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

Preliminary economic assessment

Due Date: June 30th, 2022
Submission Date: September 2nd, 2022
Work Package: **WP 8 – Evaluation of retrofitting solutions at industrial scale**
Lead Beneficiary: **RWTH AACHEN**

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Dissemination level

PU public ☒

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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 novel retrofitting technologies to cope with the increasing variability 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, namely 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 D8.2, "Preliminary economic assessment", is included in the work package WP 8 "Evaluation of retrofitting solutions at industrial scale" of the project.

In the REVaMP project, different retrofitting technologies are applied for each use case, and for this reason, the economic gain will be determined individually. This report will provide the results of a preliminary economic assessment of the retrofitting solutions, based on the already available results of the industrial demonstration cases. For doing so, the economic gain of the integrated retrofitting solutions is evaluated by the industrial partners (AMB, SID, REF, GRU, EXI), including the cost of the necessary hardware components (e.g., sensors, equipment, computer systems, etc.), software and implementation. Taking into account that the retrofitting solutions are still in an early stage of implementation at the moment of preparing this first version of the deliverable, several estimations have to be performed.

In each chapter of this deliverable, the baseline, the assumptions made, and the economic gain estimated taking into account the expected advantages to be obtained with the retrofitting solutions will be calculated in comparison with the baseline.

3. Steelmaking preliminary economic assessment

In liquid steelmaking, scrap is one of the most important metallic input materials. Novel sensors for characterisation of the composition of different scrap types will be applied, to enable the selection of the quality and cost optimal scrap mix. Decision support and model-based control tools will allow to operate the melting processes in oxygen and electric steelmaking in an energy and resource efficient way.

3.1. Preliminary economic assessment at use case of Sidenor

In order to calculate the preliminary economic assessment, the baseline for comparison is established, and the variables to be taken into account are defined. In this section, the preliminary economic assessment of the retrofitting solution compared with the baseline at Sidenor use case is evaluated.

3.1.1. Steel production process at Sidenor

The scrap melting process at Sidenor is performed in the Electric Arc Furnace (EAF). Scrap is charged into the EAF in 2 separate baskets. During the elaboration of the scrap mix recipes, special care is taken with residual, undesired elements like Cu, Sn, P as well as alloy elements like Ni, Cr, Mo. When the concentrations of residual elements are not correctly determined they may cause an elongation on the process time (e.g., further dephosphorization), reclassification of the quality produced or even complete discard of the heat (batch of production), sending it back to the scrap yard for its internal recycling. In any of these 3 cases, lots of resources would have been wasted (electrical energy, lime, coal, ferroalloys, etc.), being the complete discard of the heat the one to avoid by any means. Therefore, the use of safety margins on the estimated scrap composition for the confection of the scrap mix recipes is unavoidable, which is not optimal in terms of the use of resources.

In this project, for the use case of Sidenor, two different tools have been developed for the optimization of the scrap charged and the actual melting process in the EAF.

3.1.1.1. Baseline

The baseline has been established as average data from a comparable previous year. Since 2020 cannot be considered as a normal year due to the loss of production caused by the pandemic, the base data is set in 2021.

3.1.1.2. Retrofitting solution

The solution developed in this project is two-fold: optimization of the scrap mix and a decision support tool for the operation of the EAF meltdown and refining process.

The demonstration activities to be executed regarding the scrap mix optimization will be limited to a defined set of heats where crane operators in the scrap yard will be advised to use as close as possible the optimum recipe prescribed by the scrap mix optimizer. Then the material charge and melting costs in the EAF of the selected heats will be compared with historical data for the production of the same steel qualities.

The demonstration activities to be executed regarding the process in the EAF will also be limited to a defined set of heats. EAF operators, under the specific approval of their manager, will follow the guidelines provided by the decision support tool as far as the guidelines are considered safe and rational. The cost of the melting process following these instructions will be then compared with historical data for the production of the same steel qualities under the same boundary conditions, i.e., similar scrap charge, electrical and oxidation pattern, additions and tapping requirements.

3.1.2. Preliminary economic evaluation at Sidenor

In this section, the variables used in the preliminary economic evaluation at Sidenor will be explained, including all the assumptions that had to be taken into account to estimate the economic gain of the industrial scale.

3.1.2.1. Definition of variables at Sidenor use case

The main variables to take into account in the pilot are:

Operational expenditures OPEX:

- IT Maintenance: dedicated support from internal or external IT resources estimated in 0.01 €/t.
- Electrical energy consumption: estimated reduction of 15kWh/t considering an average price of 111.9 €/MWh in Spain in 2021, the cost reduction is estimated in 1.68 €/t.
- Metallic yield improvement: being this improvement at the very beginning of the process, this is translated in a transformation cost reduction of 1.97 €/t.
- Optimized used of the steel scrap: estimated 10 €/t savings by increasing the amount of low-cost scrap.
- CNQ improvement: Cost of non-quality reduced by about 1 €/t thanks to a better control of the liquid steel composition avoiding heats out-of-specifications that cause defects.

Capital expenditure CAPEX:

For the integration of the models in Sidenor's infrastructure, it is estimated a total expenditure of 20.000€. This initial capital expenditure includes the following aspects:

- Adjustment of PLCs to start measuring new variables.
- Collection of new variables from PLCs to organisational Data Bases.
- Pipeline creation to collect and pre-treat data to dedicated project DB.
- Dedicated computing resources for model implementation in continuous operation.
- External IT support.

3.1.2.2. Results of the preliminary economic evaluation

The models and tools installed at Sidenor are expected to provide an overall saving on the plant operational expenditures. The following table summarizes the most important cost KPIs and the estimated savings according to the improvements specified in the previous section.

Table 1. Economic KPI defined for EAF process with the improvement estimated in the calculation

Economic KPI	Explanation	Estimated savings
Energy cost	Improved process control based on a better scrap characterisation and achieved tapping conditions prediction	1.68 €/t
Transformation cost	By a metallic yield improvement.	1.97 €/t
Raw material cost	Increasing the amount of low-cost scrap thanks to a better characterization	10 €/t
CNQ	Better control of the liquid steel composition avoiding heats out-of-specifications	1 €/t

Final results of the comparison:

- Capex and OPEX retrofitting solution

The overall CAPEX and OPEX of the retrofitting solution at industrial scale is estimated as follows. Note that the OPEX of the retrofitting solution in this use case only includes the expected IT maintenance cost.

