00%	88.34%	$kg_{SO2\text{-}eq.}$
WDP	100.00%	88.24%	m^3

It can be seen that the implementation of the retrofitting solutions has lead to an improvement in all impact categories by ca. 12 % to 13 %. This is in line with the change in process data, which was explained before, where also an improvement of almost all KPIs was recorded. The largest impact factors in all categories were the usage of natural gas and alloying elements. The usage of copper as an alloying element showed a particular large impact on the MDP, FEP and HTP, with an improvement of roughly 10 % only related to this reduced material usage. Following this, the reductions of titanium and natural gas usage showed the second highest impact across multiple impact indicators.

These impacts can be further highlighted in *Figure 11*, where the most relevant flows are shown for each impact category. Here, the impact of copper in particular, but also of natural gas and titanium is visible.

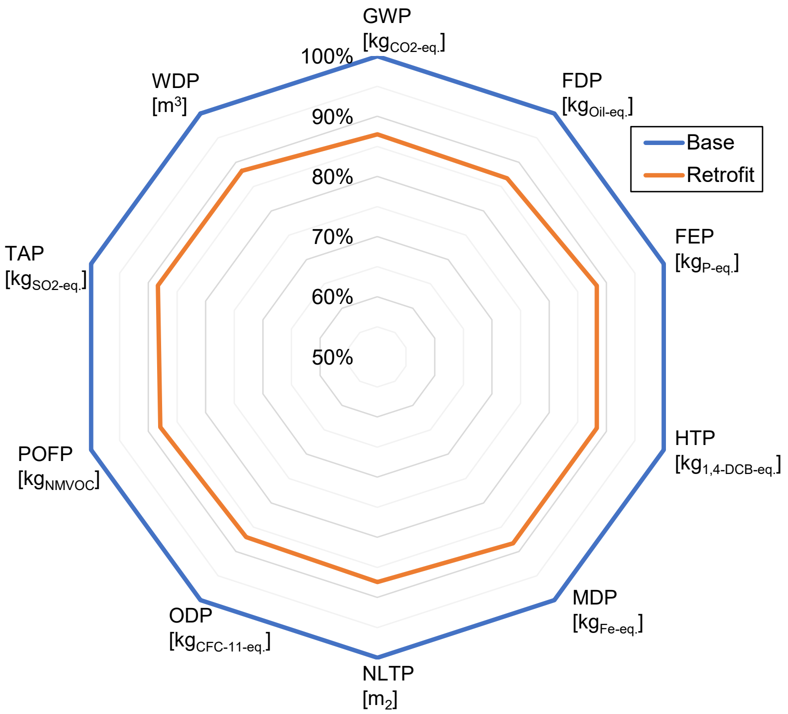


Figure 10 – Relative changes for all impact categories following the retrofit installation in the aluminium use case model

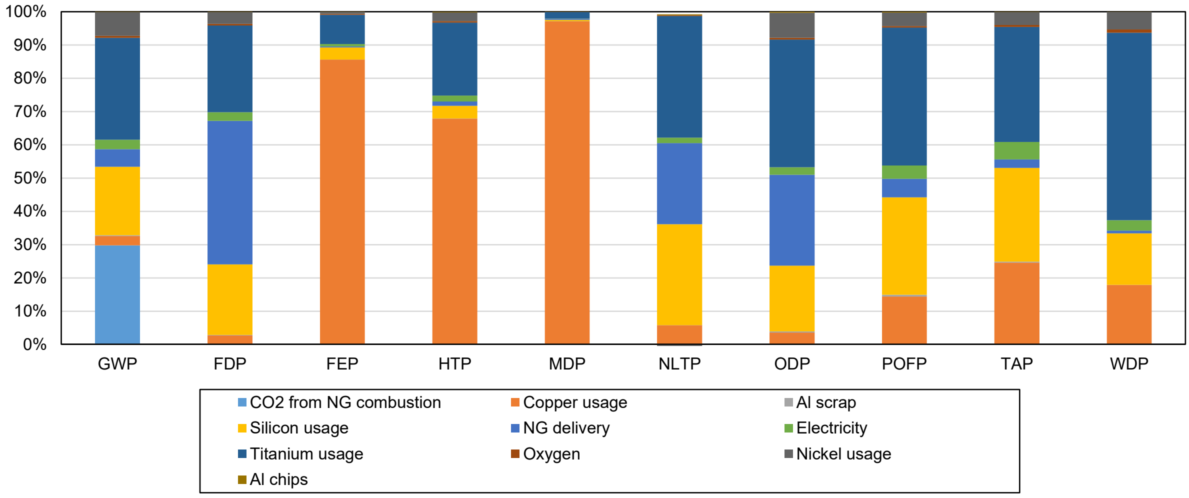


Figure 11 – Impact of different flows on impact categories for the retrofitted aluminium use case

The impact of silicon on the environmental evaluation is also prominent in many indicator categories. As explained in deliverable 6.5, silicon is the most used alloying material for Grupal Art product mix. However, it should be considered, that the usage levels of silicon where not impacted by the retrofitting solutions, as it was also previously expected (see deliverable 8.2).

Lead use case

The results for the lead use case are presented in *Table 14* as relative changes for the individual impact categories. The percentual changes of the different impact indicators are also illustrated below in *Figure 12*. Here again, the impact of the retrofitting solutions is evaluated as a whole.

Table 14 – Parameters and percentage deviation of all impact categories in the lead use case

Impact indicator	Base case	Retrofit	Unit
GWP	100.00%	105.82%	kg$_{\text{CO2-eq.}}$
FDP	100.00%	105.91%	kg$_{\text{Oil-eq.}}$
FEP	100.00%	108.19%	kg$_{\text{P-eq.}}$
HTP	100.00%	150.16%	kg$_{\text{1,4-DCB-eq.}}$
MDP	100.00%	124.33%	kg$_{\text{Fe-eq.}}$
NLTP	100.00%	103.55%	m^2
ODP	100.00%	109.07%	kg$_{\text{CFC-11-eq.}}$
POFP	100.00%	104.40%	kg$_{\text{NMVOC}}$
TAP	100.00%	101.06%	kg$_{\text{SO2-eq.}}$
WDP	100.00%	109.46%	m^3

In the lead use case, the implementation of the retrofitting solutions lead to an increase in all impact indicators, ranging from ca. 1 % to over 50 % increases. The largest increase was recorded for the HTP, where the higher amount of slag produced had a particularly large influence. Across all impact indicators, the increased usage of external lead bullion had the largest negative impact, ranging from 4 % up to 24 % for the MDP.

In *Figure 13*, the share of the individual flows is shown for each impact indicator. It can be seen, that the emissions of the smelting process have a large impact on the GWP, HTP, POFP and TAP. In all of these cases, the slag produced is the largest contributor to the environmental evaluation.

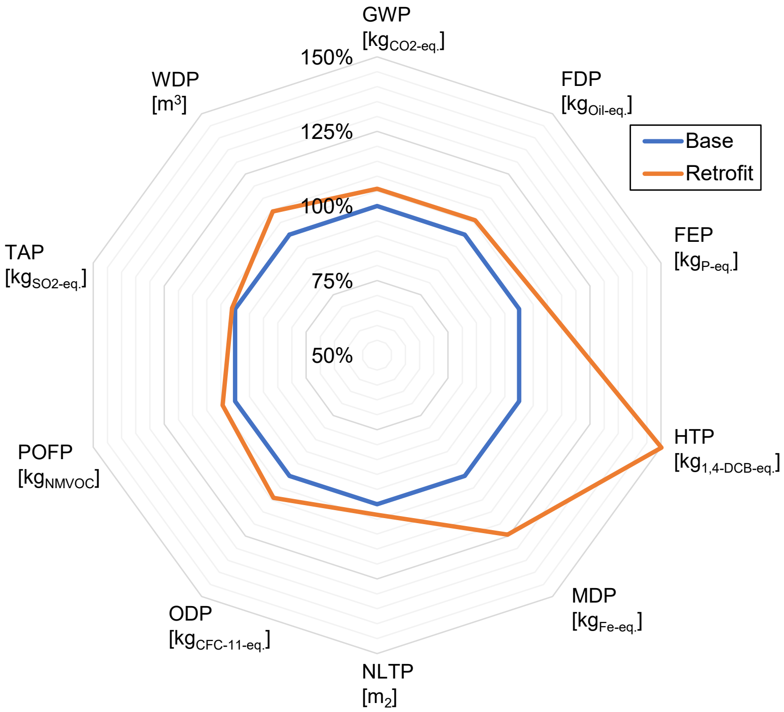


Figure 12 – Relative changes for all impact categories following the retrofit installation in the lead use case model

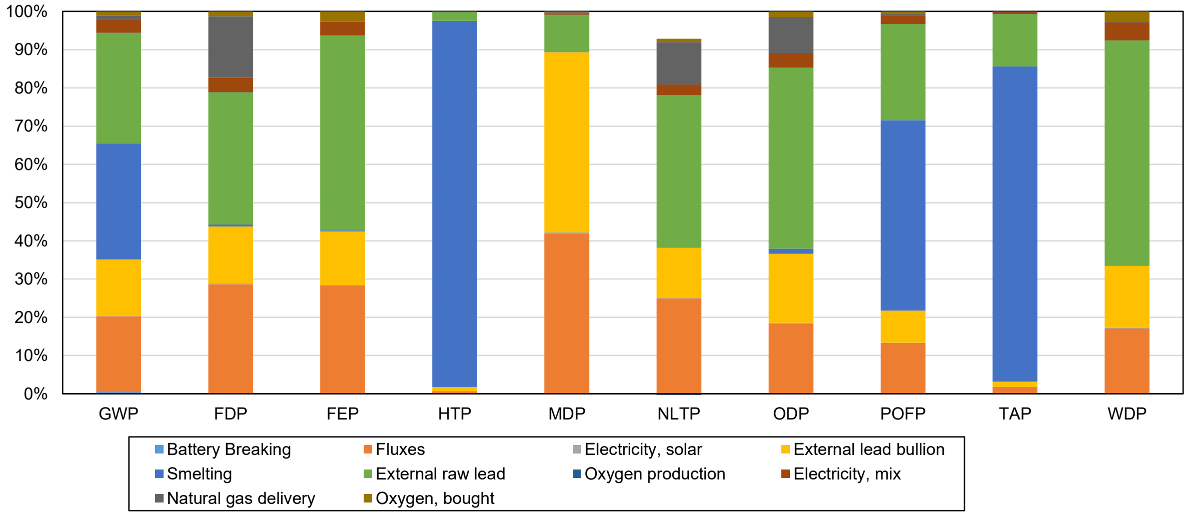


Figure 13 – Impact of different flows on impact categories for the retrofitted lead use case

The second largest impact for many impact indicators is the external raw lead and the external lead bullion. The usage of external raw lead was only slightly increased, but since the usage of external lead bullion was increased by almost 70 %, it can be seen why the values of these respective impact indicators are raised. Lastly, the fluxes were observed to be the third most important contributor to most environmental indicators. For this material flow however, no increase was recorded after the retrofitting solutions were installed.