CAPEX	OPEX
20,000 €	8,000 €

- Economic gain of retrofitting solution

The economic gain due to the retrofitted solution is estimated considering a 5-year amortization. As it can be seen in Figure 1, where savings/costs are represented by ton of production, the costs related to the implementation and maintenance of the solution are negligible compared to the estimated savings.

The total economic gain per ton of steel produced is estimated to be 14.64 €/t.

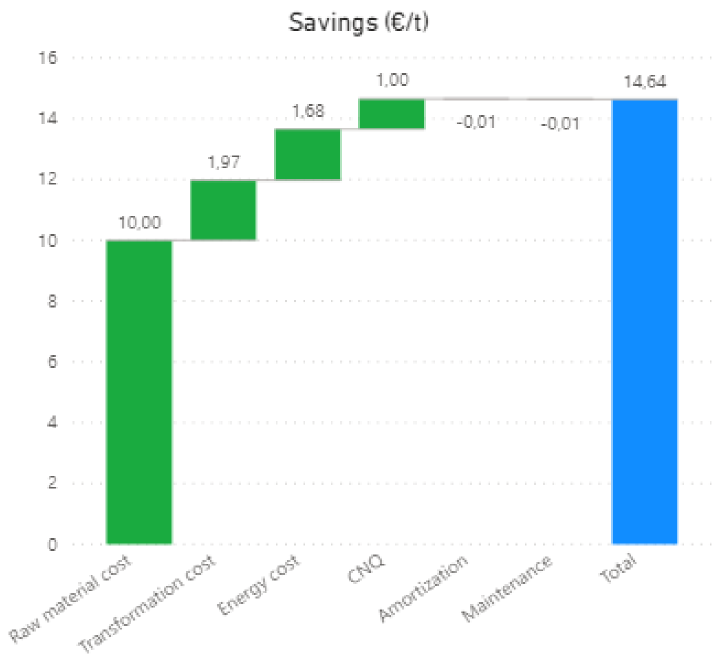

Figure 1. Increase of the economic gain due to retrofitted solution.

3.2. Preliminary economic assessment at use case of ArcelorMittal Bremen

In order to calculate the preliminary economic assessment, the baseline for comparison is established, and the variables to be taken into account are defined. In this section, the preliminary economic assessment of the retrofitting solutions compared with the baseline at ArcelorMittal Bremen use case is evaluated.

3.2.1. Steel production process at ArcelorMittal Bremen

At ArcelorMittal Bremen, steel is produced via the oxygen steelmaking route. Hot metal and scrap are charged in a converter. By blowing oxygen into the melt, the hot metal carbon content is being reduced and unwanted elements, like Si and P, are slagged. The temperature of this exothermic process is being controlled by adding scrap in the converter before start of blowing. The current steel scrap input accounts for around 20-30%. Due to high CO_2 emissions during hot metal production the target is to maximize the scrap input and minimize hot metal input and thus CO_2 emissions.

3.2.1.1. Baseline definition

Scrap input into the converter is being calculated using an existing charge mix optimization model. The total scrap amount to be added into the converter is calculated on a thermal basis using the hot metal analysis and temperature and the target steel analysis and temperature as inputs. Afterwards the model calculates the most beneficial scrap mix using a mix of different post-consumer, pre-consumer and internally recovered scrap types, considering steel quality related constraints for unwanted tramp elements like S, Al, Cu, Cr, Ni, Mo and Sn.

The chemical compositions of the scrap types used during this step are resulting from multiple regression analyses using analyses and masses of charged scrap types, hot metal, tapped steel and slag.

Due to high, and most importantly unpredictable, variance in the post-consumer scrap a significant safety margin for tramp elements, that cannot be reduced in steel (Cu, Cr, Ni, Sn, Mo) is needed. Despite of these safety margins, chemical constraint violations in consequence of scrap pollutions are common.

External pre- and post-consumer scrap is currently only visually inspected at arrival to the plant via truck, train and ship.

3.2.1.2. Retrofitting solution

During the project an installation of different sensors for analysing the load of arriving scrap trucks will be applied. For this application Laser induced Breakdown Spectroscopy (LIBS) and neutron sensors (PFTNA) will be used to analyse the scrap directly in the truck.

Using this technique will on one side allow to further precise the tramp element content of the used scrap types and will make it possible to increase the usage of inexpensive post-consumer scrap by decreasing chemical constraint safety margins. On the other side, scrap pollutions not being detectable visually will be detected and corresponding scrap deliveries rejected to avoid a constraint violation.

3.2.2. Preliminary economic evaluation at AMB

It is to be noted, that as planned, the sensor equipment for LIBS- and PFTNA-Measurements will only be installed during a trial phase for several weeks. To better evaluate the economics of the trial, CAPEX, OPEX and Economic gains will be calculated as if the sensor systems were bought and permanently installed.

3.2.2.1. Definition of variables at AMB use case

Operational expenditures OPEX:

- Workforce

This section includes the cost of the workforce, including salary, social insurance for the worker and the company, and personal income tax. This cost will depend on the type and number of employees required, from managers to administrative and commercial staff.

- Maintenance and cleaning expense

The retrofitting solution could entail a variation in cost for maintenance of the equipment, and this difference must be acknowledged from the economic point of view: dedication time, or any other cost related with new equipment maintenance.

- Production cost

This section encloses electric energy supply for the sensor systems.

Capital expenditure CAPEX:

Since the development of the systems is still ongoing, CAPEX assumptions are based on the currently discussed test setup. Therefore, the Capex consists of:

- LIBS based Sensor System
- PFTNA based Sensor System

Economic Gains:

- Average Scrap Price

If the scrap composition can be analysed, the input of unwanted tramp elements can be better controlled. Therefore, it is possible to increase the consumption of cheap scrap with potentially higher tramp element content. This would lead to a decrease of average scrap costs.

- Avoid chemical constraint violation

Scrap pollutions with unwanted tramp elements (Cu, Cr, Ni, Mo, Sn) lead currently to downgrades and scrapings of produced steel. By analysing the incoming scrap these pollutions can be detected beforehand, so that the polluted scrap can either be refused and sent back to the supplier, or used accordingly in the process, decreasing the amounts of downgrades and scrap production.

3.2.2.2. Results of the preliminary economic evaluation

It is to be mentioned, that the following CAPEX and OPEX are very general estimations since the final setup for the sensor systems is not yet defined.

CAPEX and OPEX for Sensor Systems:

SYSTEM	CAPEX	OPEX
LIBS	370,000 €	75,000 €
PFTNA	900,000 €	90,000 €

Economic Gain:

By increasing the usage of cheap scrap types as described in Chapter 3.2.2.1, a reduction of OPEX for steel scrap of 10 €/t scrap seems realistic. With an average usage of 238 kg scrap/t steel produced and a yearly production of 3.2 Mio. t/y steel this leads to a specific gain of 2.38 €/t steel produced and a yearly gain of 7.62 Mio. €.

In case of scrap pollution, it seems realistic, that 80% of downgrades or scrapings can be avoided. With a yearly production of 3.2 Mio. t/y and a ratio of 0.05% scrapings due to scrap pollution this would lead to a gain of 0.09 €/t steel and yearly gain of 279.5 k€. In this sum a CO_2 price of 82 €/t is already included.

In sum a specific gain of 2.47€ / t steel and yearly 7.90 Mio. €/y is to be expected.

4. Aluminium production preliminary economic assessment

In Aluminium refining, different kinds of old Aluminium scrap are melted to produce, mostly, casting alloys for foundries, supplied according to standards and/or customer specifications. In GRU novel sensors for analysis of the incoming scrap types will be applied. In the second plant, REF, a sensorised scrap preheating system will be installed. Both plants will be equipped with model predictive control and decision support systems to optimize melting processes, for varying charge mix and energy efficiency, respectively.

4.1. Preliminary economic assessment at use case of Grupal Art

In order to calculate the preliminary economic assessment, the baseline for comparison is established, and the variables to be taken into account are defined. In this section, the preliminary economic assessment of the retrofitting solution compared with the baseline at Grupal Art use case is evaluated.

4.1.1. Aluminium production process at Grupal Art

In the industrial process of Grupal Art, the material is melted using a gas burner with the possibility to add pure oxygen to increase the yield of the gas. The normal temperature of the furnace is between 650 and 750ºC.

The production process at Grupal Art starts with a pre-charge of the furnace with scrap. Once the scrap is melted and the furnace is at optimum temperature, the furnace is filled with aluminium chips. The selection of chips is the key to make the different qualities, and the chips are analysed punctually by melting a sample and analysing it. The next step is to analyse the content of the furnace by extracting a sample and analysing the composition of the aluminium bath. The composition is corrected by adding master alloys of each element. Previously to the extraction of each sample and adding new material, aluminium slag is removed by a floating decanting process. Once the composition is corrected and the elements adjusted to the final composition the casting process starts. The final product is reached by casting the aluminium bath into ingot moulds on a belt.

In this project, for the use case of GRUPAL ART, the retrofitting solution will be demonstrated in the production process. One of the main solutions is to implement 4 models to optimize the production process by selecting the scraps, chips, and master alloys. The other main retrofitting solution is the analysis of the full scrap and chips material by analysing the incoming materials with Large Sample Sensors (LSS). One LSS is developed by NCBJ/Syskon, a neutron sensor, and the other LSS is developed by ILT, a LIBS sensor. Both sensors shall analyse the scrap and chips being transported on a conveyor belt resp. in a container.

4.1.1.1. Baseline definition

The main process at Grupal Art is going to be the baseline of calculation, therefore, the main data of production will be analysed. The furnace is heated by a burner, and in this case, the consumption of gas per kg of aluminium will be compared before and after the implementation of the retrofitting solutions. The consumption of gas will explain the reduction of energetic costs.

At Grupal Art, in order to produce certain alloys, some elements have to be added by using master alloys. The amount of each of these master alloys vs the amount of each of the alloys produced at Grupal Art that need all these elements will be compared before and after implementation of the retrofitting solutions. Theoretically, by improving the analysis of raw materials, the final composition of the initial material fed inside the furnace can be better adjusted to reduce the amount of master alloys in the production process.

The main elements that will be evaluated are: Cu, Ti and Ni.

- **Cu** is one of the main elements used in Grupal Art alloys. Cu helps Al alloys by increasing the mechanical properties of the material. Cu also helps the material by increasing the resistance against oxidation.

  The main alloys that are going to be evaluated for Cu consumption are: EN AB-45100, EN AB-46000, EN AB-46100, EN AB-46500, EN AB-47100, EN AB-48000, AS7U3, AS7/8U3, AS8/9U3, AS9GU, AS9U3, AS12U and AS12UNG.

- **Ti** helps in the solidification process of refining aluminium grain. The refining of grain will help to final aluminium reducing the possibility of propagation of microcracks and increasing the mechanical properties.

  The main alloys that are going to be evaluated for Ti consumption are: EN AB-48000, AS7U3, AS7/8U3, AS8/9U3, AS9GU and AS12UNG.

- **Ni** forms intermetallic structures inside Al-Si alloys with Cu and Fe. Working in a hypoeutectic concentration, these structures help on the mechanical properties even at high temperatures.

  The main alloys that are going to be evaluated for Ni consumption are: EN AB-48000 and AS12UNG.

4.1.1.2. Retrofitting solution

Inside the REVaMP project Grupal Art is going to install appropriate sensors for scrap and chips analysis. Furthermore, a model to optimize the feedstock in terms of material and energy efficiency will be applied.

Two large sample sensors are being developed. A first Large Sample Neutron Sensor in PGNAA mode will be used to evaluate the composition of aluminium chips after the drying process of the chips. The process will allow to provide an average composition of each container of chips.