5.2. Impact assessment of retrofitting at aluminium scrap refinery (energy feedstock use case at Refial)

First, the value of the defined environmental indicators per tonne of target alloy EN AC 46000 were calculated for the baseline scenario at Refial, both the characterisation indicators and the EP single score representing the overall Environmental Performance (*Table 15*). The following charts depict the relative contribution of the main process steps (*Figure 14* and *Figure 16*) and of the unit processes in the baseline scenario (*Figure 16*) to every impact category indicator, as well as to the final value of the EP single score. The main process stages considered in the system for computing environmental impacts are: landfill of SHF waste (*SHF landfill*); melting scrap mix in the rotary furnace into a secondary alloy (*sec.alloy*); and alloying addition needs to correct chemical composition of the secondary alloy within EN AC 46000 alloy limits (*adjust*).

Table 15 – Environmental performance (per tonne of target alloy) of the baseline scenario of aluminium refining and SHF waste landfill. Mean values.

Process in scenario	**GWP kg CO_2 eq/t_{alloy}**	**ADP-fossil MJ/t_{alloy}**	**ADP-elem kg Sb eq/t_{alloy}**	**W kg/t_{alloy}**	**EP mPt/t_{alloy}**
SHF landfill	11.493	22.241	$3.13 \cdot 10^{-06}$	94.370	**2.970**
sec. alloy	957.620	12437.529	0.018	257.015	**167.124**
adjust	348.973	3899.992	0.090	579.211	**323.568**
TOTAL baseline	**1318.086**	**16359.762**	**0.108**	**930.596**	**493.662**

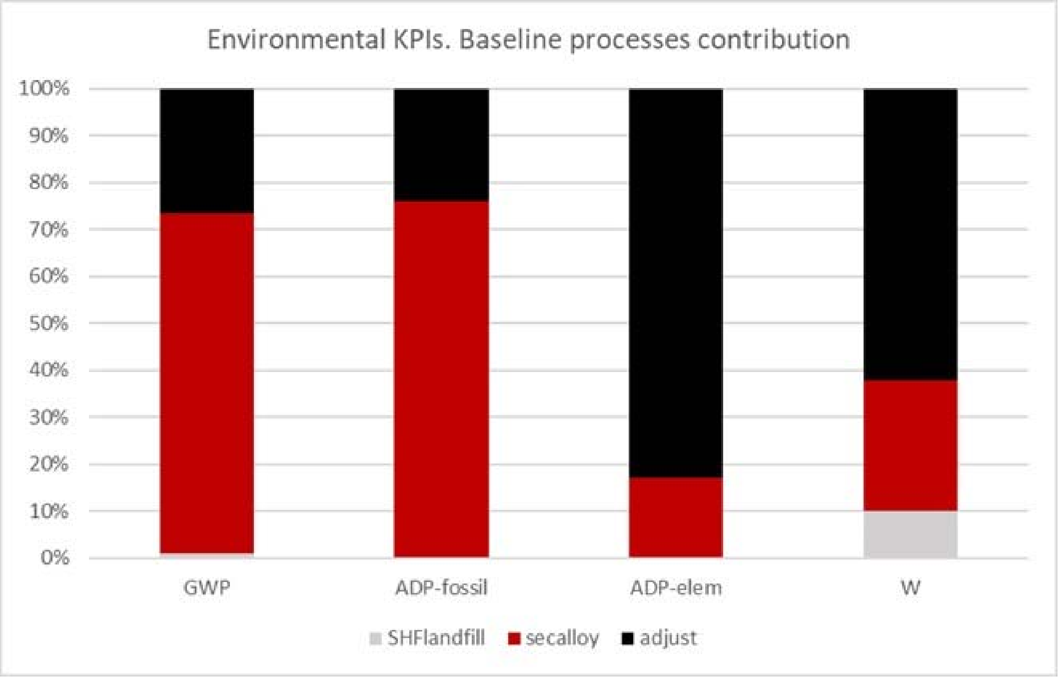


Figure 14 – Environmental profile of REF use case at the baseline. Breakdown of the impact indicators (Midpoint) per main process in the system.

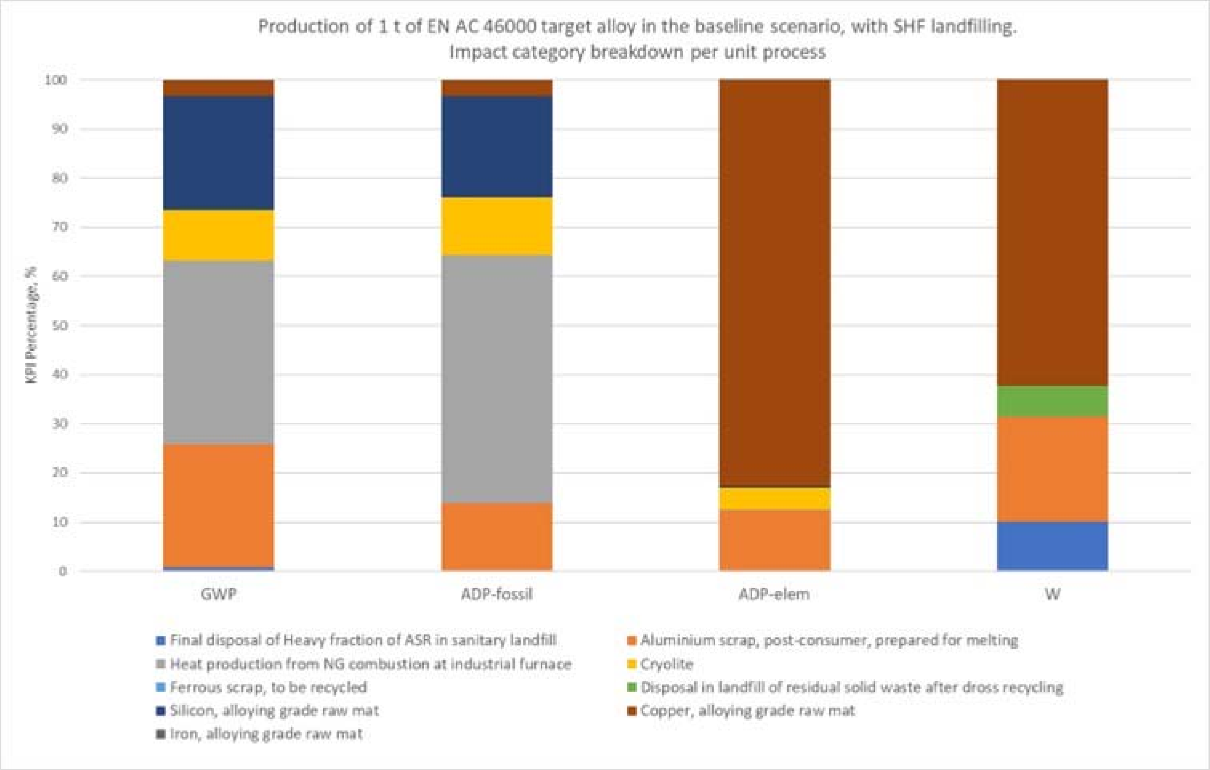


Figure 15 – Environmental profile of REF use case at the baseline. Breakdown of the impact indicators (Midpoint) per unit processes in the system.

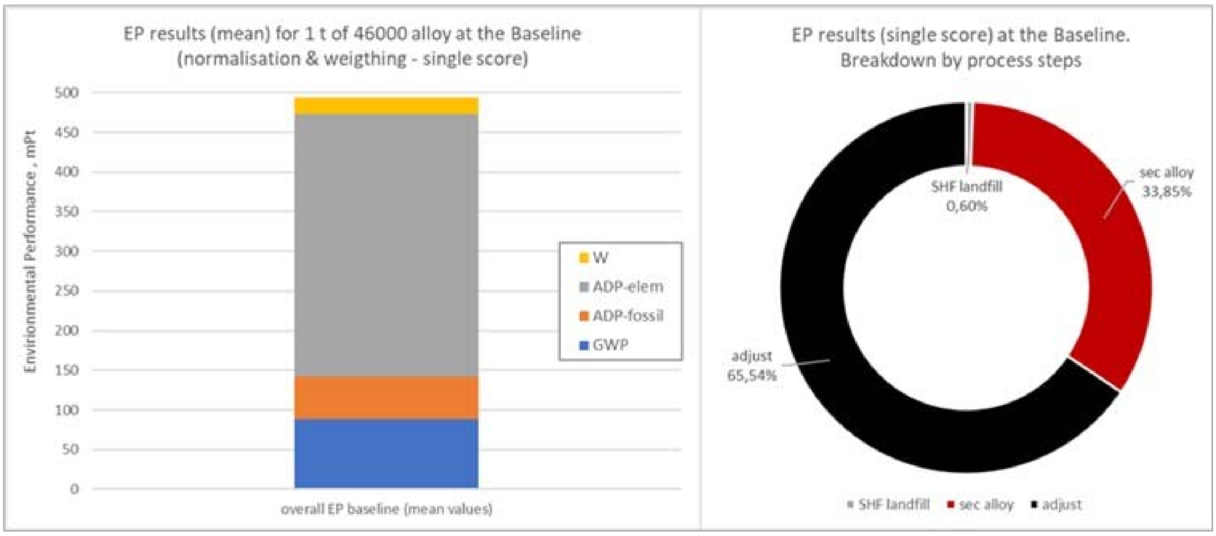


Figure 16 – Environmental Performance of REF use case at the baseline: EP single score results. Breakdown by impact category (left) and by main process in the system (right).