The second sensor in development is the LIBS sensor which will be used to analyse the composition of the aluminium chips online on the conveyor belt used to transport the chips in the drying and oil cleaning process.

The application of those new detectors will provide information about the chemical composition of the chips in different stages, but comparable with each other and with far more information than the actual analysis.

The Decision Support System (DSS) tool developed by Eurecat includes different modules to digitalize and optimize the work done in an aluminium refinery like Grupal Art. Each module focuses on specific objectives, but the tool aims to control the materials available in the warehouse, optimize the use of material, reduce the slag generation as well as the energetic consumption, decrease the final cost and predict the composition. The algorithm is explained in detail in the Work Package 4 of the REVaMP project.

The different models are:

- Main charge mix model: This model, presented in WP2, aims to optimize the cost of the final alloys. The user has to introduce the amount in kilograms of the alloys that shall be produced and the safety coefficient to apply to the alloy standards.
- Alloy adjusting model: The Alloy Adjusting Model was introduced in WP4. The aim is also to optimize the cost of the final alloy but on the ongoing casting. In this case, part of the feedstock materials are already introduced in the furnace and a sample of the mixture is acquired to measure the composition.
- Process control model: In the Process Control Model, presented also in WP4, the information is directly loaded from the Data Storage module. In the interface, the user only needs to choose which test shall be analysed. Once the model is executed, and since it is an anomaly detection model, the interface will indicate with a red or green light if any of the subprocesses in the test was anomalous.
- Mass balance module: The last module has been implemented beyond the scope of the proposal, to provide an extra tool valuable for end-users. Thus, it was not planned or explained in any deliverable. However, thanks to the close collaboration between Eurecat and Grupal Art, the need of defining this function was identified. The model is based on the mass balance equation. The user specifies the amount of each feedstock to load in the furnace and the Mass Balance Model provides the final composition.

4.1.2. Preliminary economic evaluation at Grupal Art

In this section, the variables used in the preliminary economic evaluation at Grupal Art will be explained. There will be some assumptions as of the sensors and the web applications are not ready and implemented yet.

As there is no data with the retrofitting solutions implemented at Grupal Art, there will be only estimations on the energy and cost reduction.

Grupal Art works with raw materials or commodities. All these commodities are dependent on the market value of each commodity. Therefore, it is more accurate to calculate the consumption in kg for each of these commodities and to see if there is a reduction in cost derived from a reduction in consumption.

4.1.2.1. Definition of variables at Grupal Art use case

The values of energy consumption of gas and electricity are direct readings of the general meter. In 2020, a real-time reader was not available at Grupal Art. That is why an average of annual gas and electricity expenditure is carried out to extract the average values of gas consumption per ton of aluminium produced.

The consumption of gas and electricity and raw materials is based on the market price, which is why instead of making a calculation in €, a calculation is made in Nm^3 for gas and in kWh for electricity consumption.

Even when gas and electricity are consumed in other processes, the amount is negligible compared to the large consumption in the furnace.

4.1.2.2. Results of the preliminary economic assessment

The main variables considered in the economic assessment are:

Operational expenditures OPEX:

The OPEX figures regarding average consumption of natural gas, oxygen, electrical energy and alloying materials have been assessed for the year 2021. This data is kept internally but not shown here due to the report being public.

Si is the most consumed alloy, but the program will not help to reduce the amount of Si as all alloys need the addition of Si. Cu is the second master alloy most consumed as it is used in most of the alloys produced at Grupal Art. Even a small reduction of this master alloy will reduce the production price.

Ni is one of the most expensive commodities so as the material that is most consumed by ton of Aluminium produced. Therefore, by detecting the amount of Ni and producing aluminium with high content of Ni, the amount of master alloy needed can be drastically reduced.

Capital expenditure CAPEX:

The capital expenditures are basically covering the implementation of all systems:

- Neutron sensor: The cost of the neutron sensor is estimated initially at the Grant Agreement Preparation. The price of the sensor is 450 k€.
- LIBS sensor: The LIBS sensor is estimated initially at the Grant Agreement Preparation. The price of the sensor is 210 k€.
- Decision Support System: The Decision Support System is a software; the estimation of costs is defined by Eurecat as a yearly license of 4,300 €/year.

Economic gain:

The reduction of gas, electricity and master alloy consumption is for now an estimation, as so far there are none of the retrofitting solutions (RS) applied. The estimation with all the solutions applied is:

Table 2. Consumption values for Grupal Art use case

Economic KPI	**Improvement estimated**
Gas consumption (Nm^3/t)	- 13.7%
Energy consumption (kWh/t)	-13.3%
Oxygen consumption (Nm^3/t)	-8.3%
Cu consumption (kg/t)	-22.6%
Ti consumption (kg/t)	-11.2%
Ni consumption (kg/t)	-15.1%

The reduction is achieved due to choosing better the aluminium chips due to better knowing the materials' composition, and a better choice of the feedstock materials. This optimization will also reduce the times of batches as less material is needed to correct the alloy, so less energy is needed.

4.2. Preliminary economic assessment at use case of Refial

REFIAL is an aluminium refinery dedicated to the supply of aluminium from secondary smelting, whose facilities are based on the latest technology in aluminium refining for optimum use of the waste treated. In order to calculate the preliminary economic assessment, the baseline for comparison is established, and the variables to be taken into account are defined. In this section, the preliminary economic assessment of the retrofitting solution compared with the baseline at REFIAL use case is evaluated.

4.2.1. Aluminium production process at Refial

In the industrial process of REFIAL, the material is melted using one burner supplied with oxidizer and with fuel. This melting process is usually carried out in batches, being the materials charged into the furnace in one or more successive cycles, till all the scrap is charged. The order in which the scrap charge is performed will depend on the characteristics of the selected scrap from the scrap mix, like coatings, moisture, granulometry, among others. Salt flux is also added to protect the aluminium metal from oxidation and to absorb and remove contaminants and oxides. The furnace keeps rotating to mix the scrap and the melts, being the operation temperature normally around 750 °C. Once the melting has finished, the furnace is tilted to pour the aluminium out, remaining the dry slag in the furnace. After each cycle, the dry salt slag is tipped out, and the furnace is quickly cleaned. Before the melting metal is introduced in the reverberatory furnace, a sample is taken in order to analyse the composition, that will be adjusted in the refining process. The alloy composition is adjusted by adding element additions in order to meet the adequate range for each metal defined in the corresponding standard. Finally, the resulting bath of molten metal is then poured into a casting machine to produce ingots. In the pouring process, and in the final ingots, more samples are taken in order to analyse the composition of the alloy.

In this project, for the use case of REFIAL, the retrofitting solution will be demonstrated in the pilot rotary furnace, and, for doing so, a baseline has to be defined. The retrofitting solution consists of a preheater in which aluminium scrap will be heated up by combustion of waste derived fuel (WDF), and this system will be connected to the pilot rotary furnace. In the following sections these scenarios of comparison will be described.

4.2.1.1. Baseline definition

The main process consists in a preheating step of the furnace, increasing its temperature until it is prepared to receive the scrap, then is charged manually. Afterwards, the combination of heat introduced by the burner and the rotation of the combustion chamber melts the material, generating a bath of aluminium over which the dross floats. Once the aluminium is totally melted, a probe is casted by tilting manually the furnace, and then the dross is manipulated inside the furnace to drain the remaining aluminium by the addition of salt. When this process is finished, the total amount of aluminium is weighted and the yield of the scrap is calculated. In the last phase, the dross is extracted from the furnace and the combustion chamber is cleaned. Then, the furnace is ready for another scrap sample melting (after a preheating if the chamber has lost temperature).

Specific conditions were established in order to define the baseline scenario, to compare its performance with the one that will be obtained with the retrofitting solution. Five replicated melting trials were performed in the pilot rotary furnace at those designed conditions on 5 different days, estimating their mean and standard deviation.

The fixed conditions for the baseline scenario were the following:

- **Target alloy**: EN AC-46000, that is the most commonly produced alloy 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 2).
- Use of fluxes: **no salts used, except for the one** to improve coalescence. Based on the quantity of scrap added in the pilot furnace, the nominal mass of required salt 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 five trials were scheduled at the same hour in the morning for the five days.

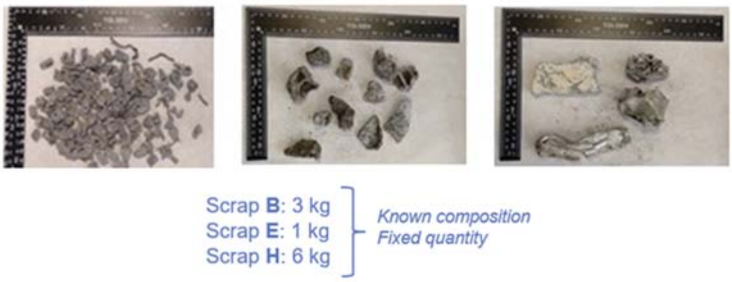

Figure 2. Fixed scrap mix composition selected for scrap charge of melting runs in the Baseline Scenario

During the experiments, time records were kept of every operation (door opening, sampling, temperature measuring, aluminium alloy tapping, slag tapping, etc.) and of the total duration of the melting process. GHI provided the corresponding data from sensors collected online: the values vs time of the following variables: door open, burner on, partial and totalised gas flow, tilting degree, tilting pump on, rotating speed.

Besides, for each melt performed, the following information was measured manually:

- Weight of each scrap type in the mix charged
- Weight of salt added
- Final temperature, before taking samples.
- Weight of the dross obtained; Weight of aluminium alloy obtained; and Weight of the samples taken for quality evaluation, using those data to calculate the metallurgical yield.
- Alloy quality, by means of onsite measurements performed by AZT researchers using the developed ALU-Q prototype: density index, oxide level, thermal analysis.
- Elemental composition of the obtained alloy (test sample) analysed by spark spectrometry. Based on the results from chemical analyses, the required additions of Iron, Silicon and Copper, to correct alloy composition, adjusting it within the standardised limits of EN AC-46000, were calculated (taking into account the metallurgical yield and composition of alloying products, based on real industrial data from REFIAL).

4.2.1.2. Retrofitting solution

The retrofitting demonstration activities to be executed at the aluminium refinery process of REFIAL comprise the retrofitting of existing pilot rotary furnace by equipping it with a sensorised scrap pre-heater. With this preheater, an additional step is proposed in the usual process of REFIAL, that consists of heating up the scrap before charging in the melting furnace, as it can be observed in Figure 3.

Figure 3. Additional step proposed in REF use case - the preheater system

Retrofitting of this existing pilot rotary furnace was made by equipping it with sensors and connecting it with a sensorised scrap pre-heater consisting of a waste derived fuel (Waste Derived Fuel - WDF) combustor and a heat exchanger.

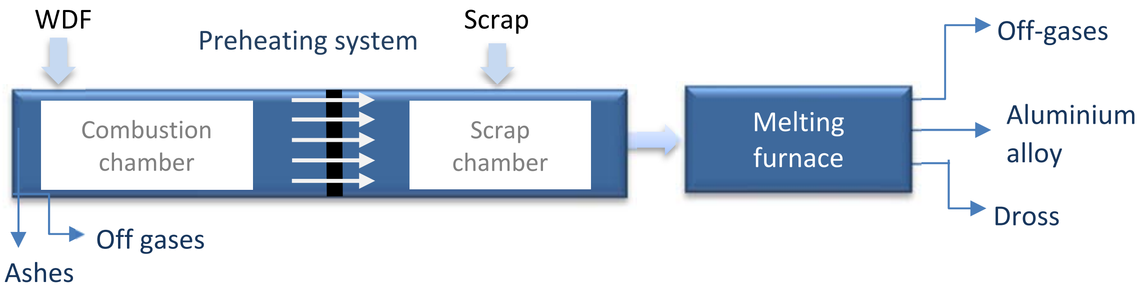

Figure 4. Flowchart of the overall process

By directing hot flue gases from the WDF combustor to a heat exchanger, solid aluminium scrap which is to be melted can be heated up, before charging in the melting furnace. Operation conditions in the preheating system and in the melting furnace will be controlled via sensors, whose recorded data will be combined and analysed by the algorithms of the monitoring and control system, so that scrap will be charged in the furnace when the pre-heating conditions are met and the melting process will be then adjusted to the measured values to optimise melt quality and process efficiency. All this will reduce fossil fuel consumption (gas) in the melting furnace while optimising metal yield and product alloy quality, by implementation of models to predict melting process performance based on furnace operation variables and temperature of pre-heated scrap being charged into furnace; and application of the Software as a Service (SaaS) tool created for optimisation calculations.