The replicate trials performed in the baseline scenario have allowed calculating the variability of the mean of their outcomes (the inventory data), and, with that, having an estimate of the random error in the environmental indicators calculated. Thus, the mean values of the normalised and weighted indicators (which add up to the mean value of 493.662 mPt for the EP score) are represented in the *Figure 17*, showing their corresponding error bars.

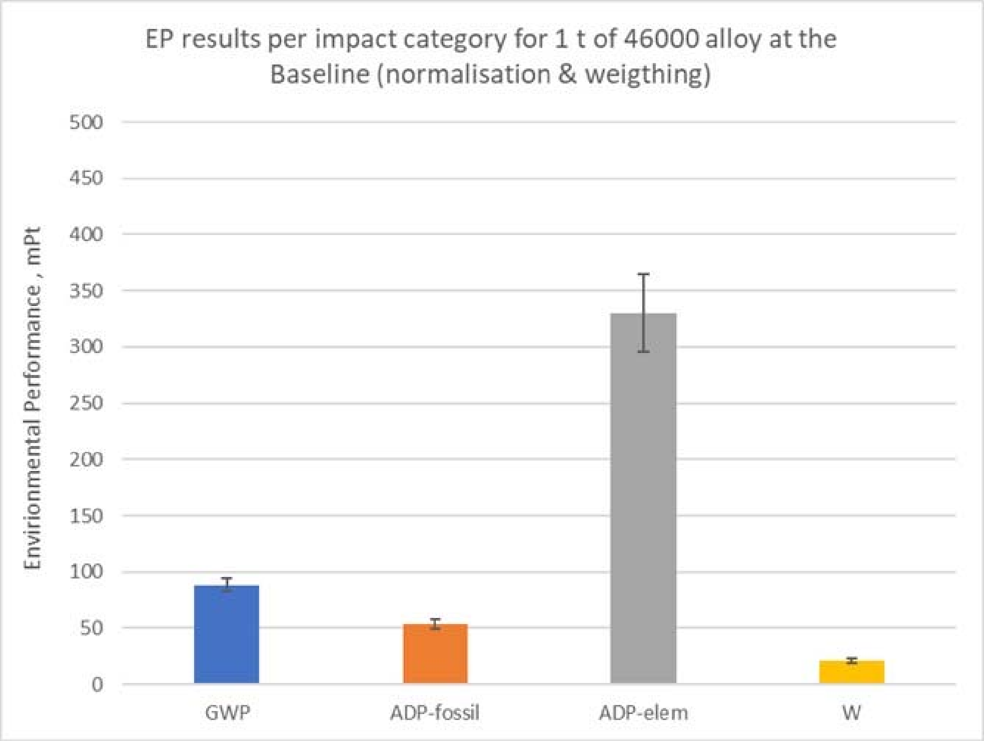


Figure 17 – Variability of the calculated values of the environmental indicators (normalised and weighted) of REF use case at the baseline.

Once that the baseline environmental performance of the system is established, the next step consists in estimating the environmental performance of the revamped scenario, with the aim of quantifying the effect of retrofitting (by scrap preheating) on the values of the environmental KPIs. Given that no experimental data were eventually available for preheating the scrap using WDF combustion, the calculation of impacts in the retrofitted scenario is limited to computing the values of the KPIs for the following process steps:

- *WDF preparation*: preparing WDF from SHF by size reduction and material sorting
- *sec.alloy (300)*: melting scrap mix (preheated at 300 °C) in the rotary furnace into a secondary alloy
- *adjust (300)*: alloying addition needs to correct chemical composition of the secondary alloy within EN AC 46000 alloy limits

The results of the calculations for the revamped scenario (preheating with WDF excluded) are detailed in the *Table 16* and graphically analysed in the *Figure 18*, *Figure 19* and *Figure 20*.

Table 16 – Environmental performance (per tonne of target EN AC 46000 alloy) of the REVaMPed scenario of aluminium refining using preheated scrap (preheating step with WDF exc.). Mean values.

Process in scenario	**GWP** **kg CO_2 eq/t_{alloy}**	**ADP-fossil** **MJ/t_{alloy}**	**ADP-elem** **kg Sb eq/t_{alloy}**	**W** **kg/t_{alloy}**	**EP** **mPt/t_{alloy}**
WDF preparation	3.941	28.110	$3.55 \cdot 10^{-06}$	34.548	**1.142**
sec. alloy (300)	630.373	7282.481	0.017	224.107	**122.419**
adjust (300)	342.462	3820.098	0.071	459.979	**263.862**
TOTAL REVaMPed*	**976.776**	**11130.690**	**0.088**	**718.634**	**387.423**

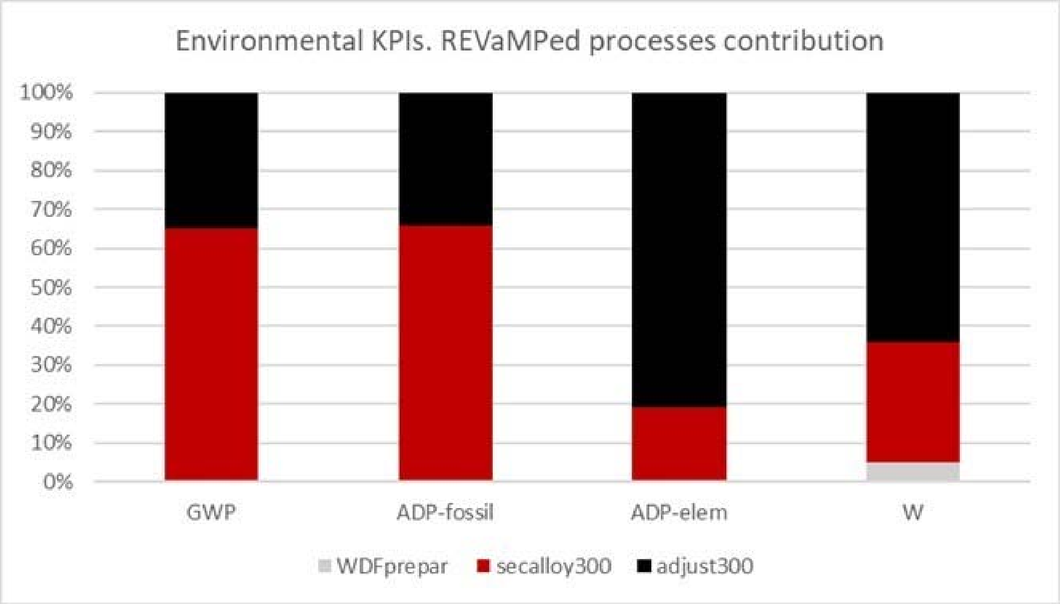


Figure 18 – Environmental profile of REF use case at the REVaMPed scenario. Breakdown of the impact indicators (Midpoint) per main process in the system.

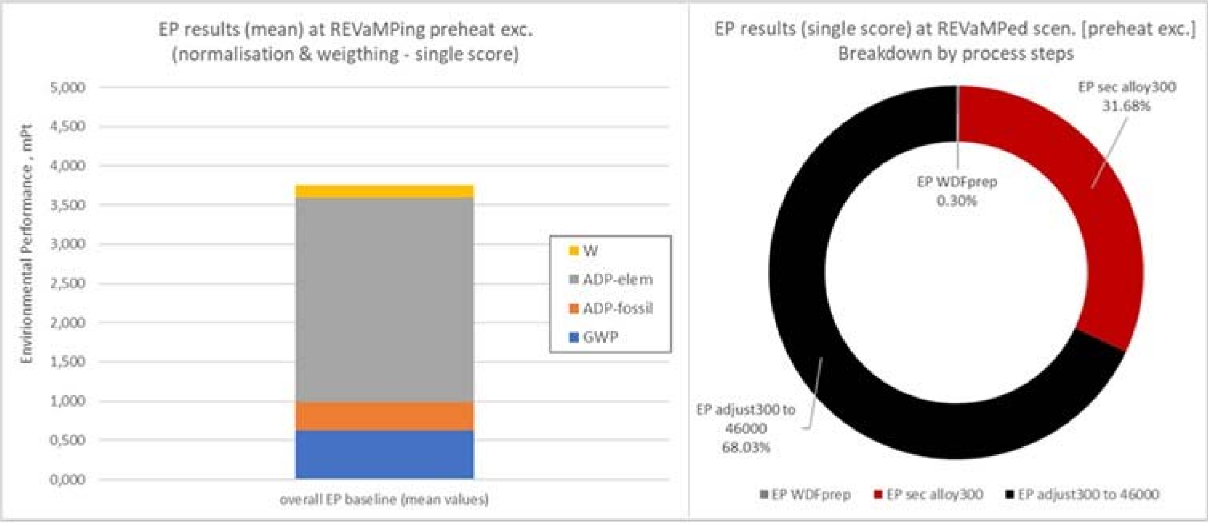


Figure 19 – Environmental Performance of REF use case at the REVaMPed scenario (preheating with WDF exc.): EP single score results. Breakdown by impact category (left) and by main process in the system (right).