In REFIAL refinery use case a polymeric fraction of Automotive Shredder Residue (ASR) will be used as fuel for the scrap preheating system. REFIAL is part of the industrial group *Grupo Otua*, formed of eight companies dedicated to recycling, distribution and research. In the recycling process of end-of-life vehicles led by other company of the group, a polymeric rejection fraction is generated in important quantities (100 kt/a) after metals separation. This waste stream is currently not recovered (mainly landfilled). Considering the specifications established in the European standard CEN 15359 for Solid Recovered Fuels (SRF), that polymeric waste reach calorific values defined for SRF which are currently used in energy intensive industries, such as cement industries. Therefore, this use case would also imply the reduction of consumption of primary resources as energy and the minimisation of total amount of waste generated by the companies in Grupo Otua, being a clear improvement of circular economy.

4.2.2. Preliminary economic evaluation at REFIAL

In this section, the variables used in the preliminary economic evaluation at REFIAL will be explained, including all the assumptions that had to be taken into account to estimate the economic gain of the industrial scale.

The procedure will be as follows: the control variables will be evaluated based on percentage variation in the pilot, in the demonstration tests performed in the project, but no structure or labour costs will be assessed at this scale. The improvements of the control variables will be extrapolated to the industrial case, in which a complete economic gain will be estimated taking into account the workforce and investment, and any other economic costs that have to be included.

4.2.2.1. Results of the preliminary economic evaluation at pilot scale

The main variables to take into account in the pilot are:

Operational expenditures OPEX:

- Energy and gas consumption: Based on the data captured by the sensors in the baseline tests, the energy consumption in the pilot by ton of aluminium alloy obtained is calculated: 0.0018 kWh/t (electric energy) and 1.7 m^3/t (natural gas). Using these numbers as reference, the annual consumption of electricity and gas are estimated in the baseline, calculated with the productive capacity of the pilot rotary furnace.
- Consumables: Based on the productive capacity defined previously, the annual cost required for the salt (0.45 kg per batch), required alloying elements and scrap mix is calculated.
- Maintenance: It is considered an annual review of burners, and a general quarterly review, summing up to 25 hours per year.
- WDF management: taking into account the productive capacity and the energy consumption of the process, the processing and shredded wear costs are calculated. Additionally, as this WDF is destined to landfill, a cost of 35 €/t is estimated.
- Sales: It is considered the price for the aluminium obtained, with the estimation of the quantity of alloy obtained. Additionally, the slag is treated in other company of the Otua Group, that generates a management cost.

Capital expenditure CAPEX:

For the pilot use case, the capital expenditure is not taken into account, as it will be estimated directly for the industrial scaling up.

Economic gain in the rotary pilot furnace:

Taking into account all these variables and estimating an initial ratio of WDF in the preheater of 50 kg of WDF/t Al, with a calorific value of 26.3 MJ/kg, with the percentage of improvement estimated at this stage, the data obtained for the retrofitting solution can be seen in Table 3.

Table 3. Economic KPI defined for the pilot rotary furnace, with the improvement estimated in the calculation

Economic KPI	Explanation	% Improvement estimated
Reduce energy cost	Lower residence time of scrap in the furnace, and partially substitution of fossil fuel by alternative WDF.	25 %
Reduce WDF management cost	Lower cost for the production of the WDF, savings for avoiding landfill.	25 %
Increase throughput	Lower residence time of scrap in the furnace, providing more throughput.	10 %

These assumptions will be applied to extrapolate to an industrial scale, which will be presented in the following section.

4.2.2.2. Extrapolation to industrial scale

For the extrapolation to industrial scale, several assumptions have to be made that will be explained in the section 4.2.2.2.1, and in the section 4.2.2.2.2. the comparison of the retrofitting solution compared with the baseline is analysed.

4.2.2.2.1. Definition of variables at REF use case - industrial

For the comparison, the variables that should be taken into account to evaluate the economic gain are the following: Workforce, Maintenance, productive capacity and production cost in the OPEX, and investment in the CAPEX.

Operational expenditures OPEX:

- Workforce

This section includes the cost of the workforce, including salary, social insurance for the worker and the company, and personal income tax. This cost will depend on the type and number of employees required, from managers to administrative and commercial staff. It is estimated three persons per work shift, and the first year is one work shift, two work shifts in the second and from them on, three work shifts.

- Maintenance and cleaning expense

The retrofitting solution could entail a variation in cost for maintenance of the equipment, and this difference has to be acknowledged from the economic point of view: dedication time, or any other cost related with new equipment maintenance. It is estimated an increase of 2€/t Al with the preheater, due to the cleaning of the ashes in the combustion chamber, and any other maintenance task in the equipment.

- Productive capacity

An increase in the efficiency of the melting process could entail a reduction in the time required for each melt, and this could be directly related with an increase in the productive capacity of the plant, and therefore, in the sales revenue. An increase of 10% of productive capacity is estimated with the retrofitting solution in this initial calculation.

- Production cost

In this variable, the following costs are included: Raw materials, Energy expenditure (including all types of fuels), WDF production cost (take into account the complete process and alternative to dumping) and waste management. It is estimated a reduction of 0.25% over sales in energy and natural gas consumption, and an increase in consumables of 0.1% over sales for the retrofitting solution.

Capital expenditure CAPEX:

In this section, the required investment of the retrofitting solution was estimated, based on the necessary elements to be purchased.

Table 4. Investment in the baseline vs retrofitting solution

Baseline	Retrofitting
1 industrial rotary furnace with peripherals and chimney	1 industrial rotary furnace with peripherals and chimney
-	A complete industrial preheater

The amortization of the investment has also been included in the calculation, considering 10 years for the equipment.