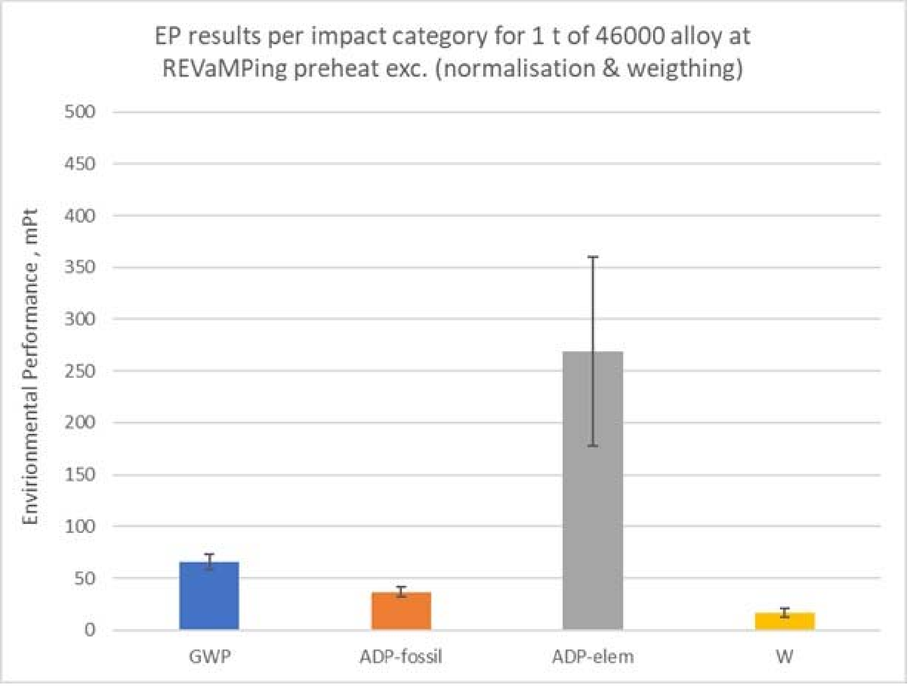


Figure 20 – Variability of the calculated values of the environmental indicators (normalised and weighted) of REF use case at the REVaMPed scenario.

6. Phase 4 – Interpretation

6.1. Interpretation of results for RWTH use cases

Before the results of the impact assessment are discussed in more detail, a sensitivity analysis is carried out for each use case. These analyses aim to illustrate the impact of individual key process parameters for the respective product system. By doing this, additional context is provided to the results of the impact assessment, and more precise conclusions can be drawn.

Steel use case: Sensitivity analysis

For the steel use case, the impact of the electrical energy demand is additionally analysed, to highlight its effect on the values of the impact indicators. As explained earlier, this value slightly fluctuates independent from the installation of the retrofit solutions. Therefore, its influence on the impact assessment provides additional context for the interpretation of the other results. Taking this parameter variation into account, two further life cycle inventories were calculated for the LCA model. The results are shown in *Figure 21* and *Table 17*.

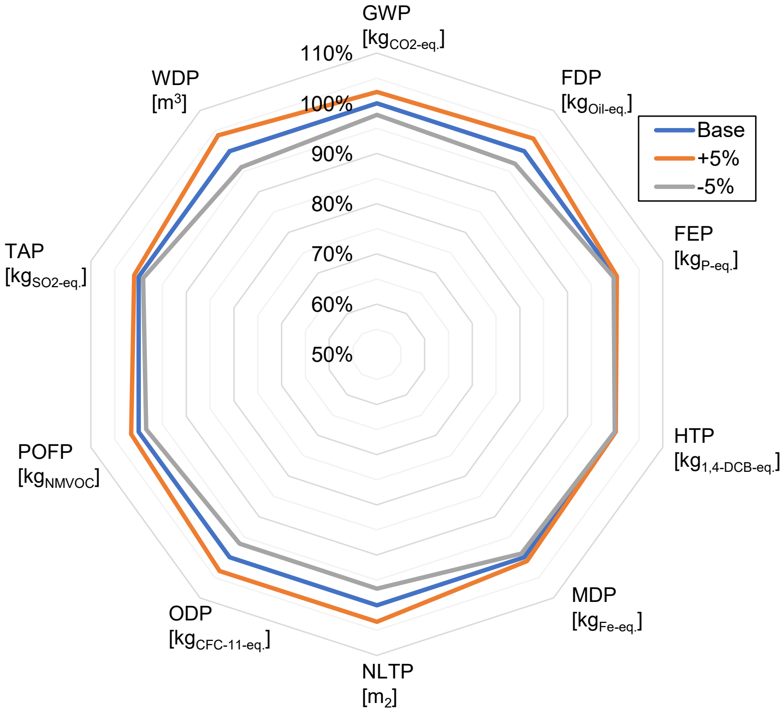


Figure 21 – Results of sensitivity analysis of electric energy demand for steel use case

Table 17 – Results values of sensitivity analysis of electric energy demand for steel use case

Impact indicator	Base case	+5% electric energy demand	-5% electric energy demand
GWP	100.00%	102.28%	97.72%
FDP	100.00%	103.10%	96.90%
FEP	100.00%	100.34%	99.66%
HTP	100.00%	100.08%	99.92%
MDP	100.00%	100.94%	99.06%
NLTP	100.00%	103.30%	96.70%
ODP	100.00%	103.39%	96.61%
POFP	100.00%	101.56%	98.44%
TAP	100.00%	100.94%	99.06%
WDP	100.00%	103.91%	96.09%

First, the sensitivity analysis results for the electrical energy demand are discussed. For this calculation, the electrical energy demand of the base case values has been increased and decreased by 5 %. The resulting impact indicator values are presented again as percentual changes relative to the base case.

Little to know influence is shown on the categories FEP, HTP, MDP, POFP and TAP. All other categories show a high dependency on the electrical energy demand, ranging from 2.2 % up to almost 4 % variation. The highest impact is recorded for the WDP impact indicator. These results can now be used, to give additional context to the impact assessment results of the retrofit solutions. The changes in FEP and TAP can be seen as robust and independent from the electrical energy demand. The changes of other impact categories (such as GWP and FDP) are heavily influenced by changes of the electrical energy demand.

Aluminium use case: Sensitivity analysis

Since the change of the electrical energy demand could not be recorded, the influence on the model is now explored via sensitivity analysis. Similar to before, the electrical energy demand of the dross removal was increased and decreased by 5 %, and the subsequent impact indicator values are shown below in *Figure 22* and *Table 18*.

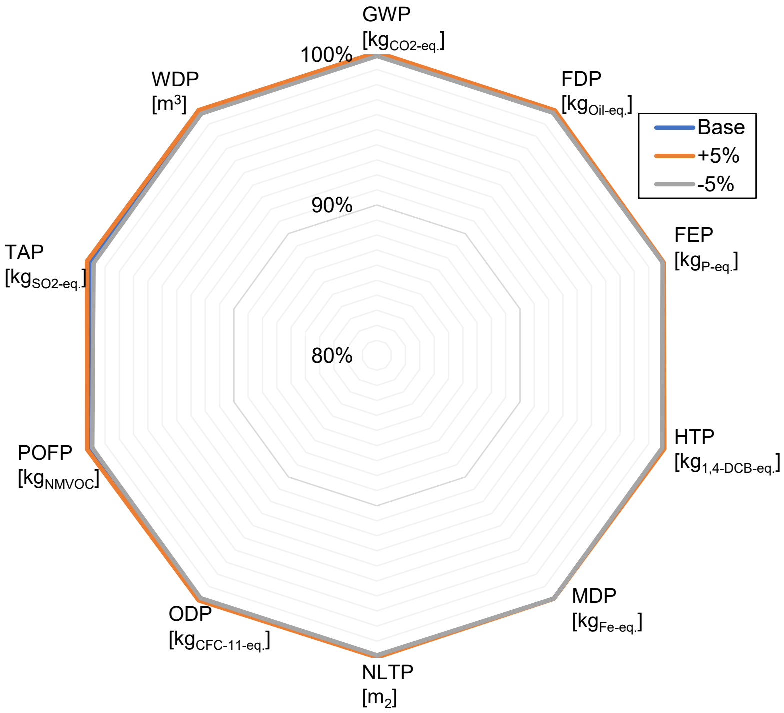


Figure 22 – Results of sensitivity analysis of electric energy demand for aluminium use case

Table 18 – Results values of sensitivity analysis of electric energy demand for aluminium use case

Impact indicator	Base case	+5% electric energy demand	-5% electric energy demand
GWP	100.00%	100.15%	99.90%
FDP	100.00%	100.14%	99.91%
FEP	100.00%	100.03%	99.97%
HTP	100.00%	100.09%	99.94%
MDP	100.00%	100.00%	100.00%
NLTP	100.00%	100.09%	99.94%
ODP	100.00%	100.15%	99.95%
POFP	100.00%	100.25%	99.90%
TAP	100.00%	100.27%	99.80%
WDP	100.00%	100.15%	99.87%

It can be seen, that influence of the electrical energy demand is negligible for all impact indicators. The change in value caused by the variation of the electrical energy demand reaches at most 0.27 %. It can therefore be said, that even without this information the results are representative.

Lead use case: Sensitivity analysis

To evaluate in detail, how the increase of impact indicators is dependent on the usage of external lead bullion, this value is varied for the sensitivity analysis of the lead use case. Again, the value is increased and decreased by 5 %, keeping all other parameters of the model constant. The results are shown below in Figure 23 and Table 19.

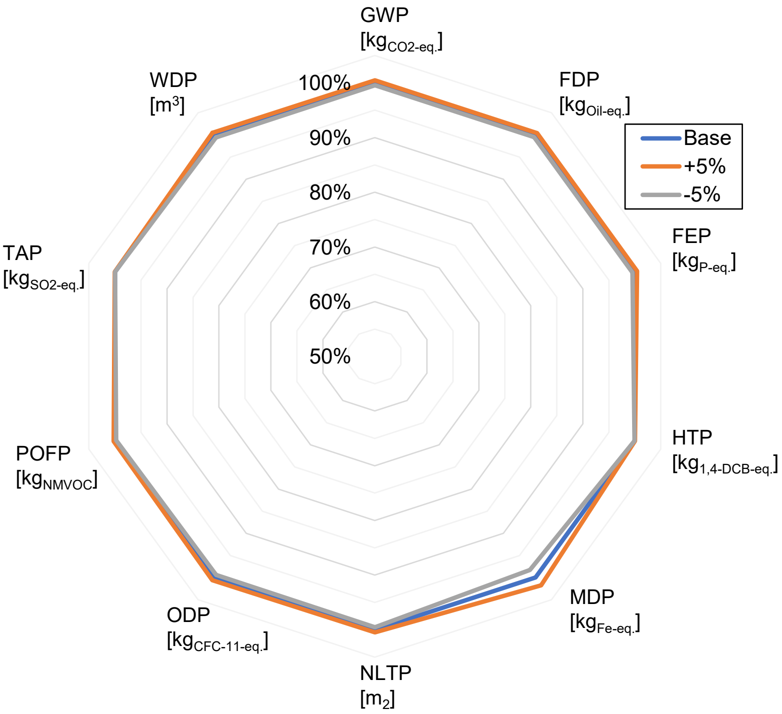


Figure 23 – Results of sensitivity analysis of external lead bullion for lead use case

Table 19 – Results values of sensitivity analysis of electric energy demand for lead use case

Impact indicator	Base case	+5% external lead bullion	-5% external lead bullion
GWP	100.00%	100.46%	99.54%
FDP	100.00%	100.47%	99.53%
FEP	100.00%	100.45%	99.55%
HTP	100.00%	100.05%	99.95%
MDP	100.00%	101.73%	98.27%
NLTP	100.00%	100.47%	99.53%
ODP	100.00%	100.58%	99.42%
POFP	100.00%	100.26%	99.74%
TAP	100.00%	100.04%	99.96%
WDP	100.00%	100.53%	99.47%

It can be seen, that the influence of the externa l bullion is most pronounced for the MDP. In the other categories, the influence of the external bullion is however almost negligible. This leads to the conclusion, that although the increase in external bullion use was very large, the increase in slag formation and other resource usage must've had a larger impact on the indicator values.

Overall interpretation of RWTH use cases results

For two of the three use cases, improvements regarding the environmental evaluation of the process could be quantified after the retrofitting solutions were installed. For the steel use case, the reduced usage of lime and coal proposed by the DPM lead to a decrease in several impact indicator categories, most notably the FEP and GWP. The SOM leads to an increased scrap usage, but on the other hand to a lower electrical energy demand and lower slag formation. These benefits outweigh the higher scrap usage per tonne of steel in terms of the environmental evaluation. It is also debatable, how negative the higher scrap usage is, depending on the type of scrap. For further evaluation, more in-depth analyses over a longer period of time would be necessary.

In the aluminium use case, resource and energy demand per tonne of aluminium could be reduced significantly, which lead to a more favourable environmental evaluation across all impact indicators. Especially the reduction of energy and alloying elements usage was shown to have a significant positive impact in this regard.

For the lead use case, the retrofit solutions lead to a higher consumption of raw materials per tonne of lead produced. Although the energy demand could be reduced, the increased resource usage outweighs these benefits in terms of the environmental evaluation. If the amount of slag produced could be reverted back to base case levels, the increase of the environmental indicators value changes could be reduced to ca. 5 % on average (except for the MDP). This represents an order of magnitude, where natural variations in the process parameters could also cause most of these impact indicator changes.

6.2. Interpretation of results in the assessment of retrofitting at aluminium scrap refinery (energy feedstock use case at Refial)

As can be noticed in the graphs of Figure 14 and *Figure 15* the melting step is the major contributor to the scores of the GWP and ADP-fossil indicators, mostly due to the impacts of the production of heat by natural gas combustion. In contrast, the adjustment step dominates in the indicators for abiotic depletion of elements and waste, because of the high scores of the copper addition in both indicators. The same trend is sustained in the REVaMPed scenario examined (see Figure 18).

When comparing the overall performance of both scenarios, it is observed that the use of preheated scrap at 300 °C in the pilot rotary furnace brings savings of energy consumption, increased yield and reduced chemical correction needs. That results in reduced environmental impacts, as depicted in Figure 24, Figure 25 and Figure 26.

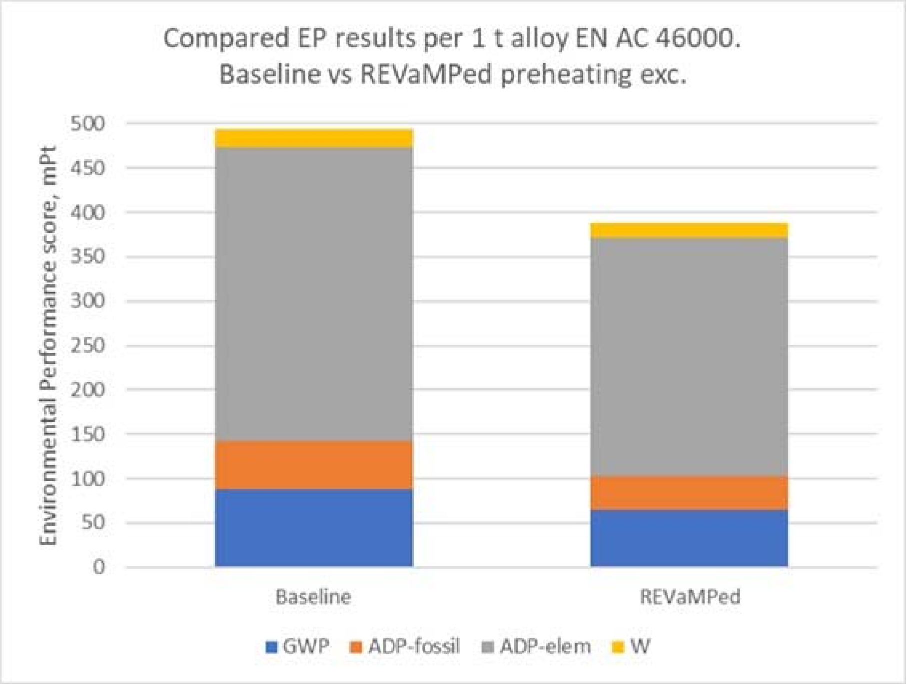


Figure 24 – Comparison of the Environmental Performance of REF use case at the Baseline and the REVaMPed scenario (preheating with WDF exc.): EP single score results. Breakdown by impact categories

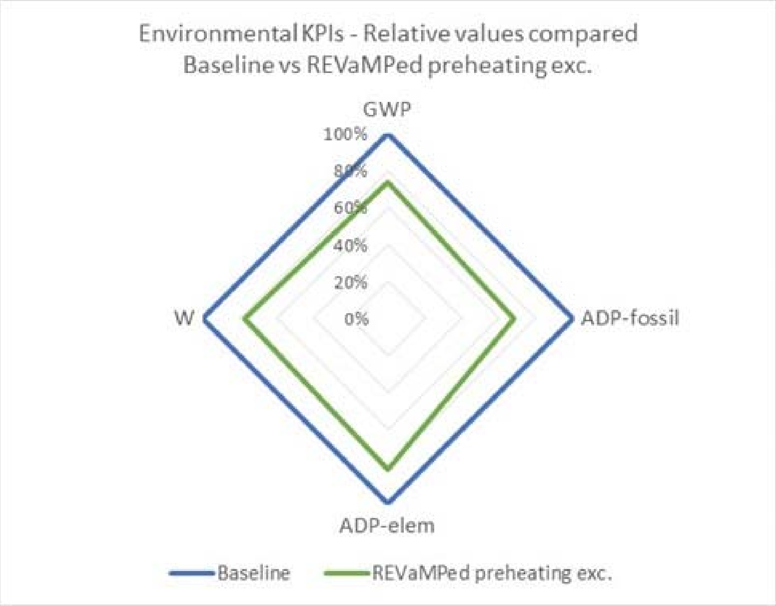


Figure 25 – Comparison of the relative values of the impact indicators (environmental KPIs) at the Baseline and the REVaMPed scenario (preheating with WDF exc.) of the REF use case

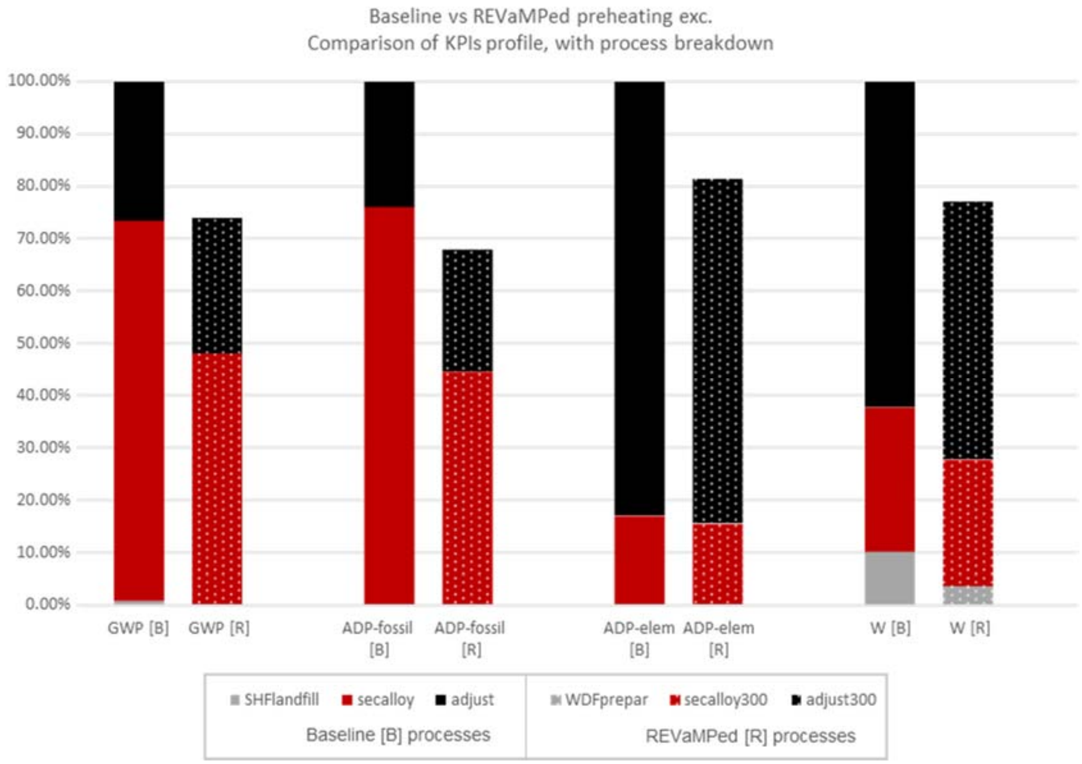


Figure 26 – Comparison of the environmental profiles of the REF use case at the Baseline and the REVaMPed scenario (preheating with WDF exc.). Breakdown of the impact indicators (Midpoint) by main processes in each system

As illustrated in the radar chart of *Figure 25*, impact reductions are achieved in the four impact categories analysed, the largest in the category of depletion of fossil fuels (ADP-fossil indicator), amounting to 32% reduction. The analysis of the impact breakdown by process steps in the two scenarios compared (Figure 26) indicates that in the GWP and ADP-fossil indicators the reduction is mainly obtained in the melting step, while in the W, and especially in the ADP-elem indicator, the global reduction is due to the decreased impacts in the alloy adjusting step. The savings gained in the values of the four KPIs are specified in the Table 20, as well as the reduction relative to the baseline value.