4.2.2.2.2. Economic gain of the retrofitting solution

The overall CAPEX and OPEX of the retrofitting solution at industrial scale is estimated as follows:

CAPEX	OPEX
357,000 €	102,290 €

More accurate numbers will be provided at the end of the project, when all the equipment required in the pre-heater at industrial scale are defined, and a proper estimation of cost can be calculated.

The economic gain due to the retrofitted solution is estimated with a maximum obtained in 2024 of more than 60,000 € / y, that decrease slightly afterwards due to the influence of the corporate income tax.

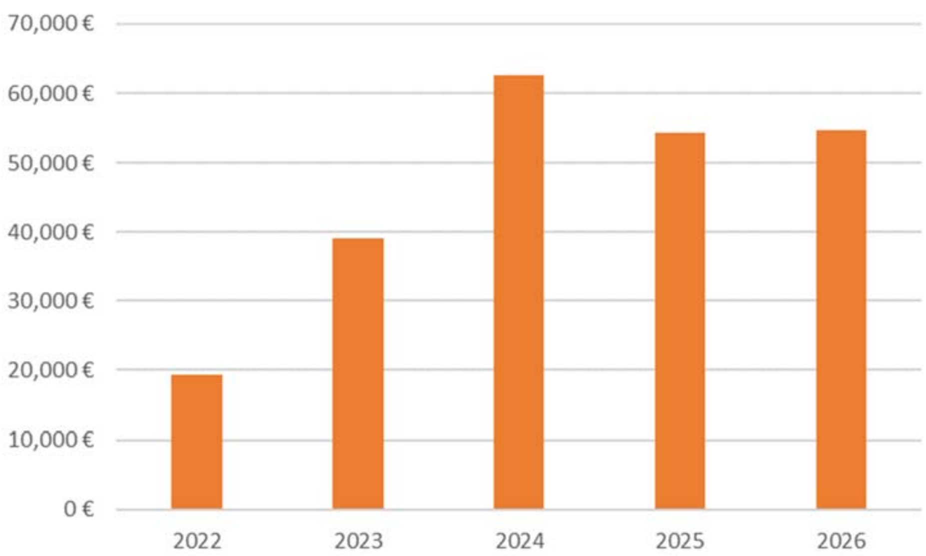

Figure 5. Increase of the economic gain due to retrofitted solution

Additionally, it is estimated the operational cost by ton of alloy ENAC 46000 in 13.34€/t Al in the baseline at the industrial plant, and 10.67€/t Al in the retrofitting solution.

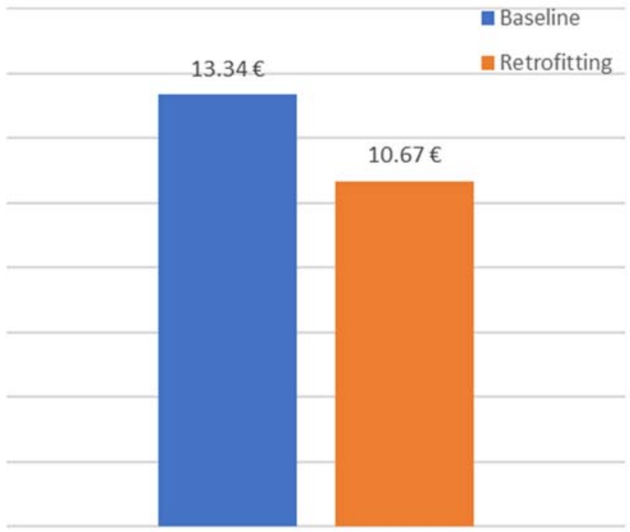

Figure 6. Estimated operational cost by ton of alloy ENAC 46000 for the Baseline vs retrofitting solution

5. Lead production preliminary economic assessment

The lead production process is based on the recycling of lead batteries and other lead containing scrap. Novel sensors will be applied for monitoring the pyrometallurgical process and for scrap characterisation. Furthermore model-based monitoring and control tools will be applied to improve the process efficiency.

5.1. Preliminary economic assessment at use case of Exide

In order to calculate the preliminary economic assessment, the baseline for comparison is established, and the variables to be taken into account are defined. In this section, the preliminary economic assessment of the retrofitting solution compared with the baseline at Exide use case is evaluated.

5.1.1. Lead production process at Exide

In Exide plant the basic charging of the rotary furnace is made by using lead products from the recycling of batteries. Feedstocks are divided into lead-bearing materials, flux and reductant components. The melting process is carried out in batches, being the materials charged into the furnace in successive cycles. The rotary furnace process take place at temperatures between 900º and 1000ºC by the combustion of a mixture of natural gas and oxygen. This temperature, necessary for the promotion of chemical reactions, is achieved by means of an oxi-gas burner. During combustion of the charge, the reducers and fluxes are heated up and the ratio between oxygen and gas depends on the phases that take place in the furnace. At the end of the process two products are obtained, the bullion that contains mostly lead and the slag. When the charge has a high dross content, there is also antimony, tin and cooper. Slag formation occurs during the melting and reduction stages as a result of the different chemical reactions that occur between the agents and the undesirable impurities or compounds in the final product. The sample of the product is taken in the pouring of the lead in order to analyse the composition and make the batch for the kettle. In the kettle the bullion is introduced in order to achieve the final parameters of the alloy.

In this project, for the use case of EXIDE, the retrofitting solution will be demonstrated in the rotary furnaces, and, for doing so, a baseline has to be defined. The main retrofitting solution consists of analysing the combustion and extraction parameters of the furnace in order to reduce the kWh/t necessary for each batch. Another retrofitting solution is the optimization of the charge in the kettles that will reduce the quantity of alloys to be added in the refining process and reduce the preparation times of the recipes.

5.1.1.1. Baseline definition

The smelting process at EXIDE is the main baseline of calculation. This complex process is carried out in the rotary furnaces and takes place in different stages that must be considered. Specifically, four phases are distinguished: organic burning, melting, reduction and casting. First of all, it is important that the loading of material in the furnaces must be carried out optimally to obtain the greatest amount of lead in the bullion and the least in the slag.

On the other hand, it is important to define the ratio between oxygen and gas and the times of each of the phases that take place in the fusion process in the furnaces. The analysis of the temperature in each of the phases has allowed the reduction of the cycle time and consequently a reduction of the consumption of gas and oxygen per casting.

Specific conditions were established in order to define the baseline scenario during 2019 to compare its performance with the one that will be obtained with the retrofitting solution. In the case of optimization tools in furnaces will take into account the consumption of gas and oxygen per ton of lead that will be compared before and after the implantation of the retrofitting solutions. At the same time, the duration of the different stages of the smelting process will be evaluated in order to calculate the reduction of energetic cost due to this solution.

For the optimization tools in the kettles, it is necessary to know the quantity of the alloying elements used. These elements will be compared before and after the retrofitting solution. The main elements that will be analysed are As, Sb, Sn and Cu.

5.1.1.2. Retrofitting solution

In lead use case, a solution called *Smart Visualization Tool* has been developed for the EXIDE plant that includes different modules to optimize the scrap mix and improve the smelting process by increasing efficiency and optimization of the energy per batch.

One of these modules is the optimization of the different phases that take place in the smelting process. The methodology applied in this study model is based on the analysis of pyrometers temperature together with the rest of the parameters of the Programmable Logic Controller (PLC) of combustion and aspiration of the furnaces. The programming is adjusted to connect the different phases of the process with the gas extraction processes inside the furnace.

All parameters are continuously monitored and recorded to optimize certain conditions and introduce improvements to optimize performance and reduce the energy consumption of each batch. By programming these variables, all the indicators can be followed automatically without depending on the operator's settings.

Another tool that will be implemented at EXIDE plant allows the optimization of the charging process in the kettles by choosing the best combination of lead bullion blocks based on the alloys to be produced. The goal is to reduce the amount of alloying elements to be added and reduce the recipe planning process.

Finally, a LIBS sensor is being developed to analyse the percentage of lead in scrap. The measurements obtained from the sensor will allow optimizing the recipes in raw material charging process and improving the efficiency of the smelting process in rotary furnaces.

5.1.2. Preliminary economic evaluation at Exide

In this section, the variables used in the preliminary economic evaluation in Exide will be explained, including all the assumptions that had to be taken into account to estimate the economic gain of the industrial scale.

5.1.2.1. Definition of variables at Exide use case

The main variables to take into account in the pilot are:

Operational expenditures OPEX:

The OPEX figures regarding average consumption of natural gas, oxygen and alloying materials have been assessed for the year 2019. This data is kept internally but not shown here due to the report being public. It is expected that a reduction of the cycle time of 5 minutes could be achievable, which would lead to lower consumption levels.

Additionally, costs for a dedicated external IT support are estimated at 0.09 €/t.

Capital expenditure CAPEX:

For the integration of the models in EXIDE's infrastructure, it is estimated a total expenditure of 40,000€. This initial capital expenditure includes the following aspects:

- PLC reprogramming and installation of data collection system.
- PC server and database.
- LIBS sensor: The sensor price is estimated initially in 210 k€.
- Dedicated computing resources for model implementation in continuous operation.
- External IT supports.

5.1.2.2. Results of the preliminary economic evaluation

In the Table 5 the estimated benefits of the implementation of solutions are shown, taking into account that the reduction in gas consumption in the furnace is due to the implementation of the load models and the reduction in the cycle time of the smelting process. On the other hand, the estimated reduction of alloying elements due to the implementation of the optimization algorithm in the crucibles is indicated.

Table 5. Improvement estimated in the calculation for the economic KPIs in the lead use case

Economic KPI	% Improvement estimated
Reduce oxygen consumption	3.8 %
Reduce gas consumption	3.2 %
Reduce alloying elements	0.9 %

The overall CAPEX and OPEX of the retrofitting solution at industrial scale are estimated as follows:

CAPEX	OPEX
40,000 €	8,000 €

The economic gain due to the retrofitted solution is estimated considering 5-year amortization and an average price of 125 €/MWh in Spain in 2022. The total economic gain per ton of lead produced is estimated to be 5.46 €/t.

6. Final remarks

In this first draft of the deliverable for the economic evaluation, only assumptions were included in the calculation, as the retrofitting solutions are not yet installed in the industrial sites, and some of them are still under development. Nevertheless, an increase in energy efficiency, in resource efficiency and a decrease in GHG emissions, utilisation of fossil resources and OPEX reduction are expected for all the use cases. Additionally, an increase in productivity is also expected with the use of the preheating equipment in the aluminium use case, but the economic gain from this improvement is hard to estimate right now.

Close to the end of the project, when accurate and reliable data can be obtained from the implemented retrofitting solutions and sensors, these calculations will be re-evaluated and updated, and a final version of the deliverable will be prepared, with actual data from the demonstration of the developed technologies and sensors.

7. Abbreviations

AMB	ArcelorMittal Bremen
SID	Sidenor
REF	Refial
GRU	Grupal Art
EXI	Exide
EAF	Electric Arc Furnace
OPEX	Operational expenditures
CAPEX	Capital expenditure
IT	Information Technology
CNQ	Cost of non-quality
PLC	Programmable Logic Controller
DB	Database
KPI	Key Performance Indicator
LIBS	Laser induced Breakdown Spectroscopy
PFTNA	Pulsed Fast and Thermal Neutron Activation
LSS	Large Sample Sensors
NCBJ	National Centre for Nuclear Research
SYSKON	Systemy Kontroli Procesów Przemysłowych
ILT	Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V. , Institute for Laser Technology
EN	European standard
AB	Aluminium ingots
PGNAA	Prompt Gamma Neutron Activation Analysis
DSS	Decision Support System
WP	Work Package
RS	Retrofitting solution
WDF	Waste Derived Fuel
AC	Component cast in aluminium
GHI	GHI SMART FURNACES
AZT	Azterlan Centro de Investigación Metalúrgica
ALU-Q	Aluminium quality prediction equipment
SaaS	Software as a Service
ASR	Automotive Shredder Residue
SRF	Solid Recovered Fuels