Table 20 – Net savings (per tonne of target EN AC 46000 alloy) and relative reduction of the environmental impacts in the REF use case achievable by using preheated scrap at 300 °C in refining (pilot scale). Mean values

REVaMPED vs Baseline	**GWP kg CO_2 eq/t_{alloy}**	**ADP-fossil MJ/t_{alloy}**	**ADP-elem kg Sb eq/t_{alloy}**	**W kg/t_{alloy}**	**EP mPt/t_{alloy}**
Net savings	-341.31	-5229.07	$-2.00\cdot10^{-2}$	-211.96	**-106.24**
reduction	-25.9%	-32.0%	-18.6%	-22.8%	**-21.5%**

It must be highlighted that, excluding the impacts of the scrap preheating step, the goal of 20% reduced utilisation of energy from fossil fuels would be met (32% reduction achieved), but the reduction of GHG emissions is below the value of 30% targeted, in the retrofitting solution evaluated at pilot scale.

Uncertainty analysis

The previously discussed results are based on the mean scores calculated for the alternative scenarios. However, it is important to understand the role of the uncertainties of the LCA results in drawing conclusions and giving recommendations. A simplified uncertainty analysis have been conducted in the environmental assessment of the retrofitting solution at Refial.

The quantified uncertainties for the results of the environmental indicators (graphically represented in the *Figure 17* for the Baseline and the *Figure 20* for the REVaMPed scenario) denote that the calculated values of the indicator for ADP-elem have the highest uncertainty. That is closely related to the natural variation of the chemical composition of the heterogenous post-consumer scrap, even within each scrap grade, that in small batches as the ones used at pilot scale is still more significant (representativeness issues). Resulting from that, there is a complete overlap of the confidence intervals for the ADP-elem values, what makes the two results to be hardly discernible alternatives in the impact category of Metal & Mineral Depletion. Overlapping ranges also occur for the values of the Waste indicator (also stemming from the variability associated with the adjustment requirements). However, in the case of the GWP and ADP-fossil indicators, the results are consistent and discernibility of 100% along pairs of trials among the two scenarios is achieved. These two impact categories have been defined as the two most relevant in the LCA study, considering the retrofitting objectives of the REF use case in the REVaMP project.

The uncertainties in the category indicators are propagated to the single score EP indicator. As shown in the Figure 27, there is a partial overlap of confidence intervals between the EP values at the baseline and the revamped scenarios. Thus, there are some likelihood that the overall EP values are not totally discernible based on the number of tests run. To overcome this weakness in the interpretation of the overall environmental performance through the values of the EP score, the improvement of the system will be tackled by assessing EP reduction that include reduction of the subset of the GWP and ADP-fossil indicators.

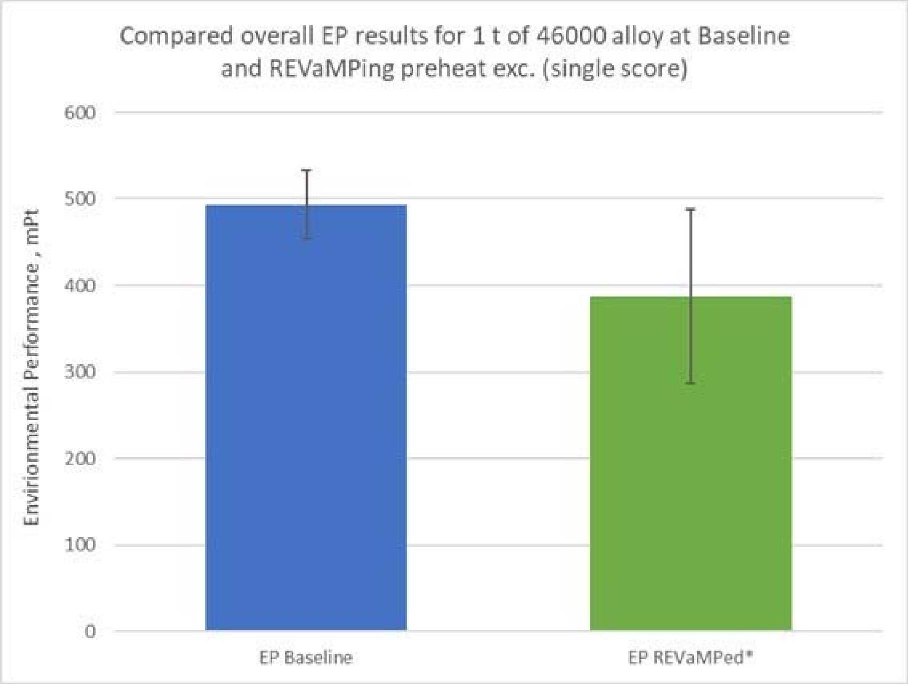


Figure 27 – Comparison of the Environmental Performance of REF use at the Baseline and the REVaMPed scenarios, showing error bars

If the uncertainty is studied by process step in the system in each scenario (charts in Figure 28), 100% discernibility is found for each of the main processes between the correspondents in the two scenarios. Thus, the improvement statements at process step level are assumed to be correctly claimed.

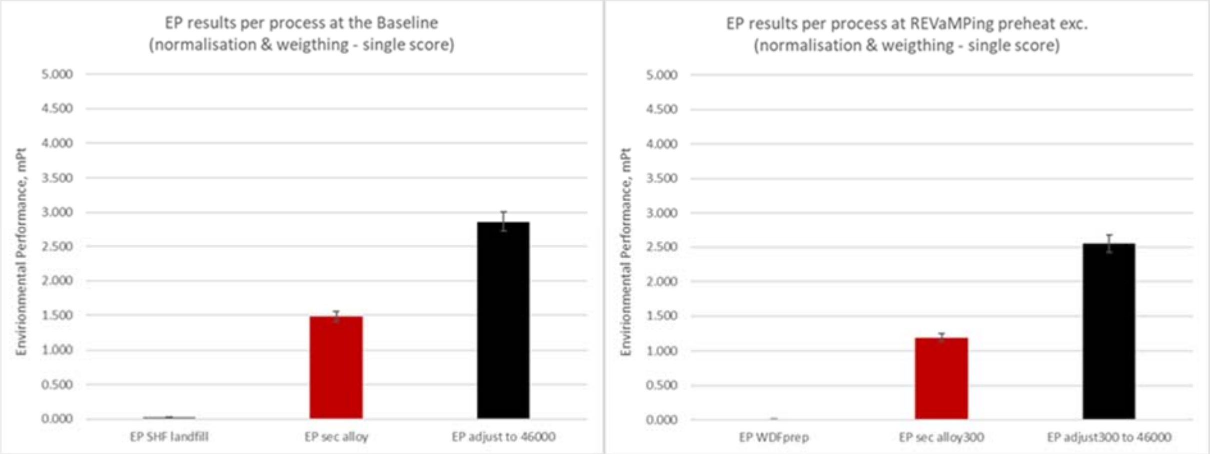


Figure 28 – Comparison of the Environmental Performance of REF use case per process step at the Baseline and the REVaMPed scenarios, showing error bars

Break-even analysis

Taking into account the results detailed in *Table 20* for the retrofitting solution at pilot scale, it can be concluded that, to produce net impact savings in the refining system, the preheating step by combustion of WDF should generate mean impacts scoring below EP=106.24 mPt per tonne of target alloy (see Figure 29). That means the sum of the impacts associated with the combustion emissions to air, with the final disposal of the bottom ashes and with the consumption of auxiliary natural gas and electricity in the pre-heater equipment. Under this criterion, some trade-off among the impact categories might be possible, provided that the overall score would be <106.24 mPt/t_{alloy}.(equivalent to 2.052 mPt/kg_{WDF} combusted, as long as the design ratio 5 kg WDF/100 kg scrap is still applicable). However, as concluded in the uncertainty analysis, the criterion for acceptance of the environmental performance of the preheating step should be established more strictly, setting also the maximum acceptable values of the indicators addressing the relevant KPIs of REVaMP project for the objectives of the use case, i.e., GHG emissions reduction (30%) and decreasing fossil fuel consumption (20%).

The utilisation of energy from fossil fuel during refining is reduced by 32% (5229.07 MJ/t_{alloy}) using scrap preheated at 300 °C. That still leaves 1963.17 MJ/t_{alloy} of energy from fossil fuels (+12% over 20% goal) usable by the preheating system (limit value of the ADP-fossil indicator for the preheating step).

The reduction in GHG emissions achieved in the system when the scrap to be refined in the pilot rotary furnace is pre-heated at 300 °C is 25.9%, i.e. 4.1% less than what was set as the goal (54.12 kg CO_2 eq./t_{alloy} outbalance). That means that not only no net GHG emissions should be originated in the preheating step, but also that CO_2 capture should happen to reach the 30% reduction target. That seems unrealistic for the WDF combustion-based preheater, with the design parameters employed.

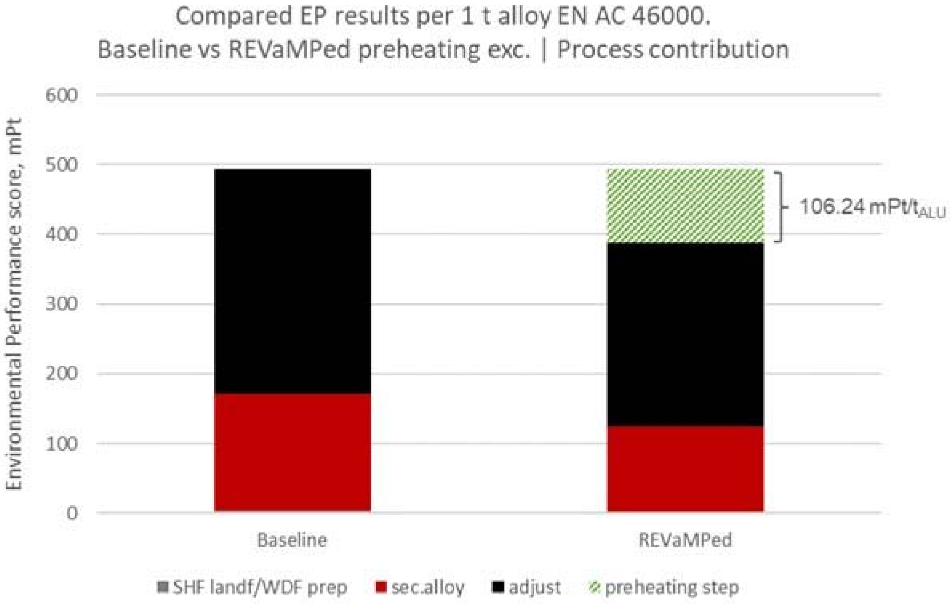


Figure 29 – Comparison of the Environmental Performance of REF use case at the Baseline and the REVaMPed scenarios. Breakdown by process steps of the single score EP values

Nevertheless, in spite of the fact that the GHG emissions reduction goal may not be achieved in the system, using the design parameters for operating the pre-heater (30 min for pre-heating the scrap, nominal electrical power 15 kW) and the modelled CO_2 emissions for WDF combustion (Table 10), the net savings when 51.77 kg of WDF are combusted (amount from the WDF:scrap ratio per 1 t target alloy) can be estimated at 221.02-209.09 kg CO_2/t_{alloy}. That makes a reduction of GHG in the range 16.8%-15.9% against the baseline. This is a rough estimate, as no other GHG emissions from the combustion are considered in the calculation; neither the combustion of assistant fuel (natural gas) in the post-combustor, nor the GWP associated with the disposal of the bottom ashes.

Using the emission coefficients for the WDF, the GWP of the step of WDF preparation and the WGP of the electricity for running the preheater, it is also possible to calculate the maximum mass of WDF that could be prepared and combusted so as not outbalance the CO_2 emissions saved by refining preheated scrap. Depending on the option of modelling in the DOKA tool, the mass of WDF at the break-even point would be 133 or 146 kg/$t_{alloy.}$ (Figure 30). Again, this is likely to be an overestimate, given all the preheater processes missing in the calculation.

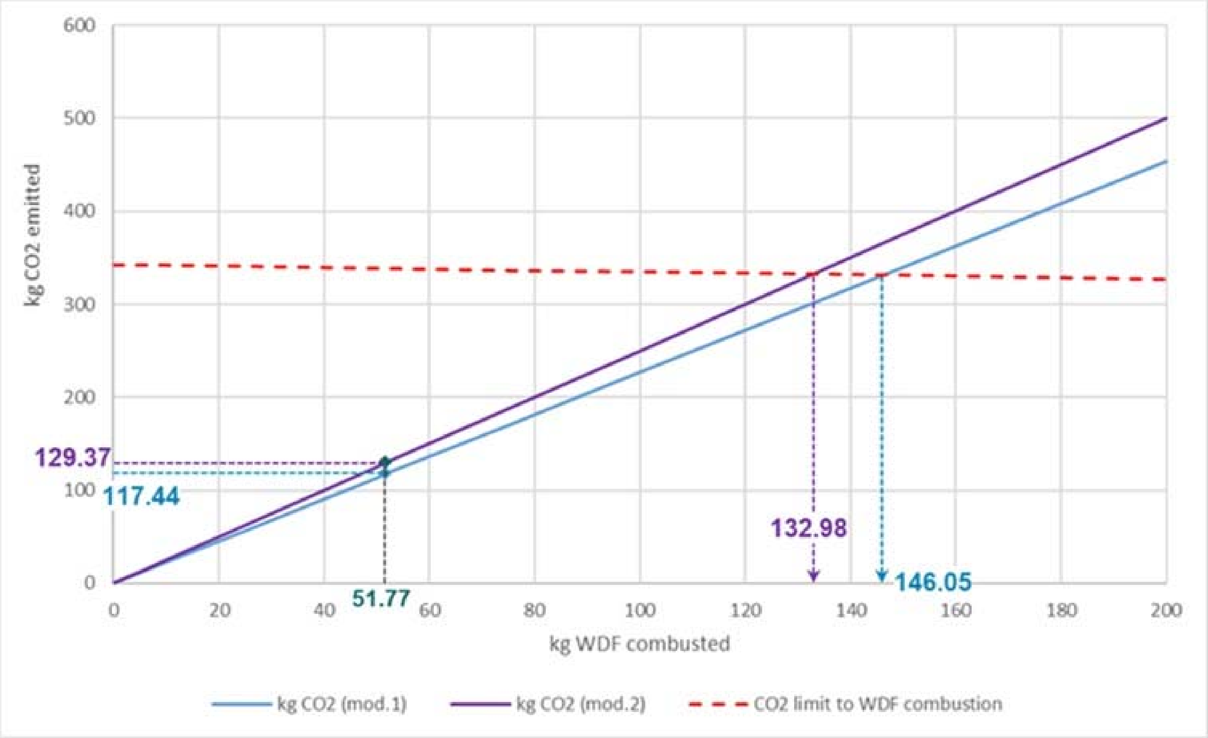


Figure 30 – Calculation of the break-even point for CO_2 emissions from WDF combustion in the REVaMPed scenario

Consistency analysis

For assuring consistency of the environmental evaluations performed by Azterlan and RWTH of the two aluminium refining/remelting cases (REF and GRU, respectively), the two partners revised the congruence of the definitions of system boundaries, hypothesis and LCI completeness of the two aluminium systems.

- Check scope definition and system boundaries for both processes
  - Cradle-to-gate
  - FU (declared unit) = 1 tonne liquid target alloy
- Inventoried flows and data gaps
  - Primary data
  - Databases for secondary data, background processes (ecoinvent)
- Methodological choices

  - LCIA method: Environmental Footprint EF 3.0 (Azterlan) *vs* ReCiPe 2016 (RWTH)
  - EoL allocation (waste & recyclables burdens): recycled content *vs* end-of-life approach
- Inherent sources of differences:
  - Process scale: pilot *vs* industrial
  - Scrap characteristics: mix of 3 heterogeneously sized scrap types, post-consumer (REF) vs chips, pre-consumer (GRU)
  - Target alloy: EN AC-46000 *vs* EN AB-46500.Alloying requirements (adjust step)

A preliminary assessment of the results of the LCAs of the baseline systems of REF and GRU use cases reveals that the values of indicators are in the same range, although main contributing processes differ: Alloying elements (esp. Mg) are the main contributors to impacts in GRU case. In REF case, melting heat (Natural Gas combustion) and cryolite are also significant contributors

Besides, Azterlan conducted a study to check the effects of the methodological choices and the specificities of each melting process. To that end, Azterlan calculated LCA results at the REF baseline scenario (pilot), using ReCiPe method (the LCIA methodology followed by RWTH) and compared the results obtained using that method vs the EF v3.0 method (the one selected by Azterlan to estimate environmental KPIs for REF). Results per tonne of target alloy are represented in *Figure 31* and *Figure 32*. For every impact category, Azterlan identified the flows being the main impact contributors, according to both LCIA methods and quantified the existing divergencies. When it comes to the three LCIA indicators (GWP, ADP-fossil, ADP-elem) chosen by Azterlan as KPIs, it has been found that both EF 3.0 and ReCiPe 2016 produce comparable results. As an example, the numerical results for the Climate Change category indicator (GWP) obtained by the EF 3.0 and the ReCiPe methods differ only by 0.22%. Not only the absolute values of the indicators were similar, but also both methods agreed in identifying the same unit processes as main contributors to the KPIs: heat from natural gas for GWP and ADP-fossil and Cu alloying for ADP-elem. That proves that the main conclusions of the environmental assessment of the REF use case are not influenced by the different LCIA methodology selected by Azterlan.

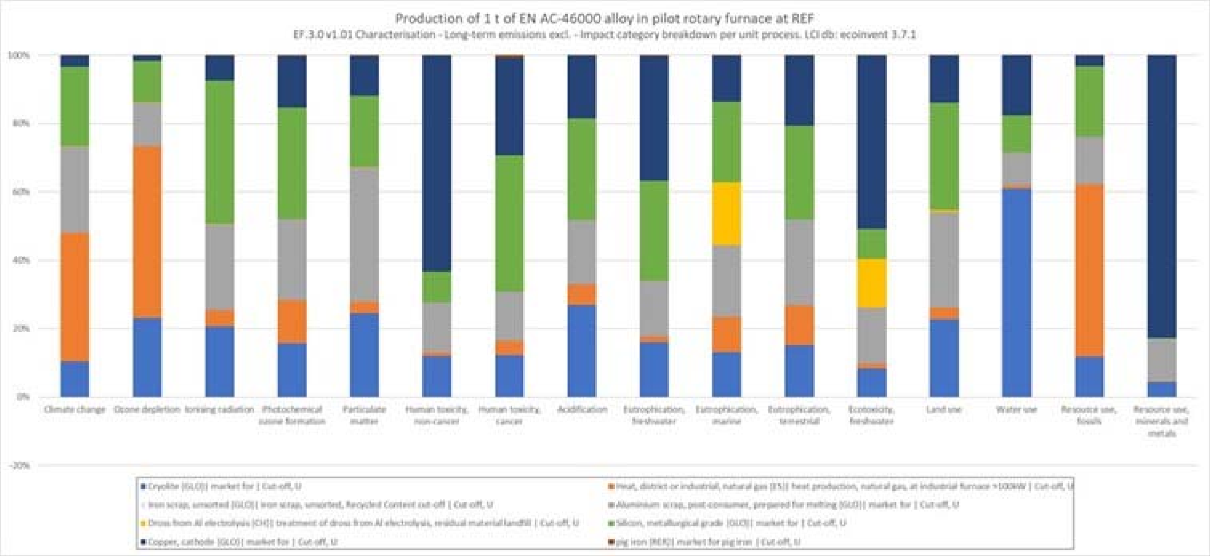


Figure 31 – Environmental profile of the production of 1 t of EN AC-46000 alloy in the pilot rotary furnace of REFIAL: LCA results (method E.F. 3.0, Characterisation) as cumulative impacts per category (unit process breakdown)

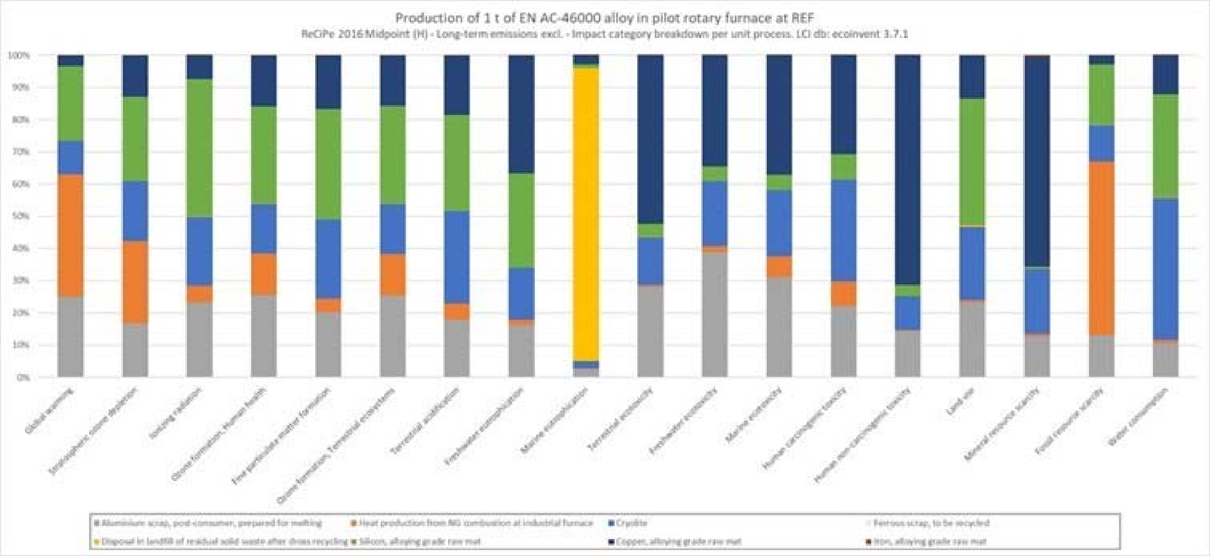


Figure 32 – Environmental profile of the production of 1 t of EN AC-46000 alloy in the pilot rotary furnace of REFIAL: LCA results (method ReCiPe 2016 v1.05 Midpoint) as cumulative impacts per category (unit process breakdown)

Sensitivity analysis

The effect of methodological choices, of using hypothesis for inventory gaps and of the proxies taken for upstream processes on the LCA results have been checked by means of a sensitivity analysis. That consisted in performing the LCA calculations applying the various alternatives to be checked and comparing the differences in the obtained results. The issues identified and checked have been:

- *Cu alloying proxy*: two possible upstream processes available in ecoinvent database: Cu cathode and Cu anode. Using Cu cathode process *vs* Cu anode results in the following differences in the calculated values of the impact category indicators

  - EF 3.0:
    - GWP (+1.3%), ADP-fuel (+1.6%), ADP-elem (-35.5%).
    - Others: Hum.Tox (-15%C; -32%NC), Water (-19%) & Land (-9.8%) Use, AP (+8.5%), EP-fresh (+11.8%)
  - ReCiPe:
    - GWP (+1.3%), Fuel scarc. (+1.4%), Min.scarc. (-23.1%).
    - Others: EcoTox-fresh (+16.4%), Hum.Tox C; -9.9%C), Water (-8.1%) & Land (-8.1%) Use, AP (+9.6%), EP-fresh (+11.8%)

- *Exclusion/Inclusion of long-term emissions in the calculation set-up*: Long term effects have been excluded in the EF 3.0 method basis for the custom-made indicators in REF use case. Excluding or including long-term emissions in the computing of the impact category indicators have the following effects for the LCIA methods:
  - EF 3.0:
    - KPIs (GWP, ADP-fuel, ADP-elem.): null/negligible
    - Largest differences found in Ionising radiation (-110.6%), EP-fresh (-1185%), EP-mar. (-82.8%)
  - ReCiPe:
    - GWP, ADP-fuel, ADP-elem.: null/negligible
    - Largest differences: Ion.Rad. (-857%), EP-fresh (-1184%), EP-mar. (-413%), EcoTox-fresh (-666066%), Hum.Tox (-308%C; -546%NC).

- *Allocation – choice of system models applied in background processes:* two different system models, namely, “Allocation, cut-off by classification“ and “Allocation at the point of substitution” (APOS) are offered in the *ecoinvent* database to meet the demand of different types of studies. They differ solely in the way they treat waste and recyclable materials. In the CUT-OFF, recyclable materials are available burden-free to recycling processes, and secondary (recycled) materials bear only the impacts of the recycling processes. The APOS system model uses expansion of product systems to avoid allocation within treatment systems. This factor is reflected in the resulting impact scores, which are otherwise quite similar. Using APOS instead of CUT-OFF would involve:
  - Adjust step: small differences in KPIs
  - Refining step: large differences. APOS model causes negative results (avoided impact originated in recyclable materials‘ effect: scrap charge and ferrous scrap recovered after melting)

7. Conclusions

In the scientific scope of this report, the implementation of retrofit solutions to optimize resource usage in several metal recycling and processing chains and the resulting environmental effects were investigated. The ecological evaluation of the retrofit solutions was carried out by a comparative life cycle assessment study according to international norms 14040 and 14044. Two participants have been in charge of performing the LCAs of the four retrofitting demo cases: RWTH for the use cases of steel at SIDENOR), aluminium at GRUPAL Art and lead at EXIDE; and Azterlan for the aluminium use case at Refial. The modelling was carried out with the softwares Umberto® LCA+ (RWTH) and SimaPro (Azterlan) in combination with the ecoinvent® database. For all use cases, a cradle-to-gate approach was used, analysing the processes of the industrial partners up to their respective final product. For all relevant input materials, upstream processes were modelled and included in the life cycle assessment by expanding the system border. During the impact assessment phase, ten impact categories were examined and analysed, when the impact assessment methodology ReCiPe-Midpoint Method was chosen (RWTH).Azterlan applied a selected set of impact indicators based on the Environmental Footprint LCIA methodology and one inventory indicator for the disposed waste, both at Midpoint and Endpoint.

The retrofitting solutions lead to an improvement of the environmental evaluation of two of the three use cases analysed by RWTH. The energy demand of the individual processes was reduced, as well as the usage of important resources for two of the three use cases. In the steel use case, environmental impact indicator values could be reduced by the reduced energy and resource usage roughly by 0.7% to 15.6 % in total, depending on the impact indicator. In the aluminium use case, a reduction of impact indicator values between 11.65 % and 13.33 % was achieved following the installation of the retrofit solutions. For the lead use case, after the implementation of the retrofit solutions, an increase between 1.1 % and 50.16 % for the impact indicators was recorded, since a significantly higher usage of energy and materials was documented.

The environmental benefits of the retrofitting solution tested at pilot scale in Refial could not be quantified due to the operational problems arisen with the pre-heater equipment based on WDF combustion. Alternatively, the environmental gains of using scrap preheated at 300 °C during refining were calculated and compared with the impacts caused by the preparation of the WDF theoretically required for the pre-heating step. This analysis demonstrated that the scrap pre-heating leads to an overall improvement of 21.5% (EP single score), with a 32% reduction in the potential of depletion of fossil fuels and CO2 equivalent emissions dropping by 25.9%. Those figures, which do not include the impacts that would be caused by the pre-heating step itself, would constitute the impact limits of the operation of the pre-heater to ensure environmental benefits. Based on the modelled CO2 emissions associated with the combustion of the designed amount of WDF (5 kg WDF/100 kg scrap ratio), and the installed electric power of the pre-heater, a reduction of 16.8-15.9% of the baseline GWP could be achieved. That savings figure should still be diminished by the GWP of the assistant natural gas used in the post-combustor chamber and the GWP of the landfill of the bottom ashes produced.

Regarding all presented results, it is important to keep in mind, that this data, and therefore also the LCA results, could change if the retrofit solutions were evaluated at the plants over a longer period of time. Again, to improve the validity of the results it would be useful to run long-term test series to obtain more data.

Overall, it was shown that the retrofitting solutions can lead to an improvement in the environmental impact. Small investments in optimized process operation or the use of innovative sensor technology can help to improve resource efficiency in the metalworking industry and reduce environmentally harmful emissions.

8. List of Abbreviations

ADP-elem	Abiotic Depletion Potential of elements (i.e. mineral & metals)
ADP-fossil	Abiotic Depletion Potential of fossil fuels
ASR	Automotive Shredder Residue
BFI	VDEh Betriebsforschungsinstitut GmbH
DPM	Dynamic process model
EAF	Electric arc furnace
EP	Environmental Performance score
EURECAT	Eurecat Technology Centre
EXIDE	Exide Technologies
FDP	Fossil depletion potential
FEP	Freshwater eutrophication potential
GHG	Green House Gases
GRU, GRUPAL ART	Grupal Art SL
GWP	Global Warming Potential
HTP	Human Toxicity Potential
KPI	Key Performance Indicator
LCA	Life Cycle Analysis/Assessment
LCIA	Life Cycle Impact Assessment
MDP	Metal Depletion Potential
MFA	Material Flow Analysis
NG	Natural Gas
NLTP	Natural Land Transformation
ODP	Ozone Depletion Potential
POFP	Photochemical Oxidant Formation Potential
REF	Refial (REFIAL - REFINERIA DE ALUMINIO S.L.)
RWTH AACHEN	Rheinisch-Westfälische Technische Hochschule Aachen

SHF	Shredder Heavy Fraction
SIDENOR	Sidenor Aceros Especiales
SOM	Scrap Mix Optimisation System
TAP	Terrestrial Acidification Potential
W	Waste to final disposal
WDF	Waste Derived Fuel
WDP	Water Depletion Potential